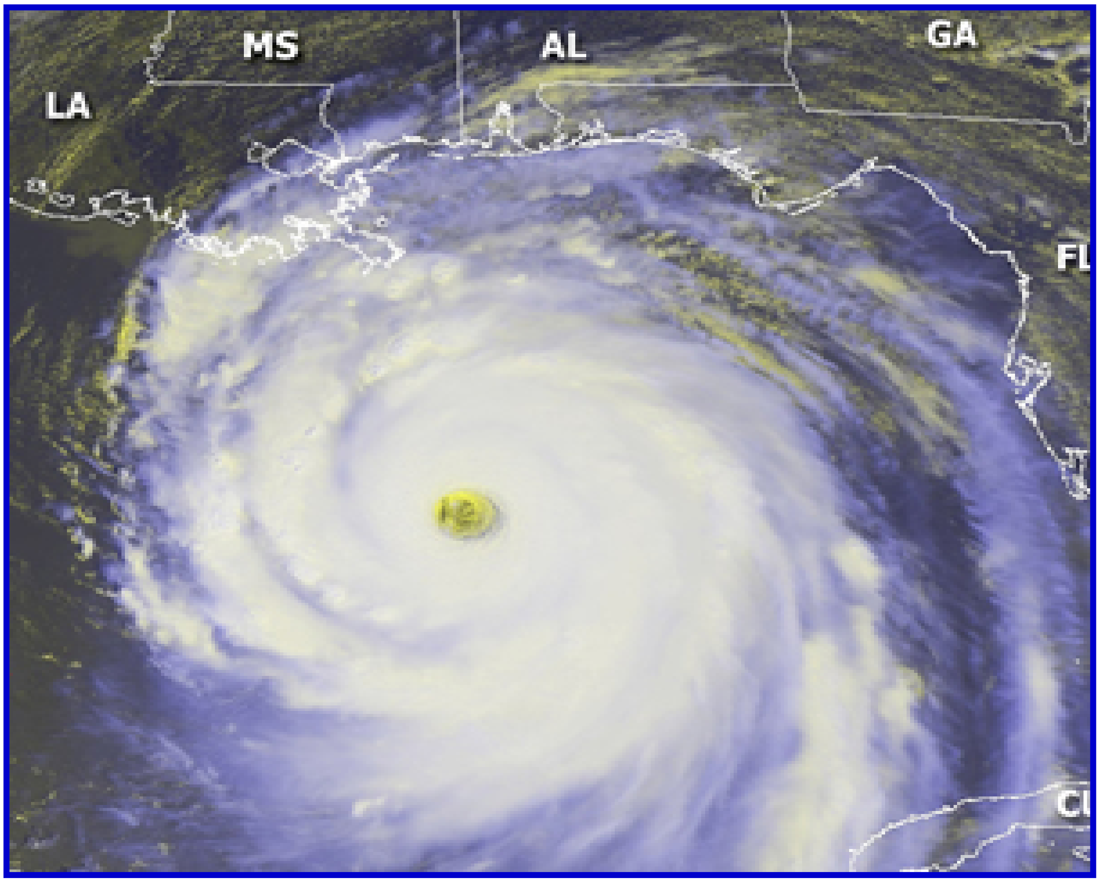
INTERAGENCY STRATEGIC RESEARCH PLAN FOR TROPICAL CYCLONES

THE WAY AHEAD

FCM-P36-2007



February 2007

Office of the Federal Coordinator for Meteorological Services
and Supporting Research

Front Cover Photo Credit
Hurricane Katrina, August 28, 2005: As of 1800 UTC, located 180 mi SSE of the mouth of the Mississippi River and moving NW at 13 MPH. Maximum sustained winds were 175 MPH, making Katrina a category 5 storm on the Saffir-Simpson scale. (Courtesy of NOAA, http://www.osei.noaa.gov)

Federal Committee for Meteorological Services
and Supporting Research (FCMSSR)

Interdepartmental Committee for Meteorological Services
and Supporting Research (ICMSSR)

Committee for Cooperative Research (CCR)

Joint Action Group for Tropical Cyclone Research (JAG/TCR)

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Office of the Federal Coordinator for
Meteorological Services and Supporting Research

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FOREWORD

The 2004 and 2005 Atlantic hurricane seasons demonstrated the vulnerability of the U.S. mainland to landfalling tropical cyclones. Given the continued economic development and population growth along the Atlantic and Gulf coasts, we know that the relatively benign 2006 season was a welcome respite but not an enduring end to the danger these storms present to persons, property, and coastal ecosystems. Economic losses to landfalling hurricanes on the U.S. mainland have roughly doubled each decade from 1900 to 2005. If a reminder were needed, there were dangerous typhoons in the western Pacific and tropical cyclones in the Indian Ocean—the same kind of meteorological event as Atlantic hurricanes, merely blowing under a different local name—to show that the tropical cyclone threat to populations and the environment, economic well-being, military operations, and U.S. interests abroad is still with us and global in extent.

In the spring of 2004, the 58th Interdepartmental Hurricane Conference recommended that a comprehensive strategy be developed to guide interagency tropical cyclone research and development (R&D) over the next decade. That recommendation was subsequently supported by both of my key coordinating committees: the Interdepartmental Committee for Meteorological Services and Supporting Research and the Federal Committee for Meteorological Services and Supporting Research (FCMSSR). This R&D plan presents a comprehensive strategy, developed over the past two years by members of my staff and the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM)-sponsored interagency Joint Action Group for Tropical Cyclone Research (JAG/TCR).

Highly accurate meteorological forecasts that can be used to ensure that credible hurricane warnings are issued in a timely manner are an essential factor in avoiding injury or loss of life and reducing property loss and economic disruption. The strategy presented here focuses on R&D and the transition of research to operations to meet the current and future operational needs of the forecast and warning centers. Equally important, all civilian and military operations in harm's way must have confidence in these forecasts and warnings; they must understand them and take appropriate actions to protect people and property and, when necessary, evacuate to safer locations. We need to continue and expand efforts to ensure that timely information from our operational centers reaches decisionmakers and that they are prepared to act on that information. For this reason, this plan emphasizes research in the social sciences, aimed at improving the efficacy of the education and dissemination factors in the end-to-end system by which the ultimate users of forecasts and warnings, those in the path of a dangerous storm, can be better prepared to respond.

Another vital element in this plan is its recognition of the diverse community already deeply involved in tropical cyclone operations and R&D. Working partnerships already exist among the operational forecast and warning centers, the operational modeling centers that support them, a number of R&D-oriented Federal entities, the academic community, and an increasing number of partners in the private sector. Capitalizing on these partnerships, the plan has taken a grass-roots approach, working from the operational priorities and current programs and plans of the FCMSSR partner agencies. It highlights future capabilities and research priorities that are required to meet the operational needs of the Nation's tropical cyclone forecast and warning centers. The plan also incorporates the strengths of existing partnerships and presents cogent recommendations for expanding and enhancing them, to achieve the effective transition of successful research results into operations.

This plan is complemented by and consistent in many aspects with two other concurrent reports—the National Science Board's Task Force on Hurricane Science and Engineering (HSE) report entitled, *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative*, and a report issued by the National Oceanic and Atmospheric Administration's Science Advisory Board (SAB) Hurricane Intensity Research Working Group (HIRWG).

I want to express my deepest gratitude for the hard work and long hours expended by my staff and the members of the JAG/TCR. As shown in the membership list on pages v–vii, you can see that the plan before you is a product of collaboration extending across multiple agencies. It provides a strategy for ensuring that collaboration and coordination remain the watchword for the next decade of work in confronting the extreme threats posed by tropical cyclones.

/S/

Samuel P. Williamson
Federal Coordinator for Meteorological Services
and Supporting Research

MEMORANDUM FOR: Mr. Samuel P. Williamson
Federal Coordinator for Meteorology

FROM: Cochairpersons, Joint Action Group for Tropical Cyclone Research (JAG/TCR)

SUBJECT: Plan on Interagency Strategic Research Plan for Tropical Cyclones

The JAG/TCR has completed its assigned task to develop a comprehensive strategy for tropical cyclone research and development to guide interagency efforts over the next decade. We are pleased to provide the subject plan, titled*: Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead.*

/S/

Dr. Frank Marks, Cochairperson
Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division
NOAA, Office of Oceanic and Atmospheric Research
U.S. Department of Commerce

/S/

Ms. Robbie Hood, Cochairperson
Marshall Space Flight Center
National Aeronautics and Space Administration

CONCURRENCES:

The undersigned concur that the plan, *Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead*, meets the tasks assigned to the JAG/TCR.

/S/

Dr. Naomi Surgi
NOAA, National Weather Service
U.S. Department of Commerce

/S/

Dr. James Goerss
Naval Research Laboratory
U.S. Department of Defense

/S/

Col Michael Babcock
U.S. Air Force Directorate of Weather
U.S. Department of Defense

/S/

Dr. Ramesh Kakar
Science Mission Directorate
National Aeronautics and Space Administration

CONCURRENCES—continued

/S/

Mr. John Gambel
Mitigation Division, Emergency Preparedness and Response
U.S. Department of Homeland Security

/S/

Dr. Stephan Nelson
Physical and Dynamic Meteorology
National Science Foundation

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Dr. Jack Davis
U.S. Army Engineer R&D Center
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Dr. Christopher Landsea
NOAA, National Weather Service
U.S. Department of Commerce

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Mr. Jeffrey Hawkins
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Dr. Mark DeMaria
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Dr. Ronald Ferek
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Dr. Scott Braun
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Dr. Daniel Melendez
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NOAA, National Weather Service
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/S/

Mr. Mark Welshinger
Senior Staff Meteorologist, OFCM
Executive Secretary, JAG/TCR

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EXECUTIVE SUMMARY

Introduction

The tropical cyclone forecast and warning program is an interdepartmental collaboration to provide the United States and designated international recipients with forecasts, warnings, and assessments concerning tropical and subtropical weather systems. The three centers that cooperate to provide the operational forecast and warning services are the Tropical Prediction Center/National Hurricane Center (TPC/NHC), the Central Pacific Hurricane Center (CPHC), and the Joint Typhoon Warning Center (JTWC) (figure ES-1).

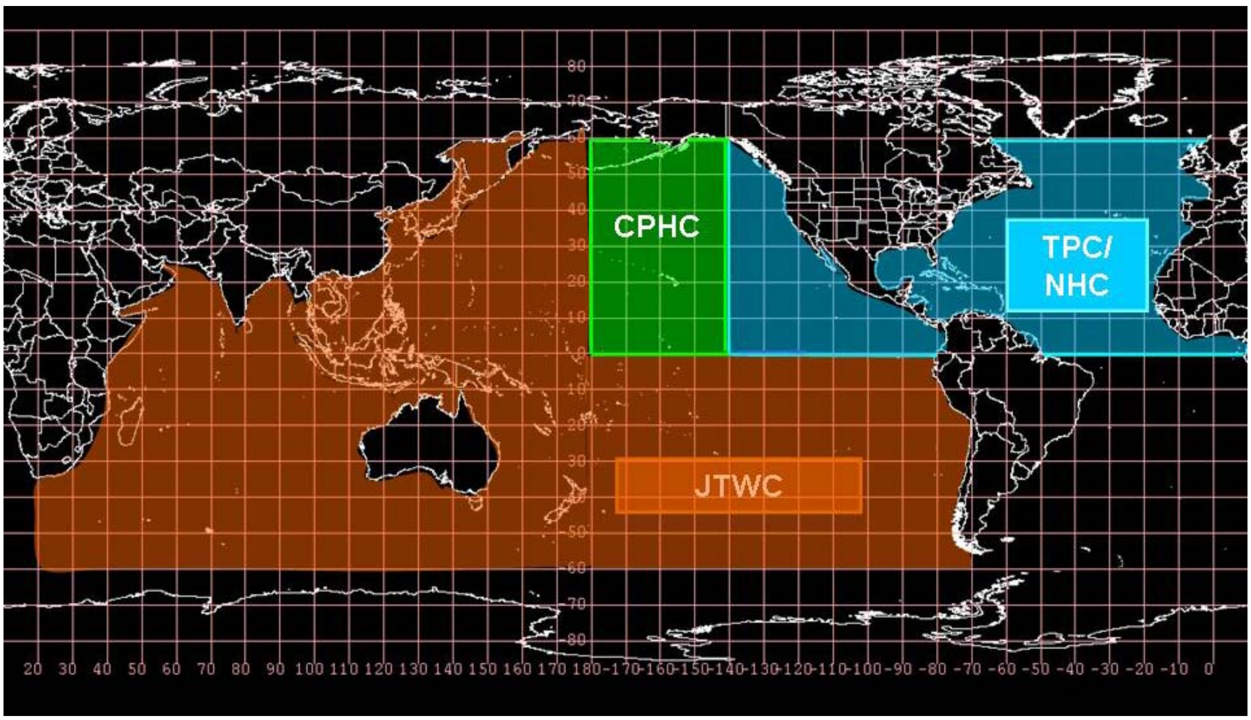

Figure ES-1. Areas of responsibility assigned to the operational tropical cyclone forecast and warning centers. The JTWC area of responsibility overlaps with those of the TPC/NHC and CPHC north of the equator in the central and north Pacific.

This plan, *Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead*, provides a strategy for continuing to improve the effectiveness of operational forecasts and warnings through strategic coordination and increased collaboration among the major players in the operational and R&D communities. The plan represents extensive efforts by the Joint Action Group for Tropical Cyclone Research (JAG/TCR), established by the Federal Coordinator for Meteorological Services and Supporting Research in 2005 to respond to a principal action item, proposed at the 58th Interdepartmental Hurricane Conference in 2004, to develop a comprehensive strategy for tropical cyclone R&D to guide interagency efforts over the next decade. The action item was reviewed and supported by both the Interdepartmental Committee for Meteorological Services and Supporting Research, in November 2004, and the Federal Committee for Meteorological Services and Supporting Research, in December 2004.

Chapter 1 of the plan illustrates the fundamental rationale for continuing the effort in tropical cyclone R&D to further improve tropical cyclone forecasts and warnings. It introduces the operational centers for the Nation's tropical cyclone warning service, serving both civilian and military needs, and the research and operations communities that support the operational centers (referred to as the community of practice).

Chapter 2 describes in more detail the community of practice. Understanding how this community works—its strengths and its limitations—is crucial for formulating and implementing a community-wide, comprehensive strategy for tropical cyclone R&D that can guide interagency efforts over the next decade. Chapter 2 also reviews recent and concurrent planning activities that were taken into account in formulating the research priorities.

Chapter 3 assesses the current capabilities and limitations of the Nation's tropical cyclone warning service. These capabilities constitute a classic end-to-end meteorological warning and forecasting system, from data collection through data assimilation and NWP modeling, to dissemination of warnings and forecasts, including end-user education, training, and outreach.

Chapter 4 uses the same end-to-end system structure to present the JAG/TCR's perspective on the future capabilities required to meet both current operational needs and emerging needs ***identified by the operational centers***. This perspective draws heavily on recent significant planning efforts, as well as on the expertise of the JAG/TCR members collectively and of the R&D and operational organizations they represent. The operational needs of the tropical cyclone forecast and warning centers, as summarized in section 4.1 of the plan, can be characterized by the following seven tropical cyclone–related, day-to-day operational forecast and warning categories (or a combination of these categories):

- Intensity
- Structure
- Track
- Sea state
- Storm surge
- Precipitation
- Observations

In Chapter 5, these future capabilities are translated into a set of research priorities, around which a comprehensive R&D strategy for the next decade can be built. Chapter 6 presents a summary of key findings and the JAG/TCR recommendations for next steps that can be taken by the cognizant Federal agencies and coordinating entities to begin implementation of this strategy.

As emphasized in the plan, meeting the operational needs in these categories will require continued advances in observations, data assimilation technologies, and tropical cyclone NWP models. Absolutely essential to these advances are sufficient human and infrastructure[1] resources

[1] Infrastructure resources are related to items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems.

for tropical cyclone R&D and the transition of R&D results to operations, along with sufficient human and infrastructure resources for the operational NWP environment.

Findings, Recommendations, and Resource Estimates

The plan highlights several key findings, which are discussed in section 6.2. The JAG/TCR's recommendations that follow logically from some of the key findings, which are discussed in section 6.3, are summarized in table ES-1. Finally, section 6.4 summarizes new investments that are associated with the recommendations. The JAG/TCR estimates the additional operational and R&D resources required (above currently programmed budgets), to enable this Nation to meet the operational needs of the tropical cyclone forecast and warning centers, at $85 million per year beginning in fiscal year (FY) 2008 and decreasing to $70 million per year in FY 2017 (in 2006 dollars). As stated in the summary of this plan:

> *Vast improvements in tropical cyclone prediction are attainable with focused research efforts; enhanced transition of research to operations capabilities; strong interagency partnerships, coordination, and planning; and <u>most importantly, sufficient resources</u>—both human and infrastructure. The capability to gain skill in forecasting rapid intensity changes and to improve predictions of hurricane intensity and structure, sea state/storm surge, and precipitation is currently on the horizon, much as improving hurricane track was two decades or so ago. The ultimate goal is to prevent loss of life and injuries and to reduce the Nation's vulnerability to these potentially devastating storms. This goal can and must be accomplished for the good of the Nation.*

Table ES-1. JAG/TCR Recommendations

No.	Category	Recommendation
1	**Tropical cyclone NWP modeling**	The continued development and implementation of the next-generation tropical cyclone forecast systems, such as the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, to improve tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state/storm surge, and precipitation should be a high priority for the Nation. a. Development and transition of research to operations: (1) The development efforts of the next-generation hurricane forecast systems should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies. (2) Sufficient human and infrastructure[a] resources should be provided to support development of advanced data assimilation and NWP modeling systems (see figure 6-1). (3) An interagency working group, under the auspices of the OFCM, should be formed to develop a plan to support the tropical cyclone NWP program. The plan should: (a) include procedures to enhance the flow of relevant research focused on improvements to the operational NWP systems; (b) improve the conduit by which the academic community could be involved in the next-generation hurricane model development and testing (e.g., through the JHT and DTC) and (c) account for having sufficient human and infrastructure[a] resources for development work and transition of research to operations activities, including sufficient resources to support collaborative ventures (see figure 6-1). b. Operations: Sufficient human and infrastructure[a] resources, including the capability to run ensembles with the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, should be provided to NCEP/EMC and FNMOC for their operational NWP tropical cyclone model programs.
2	**Tropical cyclone research and research coordination**	a. **Research** (1) The JAG/TCR recommends strong support for activities focused on the tropical cyclone research priorities identified in chapter 5. (2) Results of social science research need to be an integral part of the hurricane forecast and warning program. With increased funding, a possible venue to pursue social science research questions is through the Joint Hurricane Testbed (without compromising current projects). (3) Sufficient and sustained funding is needed for analyses of field experiment data sets. b. **Research Coordination.** An element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to perform the tasks described in section 6.2.1, paragraph #2. The JAG/TCR recommends that this coordination requirement and development of a research implementation plan be satisfied through the OFCM infrastructure.
3	**Strategic plan for tropical cyclone observations**	Through the OFCM infrastructure, a strategic plan for improved tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.) needs to be developed. The plan should consider observations <u>and</u> observing strategies for tropical cyclone forecaster needs, data assimilation for NWP models, and NWP model diagnostics and verification.

Table ES-1. JAG/TCR Recommendations

No.	Category	Recommendation
4	**Tropical cyclone warning program review**	NOAA (including OFCM), along with Federal agencies, should continue to review and improve the Nation's hurricane warning program.
5	**Education, out-reach, and work-force development**	a. Education, training, and outreach efforts concerning the public's knowledge and appreciation of tropical cyclone impacts must continue, and they must be accorded the priority they deserve. b. To resolve the deficiency within this Nation in producing enough qualified (educated) personnel with the requisite NWP modeling education and training, there needs to be strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities.

[a] Infrastructure resources are related to items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems.

1
INTRODUCTION

1.1 Why is More Hurricane R&D Needed?

The revolution in the accuracy and utility of weather forecasts that has occurred in the past several decades has improved forecasts and warnings for tropical cyclones. The last decade has brought major advances in observing systems (figure 1-1), computing technology, numerical modeling and data assimilation, and the scientific understanding of the physics that underlie various types of weather phenomena, including tropical cyclones.

Nevertheless, further improvements to the Nation's tropical cyclone forecast and warning service are feasible, within reach, and *valuable investments for our safety, security, and economic well-being*. Whether called "hurricanes" (in the North Atlantic and in the Pacific off the coasts of the Americas), "typhoons (in the Pacific west of the International Date Line), or other regional appellations, these severe cyclonic storms are causing increasing amounts of destruction, death, and injury primarily due to the increasing population density and economic infrastructure of coastal regions. Approximately fifty percent of Americans now live within 50 miles of a coastline (NRC 1999) and are thus potentially exposed to the wrath of a landfalling hurricane.

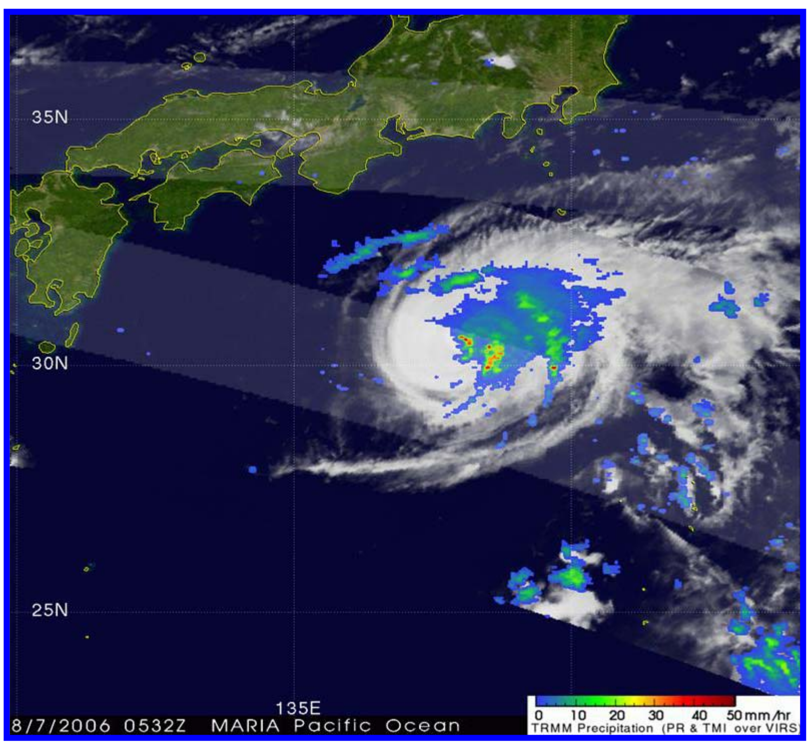

Figure 1-1. This image is made from data received from the NASA Tropical Rainfall Measurement Mission (TRMM) satellite showing Typhoon Maria closing in on Japan (August 7, 2006). Typhoon Maria subsequently weakened and passed just south of Tokyo Bay as a minimal tropical storm. Credit: NASA.

Vulnerability of the U.S. mainland to damage from tropical cyclones has increased primarily because of the growth in population (4.5 percent per year) and wealth along the U. S. coast from Texas to Maine. In a recent analysis of hurricane damages from 1900 to 2005, Pielke et al. (2007) noted that their normalization method agrees with insurance industry data in projecting a doubling of economic losses from landfalling hurricanes every ten years. Vulnerability of U.S. interests overseas reflects increased military presence in regions of high tropical cyclone activity. One important contribution to avoiding loss of lives and reducing vulnerability to hurricane landfall and tropical cyclone movement is highly accurate meteorological forecasts that can be used to ensure that credible warnings are issued in a timely manner. In addition, the public and military operations being threatened must have confidence in those warnings, understand them, and take the appropriate actions to protect property and evacuate when necessary.

The 2005 hurricane season in the North Atlantic and Caribbean region set records for damage to the U.S. mainland. On July 10, 2005, Hurricane Dennis made landfall near Pensacola, Florida, with 105-knot winds and 10-foot storm surges. Florida residents were not strangers to hurricanes, as this was the fifth hurricane to hit Florida in less than a year. On August 25, 2005, Hurricane Katrina killed 14 in southeastern Florida when it brought heavy rains and winds to that region. On August 29–30, Katrina blasted the Louisiana and Mississippi coasts, coming onshore just east of New Orleans (figure 1-2). Katrina's winds and massive flooding left thousands homeless, 2.3 million without electricity, roads and bridges destroyed, and communications inoperable. The storm surge caused by Katrina swamped the Mississippi Gulf Coast, destroying hundreds of homes, roads, and much of the coastal infrastructure. In Hurricane Katrina's wake, the estimated direct fatalities were 1,500, making it the third deadliest hurricane in the United States. Katrina also caused an estimated $81 billion in damages. [1]

Hurricane Rita, which struck the Florida Keys and the Gulf Coast in September after Katrina, is described below. Then, from October 18 to 24, Hurricane Wilma ravaged Haiti, Jamaica, Cozumel, Cancun, Playa del Carmen, and eventually southern Florida. At one point, Wilma

Figure 1-2. GOES-12 1 km visible imagery of Hurricane Katrina; August 29, 2005; 09:57:10. Credit: NOAA.

[1] Official damage and direct fatality estimates, as of January 2007, from the Tropical Prediction Center/National Hurricane Center.

strengthened to category 5 on the Saffir-Simpson intensity scale for tropical cyclones (table 1-1), and on October 19 it became the deepest (lowest pressure) hurricane on record in the Atlantic, with a pressure dropping to 882 millibars. Wilma was the fourth storm in the 2005 season to reach category 5.

The Saffir-Simpson hurricane scale is a rating from 1 to 5, based on a tropical cyclone's present intensity. The Saffir-Simpson category provides an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall.

Table 1-1. Saffir-Simpson Hurricane Scale

Category	Sustained Wind[a,b]	Storm Surge (feet above normal)[b]	Potential Property Damage
1	74–95 mph (65–82 kt)	4–5	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal flooding and minor pier damage.
2	96–110 mph (83–95 kt)	6–8	Some roofing material, door, and window damage of buildings. Considerable damage to vegetation, mobile homes, etc. Flooding damages piers and small craft in unprotected anchorages break moorings.
3	111–130 mph (96–113 kt)	9–12	Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys small structures with larger structures damaged by floating debris. Terrain may be flooded well inland.
4	131–155 mph (114–135 kt)	13–18	More extensive curtainwall failures with some complete roof structure failure on small residences. Major erosion of beach areas. Terrain may be flooded well inland.
5	>155 mph (>135 kt)	>18	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Flooding causes major damage to lower floors of all structures near the shoreline. Massive evacuation of residential areas may be required.

[a] Wind speed, measured as the one-minute average at 10 m elevation.

[b] Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline in the landfall region.

The four case studies of recent severe storms presented below illustrate both the current status of tropical cyclone forecasting and warning and some of the challenges for doing better. These current capabilities and their limitations are documented systematically in chapter 3. The limitations and a prioritized list of operational needs defined by the national operational forecast and warning centers are used in chapters 4, 5, and 6 to derive a set of research priorities and to propose the next steps by which the national research and development (R&D) community—including Federal agency, academic, and industry partners—can work together to meet the challenges posed by tropical cyclones.

1.2 Tropical Cyclone Forecasts and Warnings: Recent Cases

Three of the four storms described here were hurricanes that made destructive landfalls in the contiguous United States (CONUS). They were tracked by the Tropical Prediction Center/National Hurricane Center (TPC/NHC), an arm of the National Oceanic and Atmospheric

Administration (NOAA) in the Department of Commerce (DOC). The fourth was a super typhoon tracked by the Joint Typhoon Warning Center (JTWC), whose primary mission within the Department of Defense (DOD) is to support U.S. military operations and protect defense assets threatened by tropical cyclones in its area of responsibility. Section 1.3 describes the areas of responsibility and roles of each of the U.S. operational centers for tropical cyclone forecasting and warning, along with supporting roles played by the principal elements of the national R&D community.

1.2.1 Hurricane Floyd, September 1999

Hurricane Floyd pounded the central and northern Bahama Islands, seriously threatened Florida, struck the North Carolina coast, and moved up the United States east coast into New England (figure 1-3). Floyd's center paralleled the central Florida coast, passing about 95 miles east of Cape Canaveral on September 15. On September 13, as Floyd neared the Bahamas, it reached its peak intensity of 135 knots—at the top end of category 4 on the Saffir-Simpson scale. After striking Eleuthera and Abaco Islands in the Bahamas on September 14, Floyd weakened but was still a borderline category 3/4 hurricane. A gradual turn to the right resulted in the track parallel to the Florida coast. On the afternoon of the September 15th, Floyd was near the Florida/Georgia border and moved northward toward the Carolinas. The eyewall structure was diminishing as Floyd made landfall near Cape Fear, North Carolina, early on September 16. Storm surges up to 9–10 feet were reported along the North Carolina Coast. Weakening to a tropical storm and accelerating in forward speed, Floyd interacted with a preexisting frontal zone along the Atlantic seaboard, bringing heavy rains that set one-day records in several locations from North Carolina and Virginia to portions of New England. Of the 57 deaths attributed to Floyd, 56 were in the United States. Most were due to drowning in freshwater flooding. Insured losses totaled $1.325 billion, with total damage estimates ranging from $3 billion to $6 billion (Pasch et al. 1999).

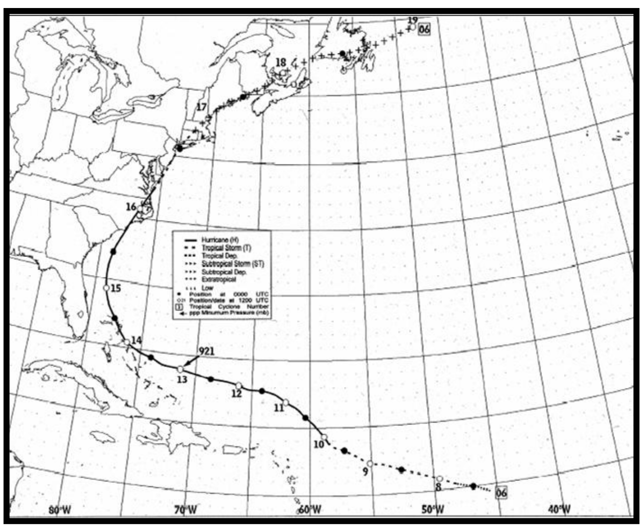

Figure 1-3. Best track position of Hurricane Floyd.

The TPC/NHC began tracking Floyd on September 2 with satellite imagery of a tropical wave emerging from western Africa. Satellite images in the visible, infrared, and microwave bands provided the evidence to name the growing system Tropical Storm Floyd on September 8, while it was still 750 nmi east of the Leeward Islands. In its Tropical Cyclone Report for Hurricane Floyd, the TPC/NHC noted that, averaged over the entire lifetime of the storm, the track forecasts were excellent. However, during the crucial period when Floyd was approaching the U.S. mainland and hurricane warnings were in effect, the official track forecasts and the objective guidance models had a westward and slow bias relative to the best track from observations. Also, the official forecasts did not capture all of the weakening in intensity that occurred after the storm peaked over the Bahamas. From

September 13 onward, the maximum sustained wind speed was overpredicted by as much as 30 to 40 knots (Pasch et al. 1999).

As Floyd moved toward central Florida, the forecast track indicated potential for the western eyewall to reach the coastline. Local forecast products and information sent to emergency managers indicated a likelihood of category 1 hurricane conditions, but they also stressed that a small deviation west of the expected track could bring category 3 winds to the coast. Based on Floyd's strength, the large radius of maximum winds, and the uncertainties in Floyd's forecast track and intensity, local officials ordered a massive coastal evacuation (Kelly, Bragaw, and Spratt 1999). More than 2 million people in Florida evacuated. Floyd's turn to the north, pulled by a mid-latitude trough, in fact came early enough that only hurricane-strength wind gusts and severe beach erosion occurred along the Florida coast.

1.2.2 Super Typhoon 04W (Typhoon Ewiniar), July 2006

An example from the western North Pacific of circumstances where more accurate tropical cyclone forecasts are needed occurred in July 2006. This intense cyclone, locally named Typhoon Ewiniar, severely disrupted military operations in the East China Sea and the Sea of Japan. Forecasts issued by the JTWC called for Ewiniar to move over Sasebo, Japan, where many U. S. military vessels are stationed. Figure 1-4 shows the forecast track issued at 1200 UTC on July 5. In view of these forecasts, ships were sortied (sailed) from Sasebo eastward into the open Pacific Ocean. To execute the sortie, large amounts of shipyard personnel time were expended to ready the ships and move them out to sea. Furthermore, these movements away from their normal stations had a substantial negative impact on the warfighting capability of the U. S. military in the region for the duration of the sortie activity.

As can be seen in the final storm track in figure 1-5, Typhoon Ewiniar in fact took a more westerly track, making landfall on the southwestern coast of South Korea. Preliminary post analysis indicates that more accurate forecasts, including improved numerical weather prediction (NWP) models, would have led to less drastic disruptions, saving money by not moving ships from their port and allowing key U. S. military assets to maintain an uninterrupted readiness posture.

Tropical cyclones like Typhoon Ewiniar and the Atlantic hurricanes impact military operations in every basin. Costs to sortie ships and aircraft can run into the millions each year as decision-makers work to keep assets protected while continuing national security missions. The costs for Hurricane Katrina alone are still being calculated for units along the Gulf Coast that were affected and for units that participated in rescue and cleanup missions. Ships and aircraft routinely operate around tropical cyclones in the northwest Pacific, where the military services incur substantial costs to divert ships or relocate aircraft to keep national security missions on track. Even so, the cost to sortie or divert is far less than the cost to replace an aircraft or ship caught unprepared by a storm-strength tropical cyclone.

Tropical cyclones in the western Pacific differ in some respects from Atlantic basin and East Pacific storms. Typhoons, as tropical cyclones are called in that region, are generally more frequent, more intense, and vary over a large size range. Each tropical cyclone season in the

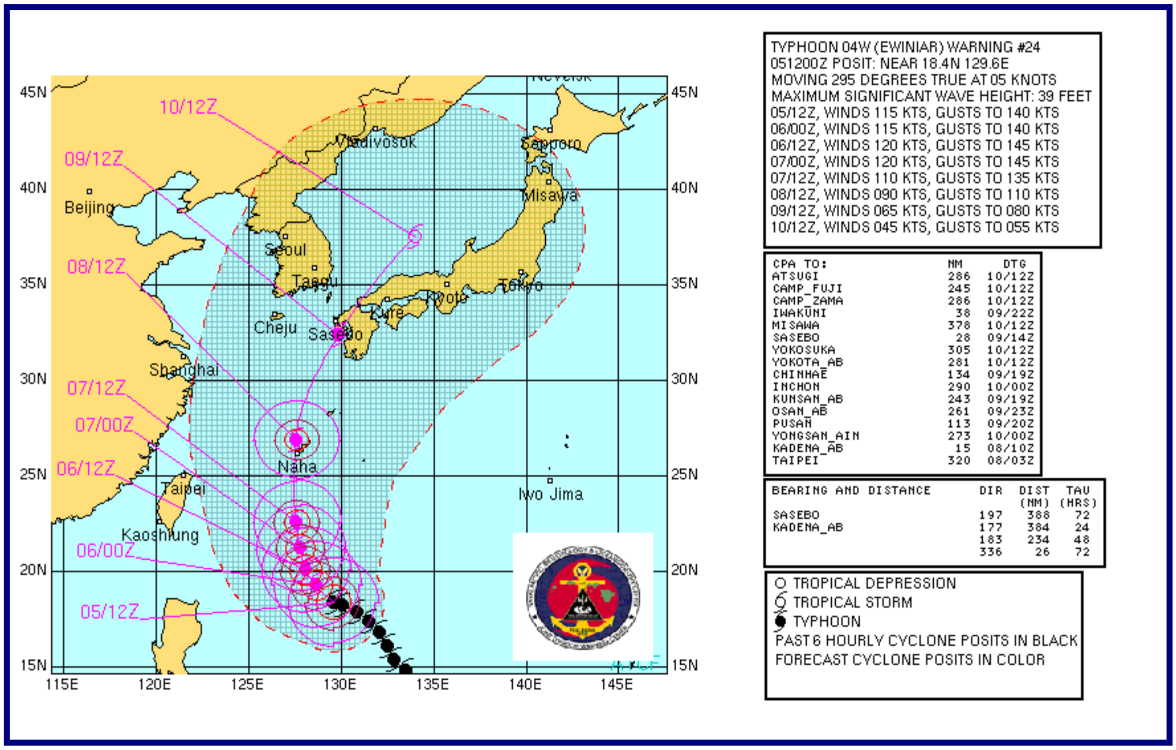

Figure 1-4. July 5, 1200 UTC, JTWC forecast indicating tropical cyclone passage over Sasebo in 96 hours.

northwest Pacific alone yields at least four super typhoons. Differences arise largely because these storms often evolve in a more complex web of dynamical processes and physical nonlinear interactions, including feedback loops associated with the Asian monsoon and imbedded disturbances. Also, tropical cyclone research and operations in the western Pacific are handicapped relative to the Atlantic by a lesser observational data base, especially the lack of aircraft surveillance and reconnaissance. (See section 3.1 for an assessment of aircraft surveillance and reconnaissance capabilities.)

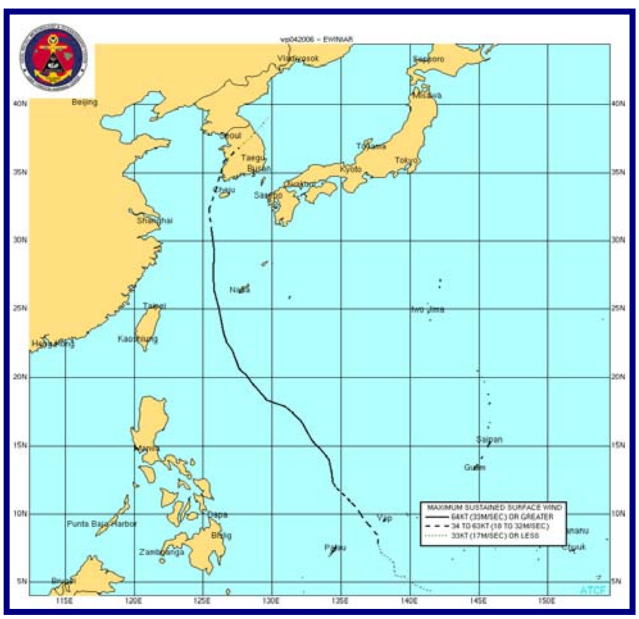

Figure 1-5. Overall track, Super Typhoon 04W (Ewiniar).

1.2.3 Hurricane Dennis, July 2005

Two of the hurricanes from the record 2005 Atlantic season provide additional examples of ways in which improved forecasts and warnings for tropical cyclones could better prepare the at-risk population. The first of these is the storm surge associated with Hurricane Dennis. Dennis made landfall on Santa Rosa Island, Florida, between Navarre Beach and Gulf Breeze, on July 10, 2005. The maximum sustained winds at landfall were 105 knots. Dennis produced a storm surge of 6-7 feet above normal tide levels on Santa Rosa Island, near where the center made landfall. This surge overwashed Santa Rosa Island near and west of Navarre Beach. A storm surge of 6-9 feet above normal tide levels occurred in Apalachee Bay, Florida, and inundated parts of the town of St. Marks and nearby areas.

This surge was higher than was supported by the wind reports known for that area prior to landfall. It was roughly 3.5 feet higher than the surge forecast from the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model. The likely explanation is that the unexpected surge was triggered by a sea-rise wave that became trapped on the oceanic shelf along the Florida west coast and propagated northward (Beven 2005). As an Associated Press article said of the impact on the St. Marks area: "This small fishing village on the picturesque St. Marks River received a nasty surprise from Hurricane Dennis: Although it came ashore some 175 miles west, Dennis pushed an 8-foot storm surge down the mouth of the river, flooding businesses and homes with chest-deep water" (Kallestad 2005). Long-time residents were "all in one piece" and happy to survive the storm surge associated with Hurricane Dennis.

1.2.4 Hurricane Rita, September 2005

The second example from the 2005 Atlantic hurricane season is Hurricane Rita, which struck in September 2005 after Katrina. On 20 September 2005, Hurricane Rita dumped heavy rains on the Florida Keys. It reached category 5 strength over the central Gulf of Mexico but eventually weakened prior to making landfall as a category 3 hurricane at Sabine Pass near the Texas-Louisiana border (figure 1-6). The strong storm surge and heavy winds caused major damage in the Louisiana and Texas coastal areas.

As stated in the TPC/NHC Tropical Cyclone Report for Hurricane Rita (Knabb et al. 2006):

> *Official forecasts issued on 20-21 September, however, were more biased to the south and were late in forecasting Rita's turn toward the northwest. Then, on 22–23 September, official forecasts within about 48 h of final landfall were once again quite accurate, except for incorrectly anticipating Rita to stall within a couple of days after moving inland (as did all of the reliable models).*

This southern bias, which called for landfall near Galveston, Texas, with effects of the storm also forecast to impact the greater Houston area, is clearly seen in the TPC/NHC's best track positions for Hurricane Rita (figure 1-7) compared to the TPC/NHC advisory #10, issued at 5 a.m. EDT, Tuesday, September 20, 2005 (figure 1-8). Given the track and storm surge predicted for Rita, the

Figure 1-6. Destruction in Sabine Pass, Texas, left in the wake of Hurricane Rita.

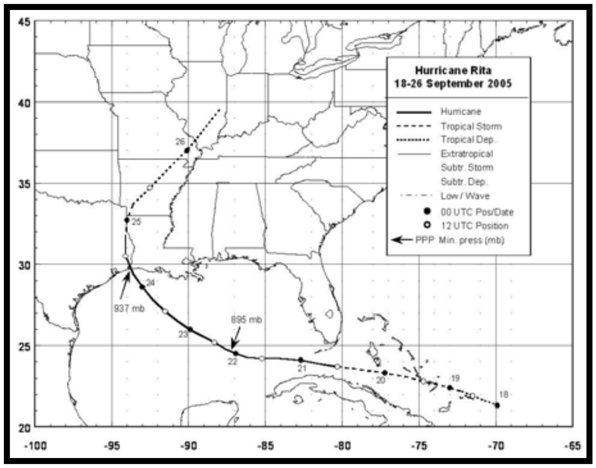

Figure 1-7. Best track position of Hurricane Rita.

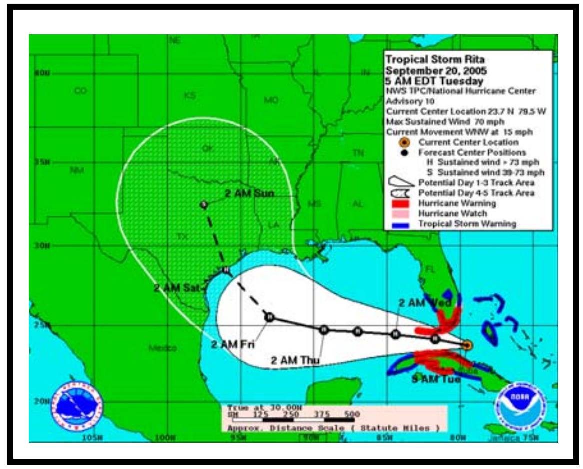

Figure 1-8. TPC/NHC Advisory #10 for Rita.

mayor of Galveston ordered mandatory evacuations of nursing homes and assisted-living facilities starting at 6 a.m. Wednesday, September 21. The mayor also ordered mandatory evacuations of other parts of the city to begin at 6 p.m. that day. In Houston, a similar scene unfolded, as the mayor of Houston ordered evacuations. In all, more than 1.3 million residents of Texas and Louisiana were ordered to evacuate and seek safety from Hurricane Rita. Highways leading out of Houston quickly became gridlocked up to 100 miles north of the city. Again, in hindsight, not all the evacuations ordered were necessary.

1.3 The Need for Hurricane R&D Priorities and Coordination

As portrayed above, tropical cyclones can have catastrophic impacts, which make accurate predictions of these events of paramount importance. There is no doubt that skill in tropical cyclone track forecasting has improved significantly during recent decades. Emergency management and other end-user responses to these improved forecasts and warnings result in lives saved, as well as reduction of property damage, physical injuries, and psychological distress. For example, in a typical hurricane season, forecasts, warnings, and associated emergency responses are estimated to save $3 billion (Willoughby 2001).

Even with these savings, more must be done to improve the Nation's hurricane and typhoon forecast and warning capability. A high priority for further tropical cyclone research is to reduce the uncertainty and forecast bias (the difference between forecast and actual conditions) in storm track, intensity, and the factors that drive them, to provide targeted warnings and emergency preparations, and to ensure that populations and locations at risk receive timely and reliable information. There are still serious forecast challenges, especially in support of the emergency management needs of growing coastal populations that are vulnerable to loss of life, property damage, and socioeconomic hardships caused by tropical cyclones. In addition, the DOD operates in environments around the world where tropical cyclones occur regularly. These national security missions must continue, and lives and assets must be protected. Military decisionmakers must allocate limited resources to both protect and complete the missions.

In addition to physical sciences research that must continue to meet these forecast challenges, greater emphasis is needed on social sciences research. A growing need exists to connect improved tropical cyclone forecasts and warnings to response actions, thereby ensuring the most appropriate responses by decisionmakers, by those who implement the decisions, and by the entire at-risk population. One such research area is how different end users of tropical cyclone forecasts and warnings receive, interpret, and act on that information. Because this and many other questions in improving the effectiveness of warnings and emergency response and preparedness require research in the social sciences, this plan includes social science research recommendations.

1.4 Operational Tropical Cyclone Forecast and Warning Centers

The purpose of this plan is to guide the next decade of tropical cyclone research efforts, justifying them through their linkages to the operational needs of the Nation's tropical cyclone warning service. A major part of the effort in formulating the plan was a compilation and assessment of these operational needs.

The purpose of this plan is to guide the next decade of tropical cyclone research efforts, justifying them through their linkages to the operational needs of the Nation's tropical cyclone warning service.

The tropical cyclone warning service is an interdepartmental collaboration to provide the United States and designated international recipients with forecasts, warnings, and assessments concerning tropical and subtropical weather systems. The three centers that cooperate to provide these operational forecast and warning services are discussed below. Figure 1-9 shows the areas of responsibility for tropical cyclone forecasts and warnings for the TPC/NHC, the Central Pacific Hurricane Center (CPHC), and the JTWC. The JTWC's area of responsibility (AOR) encompasses the entire Pacific and Indian Ocean areas, from the west coast of the Americas (north and south) to the east coast of Africa. It therefore overlaps with the AORs of the TPC/NHC and CPHC north of the equator in the central and north Pacific. In the overlap area, the JTWC normally reformats warnings issued by the TPC/NHC and CPHC into the standard format used by the JTWC and sends the information to its DOD customers.

1.4.1 Tropical Prediction Center/National Hurricane Center

The TPC/NHC is one of the nine centers comprising the National Centers for Environmental Prediction (NCEP), a component of the NOAA National Weather Service (NOAA/NWS). Located at Florida International University in Miami, Florida, the TPC/NHC is the Regional Specialized Meteorological Center (RSMC) designated by the World Meteorological Organization (WMO) for the north Atlantic Ocean, including the Caribbean and Gulf of Mexico, and the northeast Pacific Ocean east of longitude 140º W. The TPC/NHC provides general weather guidance, as well as specialized products for aviation and marine interests in the tropics.

The TPC/NHC consists of three major components:

- The **Hurricane Specialists Unit** maintains a continuous watch on tropical cyclones from May 15 in the eastern North Pacific and June 1 in the north Atlantic through November

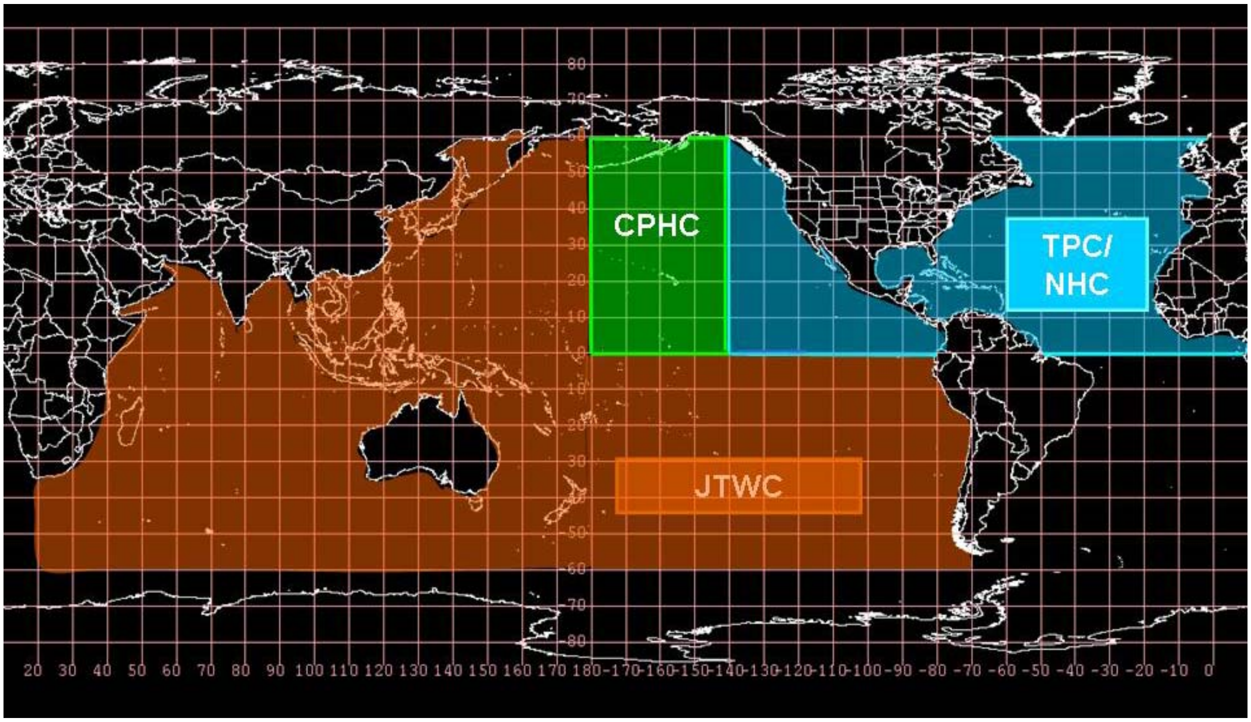

Figure 1-9. Areas of responsibility (AORs) assigned to the operational tropical cyclone forecast and warning centers. The JTWC AOR overlaps with those of the TPC/NHC and CPHC north of the equator in the central and north Pacific.

30. This unit prepares and issues forecasts, watches, and warnings for its AOR, as well as text advisories and graphical products. During the off-season, it conducts an extensive outreach and education program to train U.S. emergency managers and representatives from many other countries affected by tropical cyclones.

- The **Tropical Analysis and Forecast Branch** (TAFB) provides year-round marine weather analysis and forecast products over the tropical and subtropical waters of the eastern North and South Pacific and the North Atlantic basin. The branch also produces satellite-based weather interpretation and rainfall estimates for the international community. The TAFB provides support to the TPC/NHC through manpower augmentations and tropical cyclone position and intensity estimates based on the Dvorak technique.
- The **Technical Support Branch** (TSB) provides support for TPC/NHC computer and communications systems. The TSB also maintains a small applied research and techniques development unit that develops tools for hurricane and tropical weather analysis and prediction. TSB also has a storm surge group that provides support for the SLOSH model, which is used to calculate storm surge.

The TPC/NHC also contains the Chief, Aerial Reconnaissance Coordination, All Hurricanes (CARCAH) unit. This unit is an Operating Location of the 53rd Weather Reconnaissance Squadron (Hurricane Hunters) out of Keesler Air Force Base near Biloxi, Mississippi. CARCAH's mission is to coordinate all aerial reconnaissance requirements at the TPC/NHC (Atlantic requirements) and CPHC (Central Pacific requirements), and then task the flying units to meet these requirements.

1.4.2 Joint Typhoon Warning Center

The JTWC (figure 1-10) is a joint Air Force/Navy tropical cyclone forecasting center. Located at Naval Base Pearl Harbor, Hawaii, the JTWC is the DOD agency responsible for issuing tropical cyclone warnings for the Pacific and Indian Oceans. JTWC support encompasses more than 110 million square miles of the north and south Pacific Ocean and Indian Ocean, reaching from the west coast of the Americas to the east coast of Africa. The JTWC takes its mission direction from the Commander, US Pacific Command Instruction 3140.1w (version 1w is the latest in the series). In addition to the watch-standing operations floor, the JTWC houses the Satellite Operations Flight, charged with conducting all activities related to the satellite reconnaissance used in the tropical cyclone warning process. The JTWC also has a Techniques Development element that operationally evaluates forecast processes and transitions them to the watch floor operations. Both elements interface with the research and development community to evaluate tropical cyclone research and its utility for fast-paced military operations support. A substantial amount of the JTWC's numerical model computer support comes from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) at Monterey, California.

Figure 1-10. The Joint Typhoon Warning Center.

1.4.3 Central Pacific Hurricane Center

The CPHC has forecast and warning responsibility for the central North Pacific from 140º W longitude to the International Date Line. It is a component of the NOAA/NWS Weather Service Forecast Office (WFO), Honolulu, Hawaii (figure 1-11). The Meteorologist-In-Charge, WFO Honolulu, is also the Director of the CPHC. Because the WFO Honolulu has no authorized manpower for the specialized hurricane operations of the CPHC, the center is activated only when a tropical cyclone crosses into the area between 140º W longitude and the International Date Line. On July 1, 2001, WFO Honolulu was designated a WMO RSMC. Most outside support, such as model and techniques development and aerial reconnaissance, is provided through the same infrastructure that supports the TPC/NHC.

1.4.4 Supporting Role of Other NOAA/NCEP Operational Centers

Other NCEP centers have responsibilities dealing with forecasting the conditions and consequences of tropical cyclones. A substantial amount of the TPC/NHC's numerical modeling computer support comes from NCEP's Environmental Modeling Center (EMC) and the models are run by NCEP Central Operations. The Hydrometeorological Prediction Center (HPC) issues forecasts for some tropical cyclones after they have moved inland in the United States; it also

Figure 1-11. The NOAA/NWS Weather Service Forecast Office, Honolulu, Hawaii

issues rainfall forecasts for tropical cyclones and their remnants over the United States. The Storm Prediction Center (SPC) provides forecasts and watches for severe thunderstorms and tornadoes. For areas at sea north of 30/31º N latitude, the Ocean Prediction Center (OPC) provides forecasts to mariners that incorporate TPC/NHC official tropical cyclone forecasts. (The TAFB provides forecasts for mariners south of 30/31º N latitude.)

1.5 Introduction to the Tropical Cyclone R&D Community

While the tropical cyclone operational forecast and warning centers are few in number and have clearly defined roles and geographic areas of responsibility, numerous entities in the public and private sector, including the academic community, contribute to tropical cyclone research. To formulate a national plan for coordinating these research efforts with the needs of the operational centers, it is useful to view these decentralized, distributed research activities, in conjunction with the operational centers, as forming a *community of practice*. Chapter 2 examines the major R&D centers and other players in light of their interactions. This section provides a short introduction to the community of practice.

The tropical cyclone community of practice has grown through statutory encouragement of collaborative R&D activities. In the NOAA Authorization Act of 1992 (Public Law 102-567), Section 107, Congress mandated that the DOD and DOC establish a joint hurricane reconnaissance program "for collecting operational and reconnaissance data, conducting research, and analyzing data on tropical cyclones to assist the forecast and warning program and increase the understanding of the causes and behavior of tropical cyclones." In January 1994, the initial 5-year plan outlining this shared responsibility was forwarded to Congress. In addition to NOAA (in the DOC) and the DOD, numerous national and international universities and several other Federal agencies, laboratories, and organizations conduct tropical cyclone research.

1.5.1 Federal R&D Organizations

Federal R&D in the physical sciences either specific to understanding and predicting tropical cyclone behavior or relevant to it is conducted within or overseen by NOAA in the DOC, the National Science Foundation (NSF), the Office of Naval Research (ONR) and the U.S. Army Corps of Engineers (USACE) in the DOD, the National Aeronautics and Space Administration

(NASA), and the U.S. Geological Survey (USGS) in the Department of the Interior. The work within each of these entities is described briefly below and in more detail in section 2.2.

In addition, R&D related to emergency preparedness, response, recovery, and mitigation associated with tropical cyclones is conducted or overseen by the Federal Emergency Management Agency (FEMA) in the Department of Homeland Security. The Department of Housing and Urban Development (HUD) conducts R&D to improve the disaster resistance and durability of housing, including the impacts of tropical cyclones. The Department of Health and Human Services conducts some relevant research on the psychological stresses resulting from major hurricane strikes. The National Institute of Standards and Technology (NIST), through its Building and Fire Research Laboratory, conducts research on facility construction that includes reducing the human and economic losses from natural hazards such as tropical cyclones. The R&D roles of these entities are described in section 2.3.

National Oceanic and Atmospheric Administration

The majority of research within NOAA specific to understanding and predicting tropical cyclone behavior is conducted or managed by the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML), a facility within the NOAA Office of Oceanic and Atmospheric Research (OAR). Within NOAA/NWS, research specific to or related to tropical cyclones is conducted by the two tropical cyclone forecast and warning centers (TPC/NHC and CPHC), several other NCEP centers, particularly the EMC and SPC, and some other WFOs. The Center for Satellite Applications and Research (STAR), which is part of NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), conducts a tropical cyclone research program that emphasizes satellite-based observations. STAR is the Federal partner from NESDIS in the Joint Center for Satellite Data Assimilation (JCSDA).

National Science Foundation

The NSF is the funding source for about 20 percent of all federally supported basic research conducted by U.S. colleges and universities. The physical, biological, and ecological aspects of NSF's hurricane-related research are managed through its Geosciences Directorate (GEO) and Biological Sciences Directorate (BIO). Hurricane-related engineering research is supported through various programs within the Directorate for Engineering (ENG).

A number of major academic research centers with tropical cyclone programs and research projects receive a substantial part of their funding from the NSF, through grants managed by these NSF directorates. See sections 1.5.2 and 2.5 for further information on these centers and their role in the tropical cyclone community of practice.

Department of Defense

Within ONR, the Ocean Atmosphere & Space Research division has a Marine Meteorology and Atmospheric Effects program, whose topics of interest include problems of predictability, data assimilation into models, and tropical cyclone evolution and behavior. The Naval Research Laboratory (NRL) is the Navy's corporate laboratory and is aligned with ONR. Within NRL, the directorate most directly involved in tropical cyclone research is the Ocean and Atmospheric Science and Technology Directorate.

The USACE's R&D is led by the U.S. Army Engineer R&D Center (ERDC). Within the ERDC, the Coastal & Hydraulics Laboratory (CHL) conducts research into coastal physical phenomena. Specific areas of interest include waves, circulation, water levels, and sediment transport. CHL's research includes data collection, as well as development of numerical and physical models.

National Aeronautics and Space Administration

NASA contributions to tropical cyclone R&D are primarily in the area of developing instrumentation for and interpreting the data from satellite-based observing systems. A mandate of NASA's Science Mission Directorate is to investigate high-impact weather events, including severe tropical storms, through a combination of spaced-based observations, high-altitude research aircraft, and sophisticated numerical models. NASA investigations in these areas constitute a three-pronged strategy to better understand the physics and impacts of tropical cyclones.

U.S. Geological Survey

The USGS is working with NOAA and NASA to improve understanding and prediction of floods, landslides, and debris flows triggered by intense meteorological phenomena, including the heavy rains typical of landfalling tropical cyclones. The mechanism to integrate the research efforts underway in each of the three agencies is the proposed Hurricane-Flood-Landslide Continuum Project. The USGS components include precipitation-runoff modeling of watershed systems. These computer models are used to simulate and evaluate the effects of various combinations of precipitation, climate, and land use on stream flow, sediment yield, and other hydrologic components.

1.5.2 Academic Partners in Tropical Cyclone R&D

The National Center for Atmospheric Research (NCAR), located in Boulder, Colorado, is a federally funded research and development center operated by the University Corporation for Atmospheric Research (UCAR). UCAR is a nonprofit consortium of North American member universities, each of which grants doctoral degrees in the atmospheric and related sciences, plus an increasing number of international affiliates offering comparable degrees, and North American academic affiliates offering predoctoral degrees. NSF is the primary sponsor for NCAR, but it also receives funding from NOAA, NASA, the DOD, the Department of Energy, the Federal Aviation Administration, and the U.S. Environmental Protection Agency. Working with multiple agency sponsors, NCAR and collaborators are investigating ways to improve forecasts of changes in hurricane intensity and prediction of wind, waves, and rain at landfall.

Other academic R&D centers active in research on tropical cyclone observing and forecast methods are the University of Wisconsin-Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) and the Cooperative Institute for Research in the Atmosphere (CIRA), an R&D center at Colorado State University. Academic centers engaged in related research include the Cooperative Institute for Oceanographic Satellite Studies (CIOSS) at Oregon State

University and the Cooperative Institute for Climate Studies (CICS) at University of Maryland and several other NOAA cooperative institutes.

In general, Federal agencies that sponsor *extramural research* programs on tropical cyclone evolution and behavior, societal impacts of hurricanes and related severe weather phenomena, or satellite-based observations of relevant atmospheric and oceanic properties provide funding to university-based researchers. The research projects may be part of an ongoing program at one of the major academic centers such as NCAR, CIMSS, or CIRA, or they may be conducted by an individual principal investigator on the faculty of a college or university.

1.5.3 Coordination Roles in the Tropical Cyclone Community of Practice

With multiple Federal entities funding R&D directed at a broad array of topics related to the tropical cyclone life cycle, observing systems, computer modeling for storm prediction and warning, and the consequences of tropical storms on both land and sea, coordination of these separate programs is essential to ensuring the most productive overall return, over the long term, for the substantial investment of taxpayer dollars. Section 2.4 provides further details on the coordinating entities and mechanisms listed here:

- The mission of the **Office of the Federal Coordinator for Meteorological Services and Supporting Research** (OFCM), located within NOAA, is to ensure the effective use of Federal meteorological resources by leading the systematic coordination of operational weather requirements, services, and supporting research among the Federal agencies. The focus of OFCM coordination is on applied research necessary to meet operational needs and the effective transition of results from such research into operations. OFCM hosts the annual **Interdepartmental Hurricane Conferences**, which provide a forum for the Federal agencies with operational and R&D responsibilities related to tropical cyclones, together with emergency managers and other representatives of the agencies' user communities, to review the Nation's tropical cyclone forecast and warning service and make recommendations on how to improve it.
- The **Office of Science and Technology Policy** (OSTP) works with the Office of Management and Budget to provide all Federal agencies with general guidance on national priorities for R&D programs. The Director of OSTP manages the **National Science and Technology Council** (NSTC) for the President. This Cabinet-level council prepares R&D strategies that are coordinated across Federal agencies to form investment packages aimed at accomplishing multiple national goals.
  - One of the four primary committees of the NSTC is the **Committee on Environment and Natural Resources** (CENR), whose **Subcommittee on Disaster Reduction** (SDR) is the NSTC entity most closely related to coordination of tropical cyclone R&D across agency boundaries.
  - Another standing subcommittee of the CENR is the **United States Group on Earth Observations** (US GEO), which is continuing the strategic planning and implementation for the U.S. Integrated Earth Observation System (IEOS). IEOS represents the U.S. contribution to the Global Earth Observing System of Systems (GEOSS), an international effort to achieve comprehensive, coordinated, and sustained observations of the Earth system.

- The **National Science Board** (NSB) provides national science policy advice to the President and serves as the governing board for NSF.
- The **U.S. Weather Research Program** (USWRP) is a partnership of Federal entities with the academic and commercial communities. NOAA, NASA, NSF, and the Navy currently participate. In 1998, the fifth Prospectus Development Team for the USWRP published "Landfalling Tropical Cyclones: Forecast Problems and Associated Research Opportunities" (Marks and Shay 1998). The Joint Hurricane Testbed (JHT), which began under the USWRP, is described in section 2.4.5.
- The **Joint Center for Satellite Data Assimilation** (JCSDA) was formed by NOAA, NASA, and DOD in 2001 to expedite the process of assimilating data from new satellite-based observing systems and instruments into operational models used to prepare forecasts and warnings. As illustrated in section 1.2, advances in satellite-based imagery and observing techniques have been a major contributor to recent improvements in forecasts and warnings for tropical cyclones.

1.5.4 Other Participants in the R&D Community

The community of practice for tropical cyclone R&D and operations includes international participants. Other nations that are vulnerable to the damaging effects of tropical cyclones include Japan, China, Taiwan, Korea, and Australia. The national meteorological agencies in these countries typically have a closely allied research center or institute that contributes to the global effort to understand tropical cyclones and improve operational forecast and warning capabilities. International cooperation and coordination includes both the broad strategic planning effort of GEOSS and a number of important joint experimental activities such as the Pacific Asian Regional Campaign of the THe Observing system Research and Predictability EXperiment (THORPEX). The main objective of this regional THORPEX campaign is to advance the understanding and predictability of high-impact weather over Asia and the western Pacific, with emphasis on tropical cyclones from genesis to their decay or transition to extratropical status.

Also important to the U.S. community of practice are nongovernmental bodies representing the professional scientific community. The National Academy of Sciences (NAS) and its operational component for conducting studies, the National Research Council (NRC), have Congressional charters to advise the U.S. Government. The American Meteorological Society Policy Program has as its national priorities public health and safety, economic growth, the protection of the environment, and national security. Both bodies play important roles in communicating consensus perspectives from the scientific community to decisionmakers in the Federal policy and coordinating entities noted in section 1.5.3, as well as in the Federal agencies with operational responsibilities or R&D programs.

1.6 Formation of the JAG/TCR

The impetus for this Tropical Cyclone R&D Plan was a principal action item, agreed upon by the participants in the 58th Interdepartmental Hurricane Conference (IHC) in 2004, to develop a comprehensive strategy for tropical cyclone research and development to guide interagency efforts over the next decade. (As noted above, OFCM hosts an IHC each year.) Subsequently, the

Interdepartmental Committee for Meteorological Services and Supporting Research (ICMSSR) strongly supported this action at its November 2004 meeting (action item 2004-2.7). At the December 2004 meeting of the Federal Committee for Meteorological Services and Supporting Research (FCMSSR), the senior interagency group advising OFCM, the IHC and ICMSSR actions were discussed and supported. FCMSSR support was expressed by its adoption of FCMSSR action item 2004-1.2 (Atmospheric Research Priorities), Parts A and B. Part A states that "FCMSSR agencies will support R&D needs and requirements based on agency priorities and will continue to identify issues and concerns that are necessary for the development of capabilities required to realize societal benefits." Part B states that "FCMSSR agencies will support and facilitate opportunities for the transition of research into operational applications."

In response to the IHC, ICMSSR, and FCMSSR action items, the Federal Coordinator for Meteorology formed the Joint Action Group for Tropical Cyclone Research (JAG/TCR) in early 2005. During the group's first meeting, members developed a rough outline for this plan and agreed to compile previous research plans and efforts into one reference location. The results of these efforts are available on a Reference Report Webpage, http://www.ofcm.gov/tcr/tcr-index.htm.

The vision of the JAG/TCR was to maximize the potential of the tropical cyclone community partnerships to improve hurricane prediction, preparedness, and resiliency for societal benefit by strategically matching research results to operational requirements. The JAG/TCR members agreed that past research planning efforts clearly outlined the tropical cyclone community's priorities, objectives, and strategies, as developed and vetted through many meetings and workshops. These significant past efforts are reviewed in section 2.8.

Past research planning efforts clearly outlined the tropical cyclone community's priorities, objectives, and strategies.

The initial overarching research priorities established by the JAG/TCR included tropical cyclone intensity and structure (wind radii), track, other landfalling impacts (sea state/storm surge, precipitation, and inland flooding), and social science research.

1.7 Structure of the R&D Plan

This introductory chapter illustrates the fundamental rationale for continuing efforts to further advance tropical cyclone forecasts and warnings. It introduces the operational centers for the Nation's tropical cyclone warning service, serving both civilian and military needs, and the community of practice that supports these operational centers.

Chapter 2 describes in more detail the community of practice. Understanding how this community works—its strengths and its limitations—is crucial for formulating and implementing a community-wide, comprehensive strategy for tropical cyclone R&D that can guide interagency efforts over the next decade. Chapter 2 also reviews recent and concurrent planning activities that were taken into account in formulating the research priorities.

Chapter 3 assesses the current capabilities and limitations of the Nation's tropical cyclone warning service. These capabilities constitute a classic end-to-end meteorological warning and forecasting system, from data collection through data assimilation and NWP modeling, to dissemination of warnings and forecasts, including end-user education, training, and outreach.

Chapter 4 uses the same end-to-end system structure to present the JAG/TCR's perspective on the future capabilities required to meet both current operational needs and emerging needs ***identified by the operational centers***. This perspective draws heavily on recent significant research planning efforts and products, as well as on the expertise of the JAG/TCR members collectively and of the R&D and operational organizations they represent. In Chapter 5, these future capabilities are translated into a set of research priorities, around which a comprehensive R&D strategy for the next decade can be built. Chapter 6 presents a summary of key findings and the JAG/TCR recommendations for next steps that can be taken by the cognizant Federal agencies and coordinating entities to begin implementation of this strategy.

Literature references for the citations in the report body and the appendices are in the References section after chapter 5. Appendices A through H provide backup information on the current operational capabilities reviewed in chapter 3.

- Appendix A—Satellite data currently used in NCEP's operational data assimilation systems
- Appendix B—Impact on tropical cyclone forecast skill of improvements in global prediction models and operational high-resolution regional models
- Appendix C—Research NWP models relevant to improvements in tropical cyclone prediction
- Appendix D—Forecasts and models currently in use at the TPC/NHC and CPHC
- Appendix E—Forecasts and models currently in use at the JTWC
- Appendix F—Guidance model errors in tropical cyclone storm track during 2005
- Appendix G—Guidance model errors in tropical cyclone intensity during 2005
- Appendix H—Example of recent public education and outreach through an article in NOAA's online *NOAA Magazine*

Appendices I through P provide supporting details for chapters 4 through 6. Appendix Q lists the acronyms used throughout the report body and appendices.

- Appendix I—Satellite observations to be assimilated at NCEP as new observing instruments come on line
- Appendix J—MetOp Satellite Data Pertinent to Tropical Cyclone Analysis and Forecasting
- Appendix K—Recent developments in data assimilation for NWP modeling

- Appendix L—NCEP plan for development of improved global NWP models
- Appendix M—Future work planned for the HWRF Air-Sea-Land-Hurricane Prediction System
- Appendix N—Questions from the Air-Sea Interactions in Tropical Cyclones Workshop
- Appendix P—The JAG/TCR's recommended research areas for tropical cyclone–related social science R&D
- Appendix Q—Acronyms used in the report body and the appendices

2
THE TROPICAL CYCLONE R&D COMMUNITY

2.1 Tropical Cyclone R&D as a Community Effort

The community effort required to improve forecast and warning capabilities for tropical cyclones cannot be denied. More-accurate forecasts of tropical cyclone behavior and accurately targeted guidance for risk mitigation are critical to mitigate the impacts of these storms on many segments of society, as well as on military infrastructure and readiness. Yet, understanding the complex interactions of tropical cyclone structure, intensity, track, and environmental forcing is too large a problem for any single research group or Federal agency to address alone. The many research groups and operational organizations who work together to improve the understanding, predictability, and risk mitigation of tropical cyclones represent a *community of practice* whose members collaborate to share ideas, find solutions, and build innovations as part of the social learning process essential to provide cost-effective benefits for all.

For this communal effort to be both effective and efficient, stakeholder needs and requirements must be clearly communicated to all groups contributing to components or subsystems of the national forecast and warning system. Communication of requirements helps to set priorities for the researchers and developers so that the most effective, feasible solutions may be transitioned into applications. However, communication of stakeholder requirements should not dictate a solution that would limit the role of the researcher or developer to design the most innovative, efficient solution.

The tropical cyclone community of practice includes a range of efforts contributing to basic research, applied research, operations, and decisionmaking as depicted in figure 2-1. The black arrows in the figure represent the communication of requirements; the blue arrows represent the transfer of knowledge and information. An important element in this entire process is the clear communication of operational needs to the tropical cyclone research sector. For this reason, chapter 4 articulates a set of needs from the tropical cyclone operational community. A list of recommended research priorities to help meet these operational needs is presented in Chapter 5.

A challenge for the tropical cyclone community of practice is to realize that, to maintain steady progress, research investments must include a balanced portfolio of near-term and long-term research. An interim recommendation from an ongoing NAS/NRC review of the NSF Atmospheric Sciences program is that 5 percent of its research funding should be reserved for

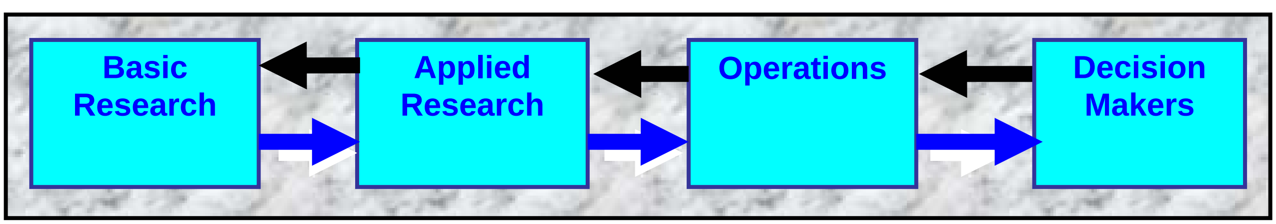

Figure 2-1. Representation of the flow of requirements (black arrows) and the transfer of knowledge and information (blue arrows) within the tropical cyclone community of practice.

innovative, exploratory, high-risk research (NRC 2005). Research investments must also be balanced so that multiple science questions across scientific disciplines are addressed to maximize the utilization of limited resources. In a closed system or enterprise, the work of the developers directly addresses the needs of the stakeholders. However, in the tropical cyclone research community, some of the developers or researchers are striving to meet multiple objectives. For this reason, potentially valuable research results may not always arise from funding dedicated to meeting an operational requirement. Promising tropical cyclone research capability may arise from other research disciplines. The synergy of the NASA research focus areas in weather, climate, and the water and energy cycle is one example in which promising tropical cyclone research with the potential for operational application may emerge from any one of these focus areas.

The next six sections of this chapter examine the organizational components and current roles in the tropical cyclone community of practice for the following sectors of that community:

- Federal entities conducting or managing research in the physical sciences (section 2.2)
- Federal entities conducting or managing research in other disciplines, notably in the social sciences and in engineering related to mitigating storm effects (section 2.3)
- Federal policy and coordination roles for tropical cyclone R&D (section 2.4)
- The role of academia in the tropical cyclone R&D community of practice (section 2.5)
- International contributions to the community of practice (section 2.6)
- External advisory and advocacy groups representing the science community (section 2.7)

The last major section of the chapter (section 2.8) reviews prior documentation of tropical cyclone operational needs and the research needed to meet currently unmet needs. As noted in chapter 1, the JAG/TCR found that, taken together, these past efforts at research planning clearly outline the tropical cyclone community's priorities, objectives, and strategies.

2.2 Federal Entities Conducting or Managing Tropical Cyclone R&D in the Physical Sciences

2.2.1 NOAA

The following statement of NOAA's origin from a number of long-standing Government entities was extracted from NOAA's website:

> *Although NOAA was formed in 1970, the agencies that came together at that time are among the oldest in the Federal Government. The agencies included the United States Coast and Geodetic Survey formed in 1807, the Weather Bureau formed in 1870, and the Bureau of Commercial Fisheries formed in 1871. Individually these organizations were America's first physical science agency, America's first agency dedicated specifically to the atmospheric sciences, and America's first conservation agency.*[1]

[1] From NOAA webpage "NOAA Legacy": http://www.history.noaa.gov/noaa.html.

Today, the mission of NOAA is to understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs.

For the protection of life and property and the enhancement of the national economy, the NOAA/NWS provides weather, hydrologic, and climate forecasts and warnings covering the United States, its territories, and the adjacent waters and ocean areas. NWS data and products form a national information database and infrastructure, which can be used by other governmental agencies, the private sector, the public, and the global community.

The majority of research within NOAA that is specific to tropical cyclones is designed and conducted by the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML), one of the facilities in the NOAA Office of Atmospheric Research (OAR). HRD has numerous partners that help conduct/coordinate hurricane research projects, including universities and cooperative institutes, other Federal agencies (in particular, ONR in the Department of the Navy and NASA), the NOAA Aircraft Operations Center, other NOAA/OAR laboratories (such as the Earth System Research Laboratory, the National Severe Storms Laboratory, and the Geophysical Fluid Dynamics Laboratory), NWS/NCEP (in particular the EMC and the TPC/NHC), and scientists at academic research centers (see section 2.5).

In addition to EMC and TPC/NHC, other organizations or offices within NOAA/NWS that conduct tropical cyclone–specific or tropical cyclone–related research include the Storm Prediction Center (another NWS/NCEP center), the NWS WFOs, and the CPHC. Within NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) is the Center for Satellite Applications and Research (STAR). STAR is involved in the planning for next-generation satellite systems, including the development of tropical cyclone observing applications. STAR researchers, in collaboration with its cooperative and joint institutes at Colorado State University (Cooperative Institute for Research in the Atmosphere—CIRA), University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW—CIMSS), Oregon State University (Cooperative Institute for Oceanographic Satellite Studies—CIOSS), and University of Maryland (Cooperative Institute for Climate Studies—CICS), are involved in improving satellite-based tropical cyclone analysis algorithms, feature track wind methods, and statistically-based forecast techniques. STAR is also a partner in the JCSDA, which is described in section 2.4.6. STAR interacts with many of the same organizations described above for HRD and has led a number of Joint Hurricane Testbed (JHT) projects. The NOAA-funded JHT is discussed further in section 2.4.5.

The NOAA Science Advisory Board (SAB) was established in 1997 under the Federal Advisory Committee Act with the responsibility to advise the Under Secretary of Commerce for Oceans and Atmosphere on long- and short-range strategies for research, education, and the application of science to resource management and environmental assessment and prediction. This 15-member advisory board assists NOAA in maintaining a complete and accurate understanding of scientific issues critical to the agency's missions. In the summer of 2005, the SAB established a 10-member Hurricane Intensity Research Working Group (HIRWG) to address the lack of progress in forecasting changes in intensity and structure commensurate with the progress over the past two decades in forecasting hurricane track. The work of the HIRWG and its interaction with the JAG/TCR are described further in section 2.8.8.

2.2.2 National Science Foundation

NSF was created by Congress in the National Science Foundation Act of 1950 (Public Law 8105071950). As stated on the NSF website (http://www.nsf.gov/about):

> *The NSF is an independent federal agency "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…" With an annual budget of about $5.5 billion, we are the funding source for approximately 20 percent of all federally supported basic research conducted by America's colleges and universities.*

The NSF is also the principal Federal agency charged with promoting science and engineering education at all levels and in all settings, from pre-kindergarten through career development. The NSF's strategic goals address: *People, Ideas, Tools, and Organizational Excellence.*[2]

The physical, biological, and ecological aspects of NSF's hurricane-related research are managed through the Geosciences and Biological Sciences Directorates (GEO and BIO). The NSF supports hurricane-related engineering research through various programs distributed throughout the Directorate for Engineering (ENG). The hurricane-related research in GEO and BIO falls into three broad categories: the hurricane as a phenomenon from formation to dissipation; the prediction of hurricane behavior/evolution; and the impacts of hurricanes on the built and natural environment. Most of the social science research on warnings and hurricane-related phenomena has been supported through ENG under the program currently called Infrastructure Systems Management and Hazard Response. A few hurricane-related projects have been funded by NSF's Directorate for Social, Behavioral, and Economic Sciences.

2.2.3 Department of Defense

Within the DOD, ONR and the U.S. Army Corps of Engineers (USACE) have specific interests and focus areas concerning their contribution to tropical cyclone research.

ONR coordinates, executes, and promotes the science and technology programs of the United States Navy and Marine Corps through schools, universities, government laboratories, and nonprofit and for-profit organizations. It provides technical advice to the Chief of Naval Operations and the Secretary of the Navy and works with industry to improve technology manufacturing processes. The mission of the ONR is to foster, plan, facilitate, and transition scientific research in recognition of its paramount importance to enable future naval power and the preservation of national security.

Within ONR, the department of "Ocean Battlespace Sensing S&T" (OBS) consists of two large divisions, "Ocean Sensing and Systems Applications" and "Ocean Atmosphere & Space Research." The latter concentrates on improving the Navy and Marine Corps' understanding of

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[2] National Science Foundation Strategic Plan, 2003-2008, September 30, 2003

environmental evolution, the assimilation of data, and the limits of predictability. It plans, fosters, and encourages an extensive program of scientific inquiry and technological development in fields ranging from environmental optics to high-latitude dynamics. One of the fields of special interest to the division is marine meteorology and atmospheric effects. The topics of interest in the Marine Meteorology Program include:

- Predictability as related to dynamical and physical processes associated with high impact marine weather systems
- Data assimilation, especially issues unique to the tropics for incorporating high data rate, asynchronous sensors (radar, lidar, remote sensing, etc.)
- Tropical cyclone behavior and evolution, especially unique genesis, intensity, and structure issues of western and southern Pacific storms

In 1992, the Secretary of the Navy consolidated existing Navy research, development, test, and evaluation engineering facilities and fleet support facilities to form a corporate community. This community consists of a single corporate research laboratory, the Naval Research Laboratory (NRL), aligned with ONR. As part of the consolidation, the Naval Oceanographic and Atmospheric Research Laboratory, with locations in Stennis Space Center, Mississippi, and Monterey, California, merged with NRL. The Ocean and Atmospheric Science and Technology Directorate of NRL performs research in the fields of acoustics, remote sensing, oceanography, marine geosciences, marine meteorology, and space science. The Marine Meteorology Division within this NRL directorate is commonly referred to as NRL-Monterey and has been active in tropical cyclone research and related atmospheric science research for many years.

The USACE has consolidated its research laboratories into the U.S. Army Engineer Research and Development Center (ERDC). The ERDC is one of the most diverse engineering and scientific research organizations in the world, consisting of seven laboratories at four geographical sites and employing nearly 2,000 engineers, scientists, and support personnel. The ERDC's research is carried out in direct support of USACE missions.

As the lead Federal agency for developing projects that reduce flood and coastal storm damages, the USACE is committed to providing solutions and infrastructure that save lives, reduce property damage, and maintain and protect the environment. The USACE is also committed to collaborating with other Federal agencies and stakeholders to forge solutions to water problems that are economically viable, socially acceptable, and environmentally responsible and sustainable.

The USACE has 11 districts responsible for all of the coastal watersheds along the East and Gulf Coasts. These districts work with local coastal stakeholders to develop projects and emergency management plans that will minimize damages and losses during and after severe coastal storms. Following severe storms, the USACE districts are called upon as necessary to save lives, reduce suffering, and support recovery efforts. They are also expected to work with local communities and State entities to evaluate the performance of existing projects during storms, develop recommendations for improvements, and implement those improvements as desired by the stakeholders and authorized by Congress.

The USACE relies on the ERDC to develop capabilities that support the specific requirements of its districts. In particular, the ERDC's Coastal and Hydraulics Laboratory (CHL) provides expertise in many of the subjects associated with tropical cyclones. The following are some recent CHL activities:

- Funding NOAA's National Data Buoy Center to add wave-direction measurements to wave gages deployed along the Nation's coasts
- Collecting continuous wave, water level, current, and bathymetry data at the ERDC Field Research Facility on the outer banks of North Carolina and pursuing the development of a data-rich test bed for evaluating new instrumentation for measuring coastal processes and for validating computational models
- Collecting tropical cyclone data in the Pacific Islands to better understand the coastal processes that occur during landfalling typhoons
- Continuing the development of coastal processes models including wave, circulation, water level, and sediment transport numerical models
- Investing in the development, coupling, and informatics integration of coastal processes models (in collaboration with other Federal agencies including NOAA, Navy, NASA, and USGS)
- Studying the impact of tropical cyclones not only on coastal regions but also on water resource projects throughout watersheds affected by a tropical cyclone (i.e., considering a tropical cyclone as a "watershed event" rather than only a coastal event)
- Developing risk-based methodologies for planning, designing, operating, and maintaining coastal (and related) projects

2.2.4 National Aeronautics and Space Administration

President Dwight D. Eisenhower established NASA in 1958, partially in response to the Soviet Union's launch of the first artificial satellite. NASA grew out of the National Advisory Committee on Aeronautics, which had been researching flight technology for more than 40 years.

NASA Headquarters in Washington, D.C., provides overall guidance and direction to the Agency. Ten field centers and a variety of installations conduct the day-to-day work in laboratories, on air fields, in wind tunnels, and in control rooms. NASA conducts its work in four principal organizations, called mission directorates:

- **Aeronautics**: pioneering and proving new flight technologies that improve our ability to explore and that have practical applications on Earth
- **Exploration Systems:** creating new capabilities for affordable, sustainable human and robotic exploration
- **Science:** exploring Earth, moon, Mars, and beyond; charting the best route of discovery; and reaping the benefits of Earth and space exploration for society
- **Space Operations:** providing critical enabling technologies for much of the rest of NASA through the Space Shuttle, the International Space Station, and flight support

NASA has been a strong contributor to national weather forecasting goals in the past, primarily through the development and use of data from space-based sensors, and will continue to do so in the future (figure 2-2). A mandate of the Weather Focus Area within the Science Mission Directorate is to investigate high-impact weather events, such as severe tropical storms, through a combination of spaced-based observations, high-altitude research aircraft, and sophisticated numerical models. These programs constitute a three-pronged strategy to better understand the physics and impacts of tropical cyclones.

2.2.5 U.S. Geological Survey, Department of the Interior

The USGS, which was established in 1879, collects, monitors, analyzes, and provides scientific understanding about natural resource conditions, issues, and problems. The USGS, NOAA, and NASA are working to focus their joint expertise on floods, landslides, and debris flows triggered by intense meteorological phenomena, including tropical cyclones. The special expertise of the USGS in this area includes capabilities to evaluate beforehand the ambient stability of natural and man-made landforms, assess landslide susceptibilities for those landforms, and establish probabilities for initiation of landslides and debris flows. Although all three agencies are conducting research on their respective aspects of this problem, the mechanism to integrate their efforts is a proposed project called the Hurricane-Flood-Landslide Continuum project.

The USGS is widely recognized as a leader in studying the interrelationship of vegetation, ambient stream flow, ground water, soil moisture, and geologic conditions in assessing the

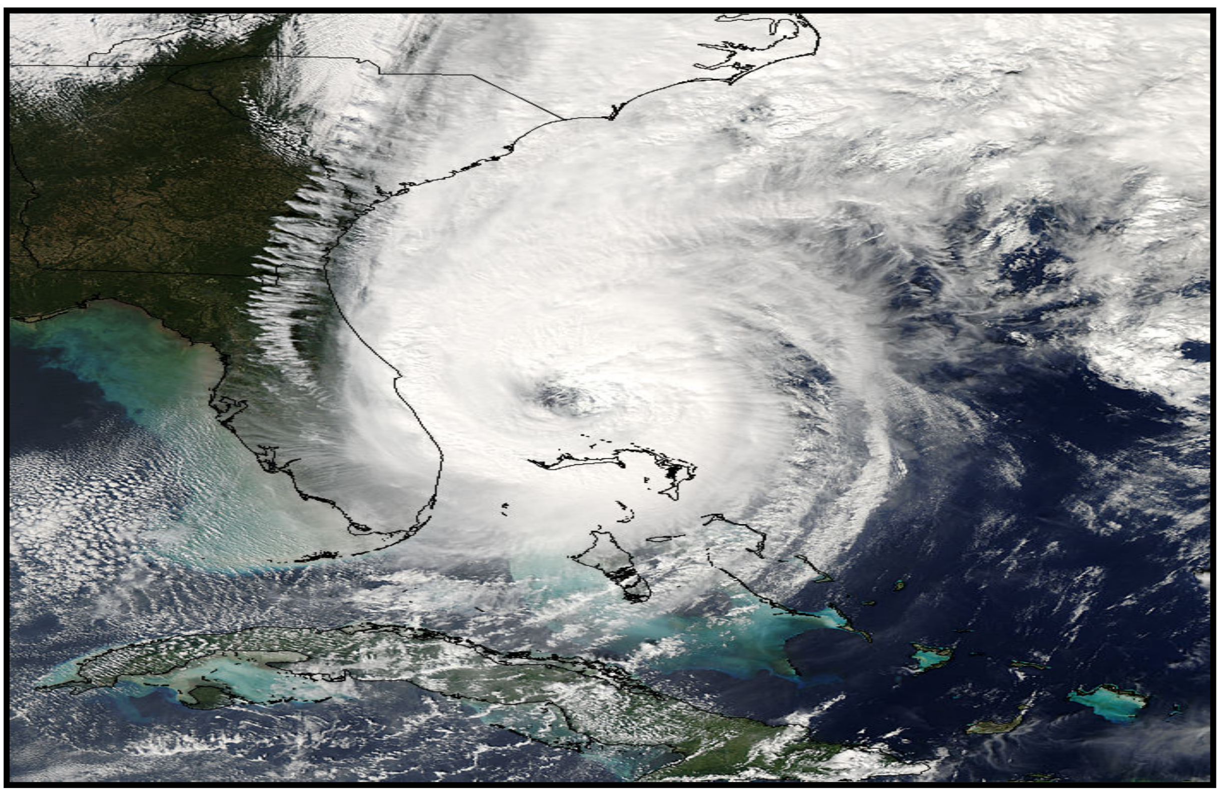


Figure 2-2. This image was captured by the MODIS instrument on the Aqua spacecraft on October 24, 2005. It shows Hurricane Wilma departing Florida after crashing into the western side of Florida early that morning. Credit: NASA

potential for floods. For instance, USGS is involved with precipitation-runoff modeling of watershed systems: the use of computer models to simulate and evaluate the effects of various combinations of precipitation, climate, and land use on stream flow, sediment yield, and other hydrologic components.

2.3 Federal Entities Conducting or Managing Other R&D Activities Relevant to Tropical Cyclone Operations

This section provides an overview of agencies that are involved in conducting or managing research in areas beyond just the physical sciences and of substantial relevance to the Nation's preparations for and response to tropical cyclones.

2.3.1 Federal Emergency Management Agency, Department of Homeland Security

The Federal Emergency Management Agency (FEMA), which is part of the Department of Homeland Security, has as its mission disaster response, planning, recovery, and mitigation. FEMA's National Hurricane Program (NHP), housed under the Mitigation Division, helps protect communities from hurricane hazards. The NHP, which was established in 1985, provides tools, technical information, and products to assist State and local agencies in developing hurricane evacuation plans. FEMA, NOAA/NWS, the U.S. Department of Transportation, USACE, and numerous other Federal agencies are partners in this program.

Although FEMA is not in general a research agency, it does provide limited funding for applied research activity. Past examples include the development of an inland wind field map and funding the development and updates of the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model, a computer model now run by the TPC/NHC. SLOSH estimates storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes by taking into account parameters of atmospheric pressure, storm size, forward speed, track, and winds. Current hurricane-related activity at FEMA includes studies to support evacuation planning, post-disaster forensic engineering evaluations, development of a state-of-the-art loss estimation model for hurricanes, and a limited number of problem-focused engineering and technical studies related to the built environment. FEMA and NOAA also collaborate to provide training and educational materials on hurricanes.

2.3.2 Department of Health and Human Services

Research managed by the U.S. Department of Health and Human Services (HHS) that is of relevance to tropical cyclones deals mainly with psychological distress. According to the Substance Abuse and Mental Health Services Administration, an arm of HHS, past research on the mental health consequences of major floods and hurricanes provides a basis for estimating the psychological impacts of the 2005 hurricanes. In those areas significantly affected by the hurricanes, 25 percent to 30 percent of the population may experience clinically significant mental health needs. An additional 10 percent to 20 percent may have subclinical but nontrivial needs. Up to 500,000 people may have been in need of assistance.[3]

[3] http://sev.prnewswire.com/health-care-hospitals/20051207/DCW03808122005-1.html

2.3.3 Department of Housing and Urban Development

HUD's mission is to increase homeownership, support community development, and increase access to affordable housing free from discrimination. To fulfill this mission, HUD embraces high standards of ethics, management, and accountability and forges new partnerships—particularly with faith-based and community organizations—that leverage resources and improve the Agency's ability to be effective on the community level.

The mission of the Office of Policy Development and Research is to provide reliable facts and analysis to inform the policy decisions of HUD, Congress, and State and local governments. Research and technology funds enable this office to fulfill this mission by maintaining and expanding information on housing needs and market conditions; evaluating current HUD programs and proposed policy changes; and conducting research on a wide range of housing, community, and economic development issues, including advances in housing/building technology. In the area of housing/building technology, HUD is concerned with developing new cost-effective ways to improve energy efficiency in existing housing and with improving the disaster resistance and durability of housing, including resistance to the effects of tropical cyclones.

2.3.4 National Institute of Standards and Technology, Department of Commerce

The National Institute of Standards and Technology (NIST) was founded in 1901 as the National Bureau of Standards, the Nation's first Federal physical science research laboratory. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life.

Within NIST, a major goal of the Building and Fire Research Laboratory (BFRL) is to reduce the human and economic losses resulting from hazards, including tropical cyclones. BFRL mitigates the public safety hazards associated with landfalling tropical cyclones through research on ways to improve the life-cycle quality and cost-effectiveness of constructed facilities. The laboratory's research includes fire science and fire safety engineering; building materials; computer-integrated construction practices; structural, mechanical, and environmental engineering; and building economics. Products of BFRL research include measurements and test methods, performance criteria, and technical data that are incorporated into building and fire standards and codes. The laboratory conducts investigations at the scene of major fires and structural failures due to earthquakes, hurricanes, or other causes. The knowledge gained from these investigations guides research and is applied to recommendations for design and construction practices to reduce hazards.

2.4 Federal Policy and Coordination Roles for Tropical Cyclone R&D

A number of Federal entities have responsibilities for coordinating R&D or formulating and overseeing policy initiatives and priorities of either direct or indirect relevance to some part of the end-to-end system for tropical cyclone forecasts and warnings. These policy and coordination roles are increasingly important to understanding the flow of requirements and the transfer of knowledge and information among the sectors of the tropical cyclone community of practice. The principal entities engaged in interagency coordination are described here.

2.4.1 OFCM

The mission of the OFCM is to ensure the effective use of Federal meteorological resources by leading the systematic coordination of operational weather requirements, services, and supporting research among the Federal agencies. OFCM operates with policy guidance from the Federal Committee for Meteorological Services and Supporting Research (FCMSSR). The Chairperson of FCMSSR is the Under Secretary of Commerce for Oceans and Atmosphere and Administrator of NOAA. The members of the FCMSSR are senior policy executives from the Federal agencies with meteorological programs. In addition to reviewing OFCM activities and providing policy guidance, FCMSSR is the final forum to resolve agency differences. One of the activities through which OFCM fulfills its mission is the preparation of an annual *Federal Plan for Meteorological Services and Supporting Research*, which documents the programs and funding of Federal agencies in the areas coordinated by OFCM during the prior fiscal year and provides a comprehensive review of plans for the coming year.

As mentioned in chapter 1, OFCM hosts an annual Interdepartmental Hurricane Conference (IHC) to educate attendees on the status and future plans of the Nation's tropical cyclone forecast and warning service. One of the major objectives is to plan and prepare for the upcoming hurricane season. New procedures, procedural changes, and agreements that are approved at the IHC and are directly related to providing tropical cyclone forecast and warning services are then documented for implementation in the National Hurricane Operations Plan (NHOP). The 44th annual edition of the NHOP was published in May 2006. Pertinent interagency action items that arise from either the annual NOAA Hurricane Conference or the annual Tropical Cyclone Conference sponsored by U.S. Pacific Command are worked (and action items are tracked) by the OFCM-sponsored Working Group for Hurricanes and Winter Storms Operations and Research. This OFCM working group meets during the annual IHC.

2.4.2 Office of Science and Technology Policy

OSTP was established in the Executive Office of the President by the National Science and Technology Policy, Organization and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on all questions in which science and technology (S&T) are important elements; articulating the President's S&T policies and programs; and fostering strong partnerships among Federal agencies, State and local governments, and the S&T communities in industry and academia. The Director of OSTP serves as Assistant to the President for Science and Technology and manages the National Science and Technology Council (NSTC) for the President.

Each year, OSTP in conjunction with the Office of Management and Budget issues the Administration's R&D priorities. These priorities provide general guidance for setting priorities among R&D programs, interagency R&D efforts that should receive special focus in agency budget requests, and reiteration of the R&D investment criteria that agencies should use to improve investment decisions for, as well as management of, their R&D programs.

2.4.3 National Science and Technology Council

The NSTC was established by Executive Order on November 23, 1993, as a Cabinet-level council to coordinate S&T policy across the diverse entities that constitute the Federal R&D enterprise. A primary objective of the NSTC is the establishment of clear national goals for Federal S&T investments in a broad array of areas, spanning virtually all the mission areas of the executive branch. The Council prepares R&D strategies that are coordinated across Federal agencies to form investment packages designed to accomplish multiple national goals. Each of its four primary committees oversees subcommittees and working groups focused on specific aspects of S&T coordination.

Committee on Environment and Natural Resources

The purpose of the CENR, which is one of the four primary committees of the NSTC, is to advise and assist the NSTC to increase the overall effectiveness and productivity of Federal R&D efforts associated with the environment and natural resources. According to the CENR's charter, "The CENR will address science policy matters and R&D efforts that cut across agency boundaries and provide a formal mechanism for interagency coordination relevant to domestic and international environmental and natural resources issues."

Subcommittee on Disaster Reduction

The SDR is a subcommittee of the CENR. In the words of its charter, the SDR "is charged with facilitating and promoting natural and technological disaster mitigation, preparedness, response, and recovery. The SDR provides a senior-level interagency forum to leverage expertise, inform policy-makers, promote technology applications, coordinate activities, and promote excellence in research."

United States Group on Earth Observations

An Interagency Working Group on Earth Observations (IWGEO) was chartered by the CENR for the purpose of developing the Strategic Plan for the U.S. Integrated Earth Observation System, which will constitute the U.S. contributions to the Global Earth Observing System of Systems (GEOSS). GEOSS is discussed further in section 2.6.2. The IWGEO's charter expired in December 2004, and the working group was replaced with a standing subcommittee under CENR, the US GEO.

2.4.4 NSF National Science Board

The National Science Board (NSB) has dual responsibilities as: (1) national science policy advisor to the President and the Congress and (2) the governing board for the NSF. The NSB is composed of 24 part-time members. Much of the Board's work is accomplished through its committees. On December 1, 2005, the NSB formed the Task Force on Hurricane Science and Engineering under the Committee on Programs and Plans. The work of this NSB Task Force and its interaction with the JAG/TCR are described further in section 2.8.8.

2.4.5 Joint Hurricane Testbed

The JHT began under the USWRP and continues today. Its mission is to transfer more rapidly and smoothly new technology, research results, and observational advances into improved tropical cyclone analysis and prediction at operational centers. The JHT prepares, with help from the JHT Steering Committee, a biennial Announcement of Federal Funding Opportunity (AFFO) that is open to the U. S. and international scientific community including the NOAA Line Offices, other Federal agencies and laboratories, NCAR and other academic research entities, and the private sector. Proposals are reviewed under the purview of the Steering Committee, with funded projects becoming a JHT activity.

The current transfer process at JHT is described in section 3.6.2. For additional information on the JHT, see its website at http://www.nhc.noaa.gov/jht/.

2.4.6 Joint Center for Satellite Data Assimilation

In the past, 2 years of preparation time have typically been required before the data from a new satellite-based observing instrument was ready for use in operational models. This delay typically represents 40 percent of a new instrument's expected lifetime. To expedite the assimilation of satellite data in operational models from both a scientific and increased data handling and management perspective, NOAA, NASA, and DOD formed JCSDA in 2001. The mission of the JCSDA is to accelerate and improve the quantitative use of research and operational satellite data for analysis and in prediction models for weather, ocean, climate, and environmental applications. The following agencies are the current JCSDA partners:

- EMC in NOAA/NWS/NCEP
- STAR in NOAA/NESDIS
- The Office of Weather and Air Quality in NOAA/OAR
- The Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center.
- The Oceanographer of the Navy and NRL-Monterey in the U.S. Navy
- The Air Force Weather Agency (AFWA) and the Air Force Director of Weather for the U.S. Air Force

In pursuit of its mission, the JCSDA is guided by four long-term goals:

- Reduce from 2 years to 1 year the average time for operational implementation of new satellite technology
- Increase uses of current satellite data in numerical weather prediction (NWP) models
- Advance the common NWP models and data assimilation infrastructure
- Assess the impacts of data from advanced satellite sensors on weather and climate prediction

Further information on JCSDA infrastructure, priority R&D areas, and recent advances can be found on the center's website (http://www.jcsda.noaa.gov). The current and future roles that

JCSDA plays in transferring research results into operational improvements are discussed in sections 3.6.2 and 4.5.1, respectively.

2.5 Role of Academia in Tropical Cyclone Research

In general, Federal agencies that sponsor *extramural research* programs on tropical cyclone evolution and behavior, societal impacts of hurricanes and related severe weather phenomena, or satellite-based observations of relevant atmospheric and oceanic properties provide funding to university-based researchers. The research projects may be part of an ongoing program at one of the major academic centers for atmospheric science and related topics, or they may be conducted by an individual principal investigator on the faculty of a college or university. Grants awarded to proposals submitted in response to announcements of funding opportunities by the various joint programs and initiatives, such as JHT and JCSDA, provide a means to steer academic research into priority areas while sustaining the competitive, merit-based process for finding and funding the best ideas.

NCAR, which receives a substantial portion of its funding from NSF, concentrates its research in the field of atmospheric sciences. NCAR has about 750 scientists and support personnel and is located in Boulder, Colorado. NCAR's mission is "to support, enhance, and extend the capabilities of the university community, nationally and internationally; to understand the behavior of the atmospheric and related systems and the global environment; and to foster the transfer of knowledge and technology for the betterment of life on Earth."

- The design of the GPS dropsonde used by "hurricane hunter" aircraft was created at NCAR in the 1990s. This dropsonde takes advantage of the Global Positioning System (GPS) to glean accurate, high-resolution measurements. On each flight, dozens of dropsondes are sent into the heart of the hurricane to measure winds, air pressure, and humidity.
- NCAR has been an active participant in the USWRP since the program began. As part of the USWRP focus on landfalling hurricanes. NCAR researchers and their collaborators are looking at ways to improve forecasts of changes in hurricane intensity, as well as forecasts of wind, waves, and rain at landfall.
- NCAR is a principal player on the team for the Weather Research and Forecasting (WRF) computer modeling initiative. A special hurricane-oriented version of WRF called HWRF is being developed by scientists from NOAA, NRL-Monterey, the University of Rhode Island, and Florida State University (see HWRF in section 4.4.2).
- Other NCAR projects, past and present, in tropical cyclone R&D are described at http://www.ucar.edu/research/storms/hurricanes.shtml.

UW-CIMSS is another academic R&D center active in research on tropical cyclone observing and forecast methods. UW-CIMSS developed the Advanced Dvorak Technique for estimating the position and intensity of tropical cyclones from satellite-based infrared and multispectral imagery. Another active research area for the UW-CIMSS tropical cyclone team has been interpretation of imagery and data products from the Advanced Microwave Sounding Unit (AMSU) instruments that are flying on NOAA polar-orbiting satellites. The UW-CIMSS work on tropical cyclone observations and data interpretation is funded by ONR, NRL-Monterey, and NOAA/NESDIS.

CIRA is located at Colorado State University in Fort Collins, Colorado. A particularly relevant project at CIRA has been the development of a new technique to estimate tropical cyclone wind probabilities, which influence the uncertainties in forecasts of tropical cyclone track, intensity, and wind structure (http://rammb.cira.colostate.edu/projects/tc_wind_prob). This new algorithm has recently been transitioned to TPC/NHC operations through the JHT. The Regional and Mesoscale Meteorology Branch of NOAA/NESDIS, which is colocated with CIRA, conducts research on the use of satellite data to improve analysis, forecasts, and warnings for regional and mesoscale meteorological events. The work of this NESDIS branch focuses on severe and tornadic storms, tropical cyclones, and mesoscale aspects of mid-latitude cyclones, including genesis, development, intensification, and prediction. Development efforts focus on mesoscale forecast and nowcast products based on multispectral satellite data integrated with other observations such as Doppler radar and aircraft reconnaissance data and with NWP models. Both UW-CIMSS and CIRA have developed automated methods to combine information from multiple satellite platforms on wind distribution in and around tropical cyclones.

There are many other academic institutions engaged in tropical cyclone research. The numerous academic contributions to tropical cyclone research are illustrated in the agenda (expanded view) of the American Meteorological Society's 27th Conference on Hurricanes and Tropical Meteorology, which is available online at:
http://ams.confex.com/ams/27Hurricanes/techprogram/programexpanded_339.htm.

2.6 International Contributions to Tropical Cyclone Research

Tropical cyclones cause tremendous damage and contribute to loss of life not just in the United States but around the world. Especially vulnerable to destructive winds, severe floods, and high storm surges are Japan, China, Taiwan, Korea, and Australia. Quite naturally, then, these countries are heavily invested in research programs which address the fundamental science and technology issues necessary to improve their operational capabilities in predicting tropical cyclones.

2.6.1 Principal Tropical Cyclone R&D Centers around the World

The principal tropical research centers are organizationally within or closely linked with the region's national operational centers:

- Australia Bureau of Meteorology (BOM)[4]
    - BOM Research Centre[5]
- Chinese Meteorological Administration (CMA)[6]
    - Shanghai Typhoon Institute (STI)[7]

[4] http://www.bom.gov.au/
[5] http://www.bom.gov.au/bmrc/
[6] http://www.cma.gov.cn
[7] http://www.sti.org.cn/en/

- Japan Meteorological Agency (JMA)[8]
    - Meteorological Research Institute9
- Korean Meteorological Administration (KMA)[10]
- Taiwan Central Weather Bureau (CWB)[11]
    - National Taiwan University[12]

The level of effort and details of the operational and R&D activities differ among these centers but are beyond the scope of this document. However, their activities share a common, consistent, and recognizable theme. Together with the U.S. community of practice and often in collaboration with U.S.-based partners and in coordination with the WMO Tropical Cyclone Programme, they are working continually toward improving the skill and value of numerical analysis and forecast systems for tropical cyclone intensity, structure, and track (including genesis). They conduct basic and applied research directed at improvements in the following area:

- Observing systems and their sensitivities, especially satellite data and adaptive sampling strategies
- Data assimilation procedures and methodologies
- Higher-resolution models
- Increased fidelity of models with the dynamical and physical mechanisms underlying tropical cyclone genesis and life-cycle evolution, whether as currently understood or as modified by results of further investigation

Another consistent theme is an increasing emphasis on ensemble prediction systems and strategies, especially in the direction of high-resolution regional model–based ensembles. Global model ensembles now are available and used extensively, for example in providing case-dependent estimates of track envelopes. Probabilistic guidance based on advanced high-resolution regional models is necessary to address adequately the forecast uncertainties in critical storm attributes such as intensity, structure, and track.

THORPEX was established in May 2003 by the Fourteenth World Meteorological Congress as a ten-year international program in global atmospheric R&D. It is a component program of the WMO World Weather Research Programme and is intended to contribute to the evolution of the WMO Global Observing System, a core component of the future GEOSS. THORPEX is conducting a series of regional and global projects, including experiments on targeted satellites and in-situ observations, data assimilation, NWP systems, and demonstrations of social and economic outcomes. One of these, projects, the THORPEX Pacific Asian Regional Campaign, is of special interest to tropical cyclone R&D.[13] Its principal focus is advancing “the understanding and predictability of high-impact weather over Asia and the western Pacific with an emphasis on tropical cyclones from genesis to decay/extratropical transition.” This international effort brings

[8] http://www.jma.go.jp/jma/indexe.html
[9] http://www.mri-jma.go.jp/Welcome.html
[10] http://www.kma.go.kr/eng/index.jsp
[11] http://www.cwb.gov.tw/V5e/index.htm
[12] http://typhoon.as.ntu.edu.tw/
[13] http://www.ucar.edu/na-thorpex/PARC.html

to bear the collective assets and resources of several countries, including Japan, China, Korea, and the United States. The field experiment phase is scheduled for June to December 2008. Research activities leading to, during, and after the field phase focus on: (1) assessing the relative importance of various physical, dynamical, and scale-interaction processes; (2) determining the importance of various components of existing and special observing systems, including aircraft-deployed dropsondes and remote sensing and adaptive satellite observations; and (3) developing and testing advanced data assimilation techniques and high-resolution models and ensemble strategies.

2.6.2 GEOSS and the Nation's Hurricane Forecast and Warning Program

Many of the observing systems used to monitor today's environment were built for a single purpose. Many of the observations collected from them connect into "stovepipe" networks that output the data in a variety of formats and dissemination methods. The purpose of GEOSS, which has been endorsed by nearly 60 governments and the European Commission, is to achieve comprehensive, coordinated, and sustained observations of the Earth system in order to improve monitoring of the state of the Earth, increase understanding of Earth processes, and enhance prediction of the behavior of the Earth system. An integrated Earth observation and data management system will enhance the Nation's capabilities to apply resources more efficiently and effectively by reducing duplication, improving coverage, and providing networks to disseminate information when and where it is needed around the world. Through U.S. participation in GEOSS, as outlined in the *Strategic Plan for the U.S. Integrated Earth Observation System* (IWGEO 2005), the integration of existing and planned observing systems, data, and quality control with efforts of other nations will help guarantee the best quality and coverage of Earth-observing data. Integrating these observing systems will enable improved analysis and prediction of the state of the atmosphere, land, streams, and oceans, which are the key to improving tropical cyclone modeling and predictions and the Nation's tropical cyclone forecast and warning service.

2.7 External Advisory and Advocacy Groups

In addition to the policy formulation and implementation entities within the Federal structure, which were described in section 2.4, several nongovernmental bodies representing the S&T communities in different ways contribute to the tropical cyclone community of practice as policy advisors and science-based advocates.

2.7.1 National Academy of Sciences and National Research Council

The National Academy of Sciences (NAS) is an honorific society of distinguished scholars engaged in scientific and engineering research that is dedicated to the furtherance of science and technology and to their use for the general welfare. Since 1863, the Nation's leaders have often turned to the NAS and (since 1964) the National Academy of Engineering (NAE) for advice on the scientific and technological issues that frequently pervade policy decisions.[14] Most of the technical work and policy studies conducted under the aegis of the National Academies are

[14] http://www.nasonline.org/site/PageServer?pagename=ABOUT_main_page. The term "National Academies" embraces the National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council.

performed by their principal operating agency, the National Research Council (NRC). The NAS, NAE, and NRC are private nonprofit organizations that work outside the framework of government, which ensures independent advice. The Board on Atmospheric Sciences and Climate (BASC), which was established in 1982 by the NRC, advances the understanding of Earth's atmosphere and climate, helps apply this knowledge to benefit the public, and advises the Federal government on issues within the board's realm. Like the other boards and standing entities within the NRC, the BASC draws on volunteer participation from the relevant scientific and technical disciplines—including but not limited to members of the NAS and NAE—to form study committees whose peer-reviewed reports are the chief mechanism by which the NRC advises the Government.

2.7.2 American Meteorological Society Policy Program

Founded in 1919, the American Meteorological Society (AMS) promotes the development and dissemination of information and education on the atmospheric and related oceanic and hydrologic sciences and the advancement of their professional applications. It has a membership of more than 11,000 professionals, professors, students, and weather enthusiasts. The mission of the American Meteorological Society Policy Program (APP) is to strengthen the connection between public policy and Earth system science and services by building policy research and by creating opportunities for policy-makers and scientists to engage and exchange perspectives to foster better-informed policy decisions. The APP focuses on five strategic goals:

- Prepare scientists to contribute effectively to the policy process
- Keep policy-makers abreast of scientific advances and their relevance
- Foster meaningful collaborations between scientists and policy-makers
- Develop the needed policy research
- Share [the AMS community's] vision and results

The APP strives to address the following national priorities: public health and safety, economic growth, the protection of the environment, and national security. The APP studies both immediate and longer-term policy issues relating to Earth system science and services. Its stated core value is to be objective in examining sound science and policy options, and it aims to bring together a diverse group of perspectives and create real partnerships across sectors and disciplines. The scope of issues addressed by the APP will include disciplines such as economics, engineering, and social science, and its studies are expected to foster research that will be inherently interdisciplinary. These issues can be scientific, institutional, budgetary, economic, or social in character and can be of regional, national, and international interest.[15]

2.8 Prior Documentation of Tropical Cyclone Operational and Research Needs

The development of this strategic research plan builds on previous work to articulate tropical cyclone operational and research needs, starting with the 1997 OFCM-sponsored *National Plan for Tropical Cyclone Research and Reconnaissance (1997-2002)*. Following the publication of

[15] http://www.ametsoc.org/atmospolicy/documents/APPstrategicplan_000.pdf

that report, a great deal of work continued to identify operational and research needs and to develop strategies to improve tropical cyclone modeling and predictions. The sections below summarize many of these important efforts.

> **The task of the JAG/TCR has been to synthesize the previous exceptional tropical cyclone work, update information as needed, and develop and coordinate a comprehensive interagency strategic research plan for tropical cyclones that links research priorities to operational needs. This document is the product of those efforts.**

2.8.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers

In June 2004, NOAA/OAR issued an AFFO entitled "Joint Hurricane Testbed Opportunities for Transfer of Research and Technology into Tropical Cyclone Analysis and Forecast Operations." Included in this announcement was the TPC/NHC's summary of 14 operational forecast improvement needs and four high-priority areas identified by the NCEP/EMC for advancing NWP modeling and forecasting capabilities.

A strategic planning session conducted at the 59th IHC validated these 14 operational needs of the TPC/NHC. The DOD participants in this session emphasized their top three priorities for military operations, which are indicated in the bullets below. DOD's remaining needs were the same as the 14 operational needs specified by the TPC/NHC.

- Track forecast: to 5 days
- Structure: radius of 50-kt and 35-kt wind radii
- Wave heights; radius of 12 foot seas

The 14 TPC/NHC operational needs were updated in another NOAA/OAR AFFO issued in June 2006. The updated 14 operational needs, along with DOD's priority needs, thus represent the best available compilation and prioritization of operational needs across the three U.S. centers: TPC/NHC, JTWC, and CPHC. The operational needs are presented in section 4.1.

2.8.2 Interdepartmental Hurricane Conferences

As part of the annual review of the Nation's hurricane forecast and warning capability at each IHC, the panel sessions, breakout sessions, poster sessions, and/or workshops provide opportunities for appropriate personnel to give status updates and identify potential needs and challenges for operations and research. The following functional areas have been routinely included in recent IHC agendas:

- Tropical cyclone observations and reconnaissance
- Tropical cyclone modeling and prediction
- Impacts of tropical cyclones (e.g., winds, storm surge, heavy precipitation/inland flooding)
- Tropical cyclone research; science and technology
- Transitioning tropical cyclone research to operations

- Tropical cyclone decisionmaking products and services
- Tropical cyclone warning system and response

Documented needs and requirements brought before the IHC in these venues have resulted in participant consensus on recommended actions. These actions were subsequently addressed through the interagency collaboration that the IHC facilitates. The following significant improvements to the Nation's hurricane forecast and warning service have resulted from this process.

- **Tropical Cyclone Forecasts Extended beyond 72 Hours.** The official forecast issued by the tropical cyclone forecast and warning centers was extended from a 72-hour (3-day) forecast to a 120-hour (5-day) forecast. In 2001, the TPC/NHC extended its forecasts to include 96- and 120-hour forecasts but did not publicly distribute the forecasts. In 2003, the TPC/NHC began public distribution of the extended forecasts. The JTWC began experimental 96-hour and 120-hour forecasts in 2000 and began to release these forecasts officially in May 2003.
- **Stepped-Frequency Microwave Radiometer (SFMR)**. The original SFMR design involved a single nadir-viewing antenna and receiver capable of making measurements of radio emission from the sea surface at four selectable frequencies between 4.5 and 7.2 GHz. The stepping procedure enabled estimates of the surface wind speed in hurricanes by correcting for rain-induced effects in the measurements, thereby deriving a rain rate. The first measurements with this original SFMR were made from NOAA aircraft in Hurricane Allen in 1980. Agreement between surface (20 m) winds extrapolated from the 1500 m flight-level and the SFMR estimates for independent flight legs were within ±10 percent. Despite the success in Hurricane Allen, this instrument was never again flown into a hurricane. With support from the OFCM, a new horn antenna was developed in 1993. The new antenna, with a new set of six frequencies, was flown in Hurricane Olivia (1994) and retrieved high-quality wind estimates. Further funds were provided by the OFCM for an upgrade of the SFMR's receiver to increase calibration stability. Since 1980, the SFMR has flown on over 150 flights in 50 tropical cyclones. As will be highlighted in chapter 3, surface wind and rain rate data obtained by the SFMR are essential for real-time interpretation of rapidly changing events, especially near landfall. Airborne-derived observations, including the SFMR, will become increasingly assimilated into hurricane computer models, which will lead to improved forecasts.
- **GPS Dropwindsonde.** The GPS dropwindsonde represents a major advance in both accuracy and resolution for atmospheric measurements over data-sparse oceanic areas of the globe. It provides wind velocities accurate to within 0.5 to 2.0 $m\ s^{-1}$ with a vertical resolution of approximately 5 m. One important advance over previous generations of sondes is the ability to measure surface (10 m) winds. The new dropwindsonde has already been used extensively in operational and research hurricane flights. It has been deployed from different aircraft including NOAA's WP-3Ds and Gulfstream IV jet, as well as the Air Force WC-130s.

During the 59th IHC in 2005, the JAG/TCR conducted a strategic planning session to begin developing a framework for this strategic research plan. Additionally, the OFCM planned a workshop during the 60th IHC on "Tropical Cyclone Research: Priorities for the Next Decade," which included a review of a draft version of this document. The workshop is discussed further in section 2.8.8.

2.8.3 USWRP Implementation Plan for Hurricane Landfall

The U.S. Weather Research Program (USWRP) was established in 1994, originally with nine Federal agencies participating. The three initial foci of the program were landfalling hurricanes, heavy precipitation and flooding, and the societal and economic impacts of severe weather. Advice and direction from the scientific community has come through prospectus development teams (PDTs): small groups of scientists and technical experts who met in a workshop format to discuss issues and report findings and recommendations. The fifth of these teams (PDT-5) met in April–May 1996 “to identify and delineate emerging research opportunities relevant to the prediction of local weather, flooding, and ocean currents associated with landfalling U.S. hurricanes…and tropical cyclones…in general” (Marks et al. 1998). In 1997, a workshop with about 70 participants considered the operational hurricane forecast needs and the socioeconomic impacts of hurricane landfall in prioritizing observational and research opportunities. An implementation plan was completed in 2002 that matched forecast needs with observational and research opportunities.

The following hurricane program goals were extracted from the implementation plan:

- Reduce landfall track and intensity errors by 20 percent
- Increase warning lead-time to 24 hours and beyond with 95 percent confidence without increasing the present 3 to 1 overwarning
- Make skillful forecasts (compared to persistence) of gale- and hurricane-force wind radii out to 48 hours with 95 percent confidence
- Extend quantitative precipitation forecasts to three days and improve skill of day-three forecasts to improve inland flooding forecasts

A coordinated research program among four agencies (NOAA, NSF, ONR, and NASA) was outlined in this plan. In each aspect, the state of the science, technology, and prediction capability was indicated; deficiencies vis-à-vis the above goals were identified; and the proposed research programs were described.

Other areas of research identified for attention include the following:

- Outer wind structure analysis and prediction
- Inner wind structure (intensity) analysis and prediction
- New conceptual models for explaining localized wind-damage streaks
- Exploitation of new observations from Doppler radars, portable Doppler radars and wind profilers, rapidly deployable automatic surface observing system, and deployable meteorological towers
- Social-economic research focused on each aspect of the hurricane warning service—forecast preparation and communication; dissemination by emergency management,

media, and private industry; and sociological aspects of public response to warning content, frequency, and consistency

2.8.4 HWRF Model Workshop

The Hurricane Weather Research and Forecast (HWRF) model is a high resolution, next generation atmosphere-ocean-land prediction system, with operational implementation at NCEP/EMC planned for 2007. At the initial HWRF workshop held in 2002, the participants discussed: (1) the structure of the next generation hurricane forecast model, (2) the data and data assimilation techniques needed both to initialize this model and to provide direct forecast support, and (3) the key impediments that must be addressed by the research community to support the operational implementation of the HWRF (Surgi et al. 2002). The workshop consisted of two working group sessions: (1) observations to address the hurricane initialization problem, geared toward upgrading the Gulfstream IV aircraft; and (2) modeling physical processes for a high resolution, coupled air/sea/land hurricane prediction system.

The workshop participants agreed upon the following statements on research needs (Surgi et al. 2002):

- Given the requirement for an accurate initial and predicted vortex structure to get the correct response to forcing, a high-resolution, nested, moving, two-way interactive numerical model is required.
- The ultimate success of the hurricane landfall research model for intensity and precipitation will depend on how well the physical processes of the boundary layer and convection are predicted.

In the same report, the following were listed as the “showstopper” and “most difficult tasks” in implementing such a high-resolution, next generation model:

- Inadequate observations to define the initial conditions, especially for mesoscale features in the eyewall and rainbands including the microphysical species, and also including accurate and representative humidity measurements, and then the communication bandwidth for transmitting aircraft and satellite remotely sensed observations to the operational centers
- Inadequate data assimilation techniques to incorporate the existing and future atmospheric observations on the mesoscale, also data assimilation for the ocean surface wave and subsurface in response to hurricane forcing, and inadequate linkages and researchers to work with the operational centers in data assimilation
- Inadequate computer resources at the operational centers within the next 3 to 5 years to develop even the minimally acceptable model
- Inadequate transition of numerical model results to viable and sufficiently accurate tropical cyclone intensity and precipitation guidance products to achieve forecast accuracy goals, especially considering track accuracy deficiencies, or a means to account for uncertainties in track, wind structure, and precipitation via a probabilistic approach
- Inadequate coastal ocean and land surface modeling capability to account for modifications of wind structure and precipitation during and following hurricane landfall

2.8.5 NOAA/OAR Science and Technology Infusion Plan

In 2003, NOAA/NWS and NOAA/OAR outlined a plan to improve the infusion of science and technology into operations to improve forecast accuracy and other NWS products and services. This Science and Technology Infusion Plan (STIP) defined strategies and capability improvements the NWS will pursue to meet operational requirements and exploit scientific opportunities. The STIP is linked to the NWS Services Improvement Plan and other plans all working together toward NOAA and NWS strategic goals. It outlines the goals and enabling science and technology for the next 5–10 years, and a vision for 20 years in the future. In the area of tropical cyclones, the STIP goals and capability improvement plans focused on the 48-hour track and intensity forecast errors.

For the 48-hour track error, the target goals were [not more than] 128 nm by 2007, [not more than] 90 nm by 2012, and a vision of 85 nm by 2025. While the 2005 48-hour track error of [not more than] 99 nm is better than the goal for 2007 by a considerable margin, it was believed that these improvements would eventually asymptote near a theoretical predictability limit around 85-90 nm.

The goals for the 48-hour intensity errors were [not more than] 15.4 kt by 2007, 13.9 kt by 2012, and a vision of 12 kt for 2025. While the 2005 48-hour intensity error of 14.6 kt is slightly better than the 2007 goal, the improvement is much less than that for track error.

The STIP identified the following forecast gaps that need to be addressed to meet the goals:

- Improved forecasting of rapidly changing storms
- Understanding of model guidance uncertainty
- More precise position of circulation center
- Higher resolution storm wind data

For each gap, the STIP identified solutions to remedy the gap and the anticipated impact of each solution, as shown in table 2-1.

Finally, the STIP listed the outstanding research and development needs:

- Rapid intensity changing storms
- Shear effects on track and intensity
- Statistical “guidance-on-guidance” on model output
- Improved data assimilation
- Improved model physics (e.g., microphysics, air-sea fluxes)
- Model physics sensitivities
- Ensemble techniques
- Adaptive observations/targeting
- Predictability limits

Table 2-1. Tropical Cyclone Gaps, Solutions, and Impacts (from NOAA STIP)

Gap	Solutions	Impact
More Accurate Cyclone Track and Intensity Forecast	• Targeted/adaptive observations • NOAA Aircraft Instrumentation Upgrade • Advanced data assimilation of remote and in-situ atmosphere and ocean observations • Aircraft and WSR-88D Doppler radar winds • Ensembles and HWRF model • JHT Results	• About 12% Increase in Numerical Model Intensity Forecast Skill • About 25% Increase in Numerical Model Track Forecast Skill
Understanding of Model Guidance Uncertainty	• Ensembles • Statistical Guidance • JHT Results • Training	• Reduced Overwarning of Coastal Hazards
Improved Forecasting of Rapidly Changing Storms	• JHT Results • Ocean Observations • HWRF model (Improved Physics) • GPS Dropsonde • SFMR	• Saved Lives/Enhanced Public Safety • Improved Track and Intensity Forecasts • Improve Other Measures (Marine, Quantitative Precipitation Forecast (QPF), Aviation)
Higher Resolution Wind Data	• Aircraft Doppler radar winds • Aircraft Instrumentation Upgrades (e.g., SATCOM) • NEXRAD radar (Weather Surveillance Radar-1988 Doppler, WSR-88) winds	• Improved Intensity and Track Forecasts • Improved Storm Physics • Improved Storm-Surge Forecast • Improved QPF
More Precise Position of Circulation Center	• Satellite/Aircraft Remote Sensing	• Reduced Track Error

2.8.6 Workshop on Air-Sea Interactions in Tropical Cyclones

In a continuation of previous successful modeling workshops, NOAA/NWS/NCEP hosted a workshop on Air-Sea Interactions in Tropical Cyclones in May 2005. A broad cross-section of researchers, numerical modelers, operational forecasters, and managers of governmental and university research programs participated in the workshop to address the near- and far-term theoretical, observing, and modeling challenges in developing the next generation coupled ocean-hurricane prediction system. Key recommendations from the workshop fell into four categories:

- Air-sea parameterizations
- Data archive
- Sampling approach
- Ocean model initializations and mixing parameterizations

The workshop report highlighted some of the challenges facing the Nation's hurricane forecast and warning system:

> *Although significant progress has been made over the past several decades in advancing our Nation's hurricane track forecasting capability, scientific and*

> *forecast challenges remain that need to be addressed by the next-generation coupled ocean-wave-atmosphere hurricane prediction system, which includes understanding the role of the upper ocean on hurricane intensity through the air-sea interface and the atmospheric boundary layer. Given a spectrum of differing track scenarios such as erratically moving storms, storms that accelerate, and storms that stall, any improvements to the hurricane intensity forecast must not degrade track forecasting. In the case of a tropical cyclone interacting with the upper ocean, any subsequent intensity change is sensitive to the track forecasts. Notwithstanding, when the forecast track is fairly certain within 36 hours of landfall, understanding the ocean's role on the intensity change through air-sea interactions becomes of paramount importance as deep ribbons of high oceanic heat content water surround the US coastline. By providing better initial ocean conditions, and improving air-sea parameterization schemes in the coupled models, we may expect improved forecasts of the tropical cyclone surface wind field, the ensuing storm surges and the inland flooding...*
>
> *To meet these forecast challenges, significant advances must concurrently occur in observations, data assimilation techniques, and model development for both the hurricane environment and the hurricane core to properly simulate the complex interactions between the physical and dynamical processes on different scales of motion that determine the hurricane motion, and to forecast intensity changes over the open and coastal ocean during hurricane landfall. The HWRF will be a high-resolution, coupled air/sea/land hurricane prediction model with advanced physics. Other planned advancements in the HWRF system include a local advanced atmospheric data assimilation capability to address the next generation initialization of the hurricane-core circulation. It is envisioned a similar process must occur for oceanic data assimilation on the basin scale, such as from the ongoing Global Ocean Data Assimilation Experiments (GODAE).*
>
> (Shay et al. 2005)

Additional information concerning this workshop can be found in section 4.4.2, under the heading "The Atmospheric-Ocean Boundary Layer in the HWRF Prediction System.".

2.8.7 Previous Efforts in Social Sciences

The ultimate goal of tropical cyclone monitoring and forecasting is to prevent loss of life and injuries and to reduce the Nation's vulnerability to these potentially devastating storms. To this end, warnings and forecast products must be received, understood, and used effectively by a variety of end users including coastal managers, emergency managers, government officials, and the general public. The important role of the social sciences in this process is gaining increased recognition, as indicated by several public and private initiatives that inform the social science research areas highlighted in section 5.3.

Impacts from Hurricane Isabel on the Nation's capital in September 2003 prompted an effort by NOAA and the Societal Impacts Program of NCAR to form an ad hoc working group, the Hurricane Forecast Social and Economic Working Group (HFSEWG), to identify social science research capabilities, needs, and priorities for the tropical cyclone forecast and warning system.

In an effort to move toward a social science research agenda, a number of white papers were prepared (http://swiki.ucar.edu/.sip/hurricane), followed by a workshop in Pomona, California, in February 2005. At the Pomona workshop, experts from government, academia, and the private sector worked toward a consensus social science research agenda for the tropical cyclone forecast and warning system. This work continued with sessions at both the 2004 and 2005 Natural Hazards Workshops, held in Boulder, Colorado.

The NSB's program, Toward a National Agenda for Hurricane Science and Engineering, involved three workshops in 2006, including a session on Social, Behavioral, and Economic Sciences. The First Symposium on Policy and Socio-Economic Research was held at the 2006 annual meeting of the AMS, and a second symposium is scheduled for 2007.

NOAA's Coastal Services Center has several initiatives related to the social sciences, including the following websites:

- "Applying Social Science to Coastal Management" (http://ekman.csc.noaa.gov/socialscience_2/)
- "Social Science Methods for Marine Protected Areas" (www.csc.noaa.gov/mpass)

The Coastal Services Center has also developed a wheel tool entitled "Understanding the Human Dimension of Coastal Management Using Social Science." A current social science project at this center is examining how surge information is communicated and understood by various user groups. Similarly, the OFCM funded an exploratory review study of information dissemination (communication) of hurricane information.

NCAR's Societal Impacts Program, funded by the USWRP, has a number of initiatives including a WxSoc Weather and Weather Forecasting Newsgroup, a Societal Aspects of Weather website at the University of Colorado,[16] and a Weather and Society program that provides workshops to teach social scientists about weather.

The NAS/NRC has a long history of multidisciplinary research and dissemination activities related to natural disasters, some of which have addressed tropical storms specifically, with others focusing on other hazards or cross-hazards issues. The social sciences have been an important part of these multidisciplinary initiatives. NAS/NRC initiatives in the disaster area involve studies carried out by appointed committees, which produce reports, and by roundtables that organize workshops for the purpose of knowledge exchange.

The appointed NRC Committee on Disaster Research in the Social Sciences recently completed a comprehensive, multihazard report entitled, *Facing Hazards and Disasters: Understanding Human Dimensions*, which is available from the National Academies Press.[17] The study, funded by the NSF, included an assessment of what is known from a social science perspective about a variety of disaster agents, including their impacts and society's efforts to mitigate, prepare for, and respond to them.

[16] http://sciencepolicy.colorado.edu/socasp/toc_img.html
[17] http://newton.nap.edu/catalog/11671.html

The Disasters Roundtable (DR) is the NRC's focal point for furthering the exchange of knowledge and perspectives between hazards and disaster researchers, policy-makers and practitioners, and the general public. Funded by such agencies as NSF, NASA, NOAA, USGS, and Department of Homeland Security, as well as private sector organizations such as Pacific Gas and Electric, the Public Entity Risk Institute, and PB Altech, the DR holds public workshops three times a year that focus on timely topics related to hazards and disasters selected by its multidisciplinary steering committee, which includes social scientists.[18] Tropical storms have been among the workshop topics, such as the 2005 workshop entitled, "Lessons Learned Between Hurricanes: From Hugo to Charley, Francis, Ivan, and Jeanne," and a June 2006 post-Katrina workshop that the DR organized with two other NRC roundtables entitled, "Rebuilding Health, Sustainability, and Disaster Preparedness in the Gulf Coast Region." While all previous DR workshops were held in Washington, DC, because of the access to important decisionmakers, the Katrina workshop was held in New Orleans. It is expected that the NRC will continue to give attention to the need for both future studies and roundtable workshops on tropical storms and related hazards.

These examples highlight a growing recognition of the important contribution of social science research and applications to promoting the goals of the national hurricane program and increasing the effectiveness of the tropical storm forecast and warning system.

2.8.8 Concurrent Hurricane Projects/Studies

While the JAG/TCR was developing and coordinating this interagency report, two other concurrent hurricane research projects/studies were taking place. One of these was the NOAA Science Advisory Board (SAB) Hurricane Intensity Research Working Group (HIRWG). The second was the NSB's Task Force on Hurricane Science and Engineering (HSE).

To ensure that these three efforts—NOAA/SAB, NSF/NSB, and OFCM's JAG/TCR—were aware of, and able to learn from, each other, the OFCM planned a workshop during the 60th IHC, held in Mobile, Alabama, entitled Tropical Cyclone Research: Priorities for the Next Decade. The workshop was moderated by Dr. Robert Serafin, NCAR Director Emeritus and Chair of the BASC. Dr. Michael Crosby, Executive Officer for the NSF/NSB, provided an update on the Task Force on HSE. Following Dr. Crosby, Dr. John Snow, College of Geosciences, University of Oklahoma, presented an update on activities of the NOAA/SAB HIRWG. The last item in the research workshop was a review of an early draft of this document. Dr. Frank Marks (NOAA/AOML/HRD) and Ms. Robbie Hood (NASA Marshall Space Flight Center, Global Hydrology and Climate Center), cochairs of OFCM's JAG/TCR, along with Dr. Naomi Surgi (NOAA/NWS/NCEP/EMC), led this portion of the workshop. The workshop was of great benefit to all three project groups, and other participants at the workshop were able to hear about, and interact concerning, these complementary ongoing efforts.

2.8.9 Results of the 60th IHC

Significant items relating to (1) tropical cyclone research and (2) the hurricane forecast and warning program resulted from the 60th IHC, held in March 2006 in Mobile, Alabama.

[18] Summaries of the DR workshops are available through the NRC Web site at http://dels.nas.edu/dr.

Tropical Cyclone Research

The conclusions from the 60th IHC pertaining to tropical cyclone research included:

- Overarching tropical cyclone priorities established by the JAG/TCR for areas that need further improvement (referenced in Chapter 5 of this report) were very good (i.e., intensity and structure; track; other landfalling impacts [sea state/storm surge, precipitation and inland flooding]; and social science).
- An end-to-end research program needs to include seasonal forecasting; climatology/variability of tropical cyclone intensity and frequency at annual, interannual, and longer time scales; causes of variability; stochastic components; and climate change influences (i.e., the above are to be included in the priorities outlined in Chapter 5 of this report).
- This research plan should advocate a National emphasis on mitigation planning to include event-specific actions, long-range planning, and impact simulations.
- Results of social science research need to be an integral part of the hurricane forecast and warning program. The tropical cyclone community needs to seek opportunities to identify social science research priorities.
- Empirical research should be encouraged and supported to develop and test modifications to current terminology used to define levels of hurricane threat (e.g., watch, warning, hurricane categories 1–5, etc.).

Proposed New Model for Tropical Cyclone Forecast and Warning Communications

During the 60th IHC, an important workshop session was held entitled “Getting the ‘Right’ Message to the Customer.” One of the outcomes of this workshop was a proposed new model for communications, which reflects the divergent information needs of various users. Among the key points of the proposed communications model were the following:

- The model should recognizes that outreach, education, and relationship building are necessary in order for the model to work optimally.
- The model should focus first on understanding different receiver needs (e.g., mainstream receiver, underserved populations) and response mechanisms.
- Receiver needs drive the message and specific channels of delivery (e.g., emergency management, local/state official, community-based organizations.
- Community organizations are the primary channels of information for various receiver groups (e.g., the local chamber of commerce, churches, and civic organizations).

A general conclusion from this workshop was that the Nation’s hurricane warning program warranted a review, which should incorporate the following actions:

- NOAA, in conjunction with its partners, should work with diverse user groups to develop and test message format modifications.
- Test messages should build upon current formats/products/procedures and change as necessary to optimize desired outcomes.

- Two types of messages should be considered: technical and actionable.
- NOAA's TPC/NHC should review its product timing cycle for better coordination with end users, especially for media news cycles.
- The OFCM will organize meetings to bring together the appropriate Federal agencies to begin the process of reviewing and improving the National hurricane warning "system." The tasks include:
    - A review of all elements of the full end-to-end "system," incorporating concepts from the new proposed communications model that reflects the divergent information needs of various users
    - Examination of important elements of the end-to-end review, such as protocols, responsibilities, key organizations (including community-based organizations [e.g., YMCA, chamber of commerce, churches, civic organizations]), and communications

2.8.10 Summary on Prior Documentation of Operational and Research Needs

The development of this strategic research plan builds on the previous work described in this section to articulate tropical cyclone operational needs and to formulate the research priorities outlined in chapter 5. The results of the planned R&D will need to be transitioned to operational NWP models to reap real benefits for the Nation. Gaining knowledge and understanding of tropical cyclone intensity and structure (wind radii), track, sea state and storm surge, and precipitation will save lives, reduce property damage, reduce the costs to the military, and significantly reduce the socioeconomic impacts of a hazard that has so often had disastrous consequences for American citizens. In summary, this plan articulates the interagency tropical cyclone research priorities and recommendations to further improve the effectiveness of the Nation's tropical cyclone forecast and warning service for the next decade.

3
CURRENT CAPABILITIES AND LIMITATIONS

This chapter examines the current capabilities and limitations of the Nation's tropical cyclone forecast and warning system. Operational capabilities in tropical cyclone forecasting and warning reflect the efforts of many experts since the Nation's operational forecast and warning centers were formally established. The JTWC was established in 1959; the TPC/NHC and its predecessor evolved from the continual efforts of the U.S. government, from the late 1800s to the present to develop and improve warning services for tropical cyclones (Sheets 1990). In 1955, the Miami forecast office was officially designated as the National Hurricane Center.

Operational capabilities in each step of this end-to-end system have improved significantly since the inception of the tropical cyclone forecasting centers. These operational capabilities require specialized atmospheric and oceanic observations from many platforms and sensors, both in situ and remote; specialized NWP models; highly trained people to develop and disseminate forecasts and warnings; and an active outreach program. The gains made over the past several decades in our understanding and forecasting of tropical cyclones have paralleled the improvements in observational capabilities (e.g., instrumented aircraft, land-based and airborne Doppler radars, usage and quality of satellite data), improvements in NWP model physics, and the use of these observations through more sophisticated data assimilation capabilities to provide improved initial conditions for the models.

The fact that a tropical cyclone spends the majority of its life over the tropical ocean, where few data are available, has forced the community to pioneer adaptive observing strategies to provide critical observations for the operational forecast and research communities. In addition, these techniques have evolved to include measurements of the upper ocean and atmosphere in the vicinity of the storm. Continuing to improve our tropical cyclone forecasting capabilities will require sustaining and fostering this synergism between observations and NWP models.

3.1 Data Collection and Observations for Tropical Cyclone Fixing and Analysis

Various observational platforms and sensors are used to monitor and analyze the atmospheric and oceanic environment in and around a tropical cyclone. Observations obtained from sensors on or dropped from reconnaissance aircraft, satellites, buoys, and radar are the basis for all forecast and warning products issued by tropical cyclone forecast and warning centers. The quality, quantity, and timeliness of remote-sensing observations are critical for accurate and timely forecasts and warnings. Additionally, the fine-scale interaction between the wind and ocean surface drives hurricane intensity, so observations will be critical in developing more advanced hurricane models.

3.1.1 Operational and Research Aircraft for Observing Tropical Cyclones

Specially equipped aircraft play an important role in forecasting hurricanes traversing the Atlantic Basin and Gulf of Mexico. There is no current or planned aircraft weather reconnaissance capability for coverage in the Western Pacific. Much of the data collected during tropical cyclones by these flying meteorological sensor platforms and from a variety of other sources are assimilated into numerical computer models for tropical cyclone forecasting (e.g., track, intensity, etc.).

Three different types of aircraft are mainly used for the purpose of obtaining information within and around hurricanes to fulfill both the operational and research needs of forecasters, modelers, and research scientists. One type of aircraft, a WC-130J, is operated by the U.S. Air Force Reserve Command (AFRC) 53rd Weather Reconnaissance Squadron, which operates from the squadron's home base at Keesler Air Force Base (AFB) in Biloxi, Mississippi, or from a forward deployment site. Two other types of aircraft, two Lockheed WP-3D Orions and one Gulfstream G-IV SP (G-IV), are operated by NOAA's Aircraft Operations Center. They normally operate from MacDill AFB in Tampa, Florida.

Each of these three types of versatile aircraft plays a different but important role in hurricane research, surveillance, and reconnaissance missions. Table 3-1 shows the missions that each type of aircraft performs, along with its physical specifications and operational capabilities,.

Table 3-1. Physical Specifications and Operational Capabilities of Hurricane Aircraft

Specification	Agency/Aircraft Type		
	AFRC WC-130J	**NOAA WP-3D**	**NOAA Gulfstream IV**
Missions	- Operational Reconnaissance - Operational Surveillance	- Operational Reconnaissance - Research	- Operational Surveillance - Operational Reconnaissance (in progress) - Research
Avg. mission time	8-12 hours	8-10 hours	8 hours
Avg. mission range	2100-3800 nm	2225-3600 nm	3800 nm
Operational air speed	180-320 knots	170-250 knots	450 knots
Ceiling	33,000 feet	27,000 feet	45,000 feet
Length	97 feet 9 inches	116 feet 10 inches	87 feet 7 inches
Wing span	132 feet 7 inches	99 feet 8 inches	77 feet 10 inches
Height	38 feet 10 inches	34 feet 3 inches	24 feet 5 inches
Engines	4 Turbo Prop	4 Turbo Prop	2 Turbofan Jet
Max. takeoff weight	155,000 pounds (peacetime)	135,000 pounds	74,600 pounds
Crew	6	8 to 20	6 to 11

AFRC WC-130J Aircraft

The AFRC uses ten WC-130J aircraft to gather tropical cyclone data. A flight crew consists of six people: aircraft commander, copilot, flight engineer, navigator, weather officer, and a dropwindsonde system operator. The weather officer collects flight-level data, including position, temperature, dew point, and pressure, at 30-second intervals. The weather officer also transmits reconnaissance observations enroute and vortex messages in the eye of the storm, these transmissions include elements visually observed.

The dropwindsonde system operator makes periodic GPS dropwindsonde releases. Of particular importance are the flight-level data and dropwindsonde data from the eye and eyewall of the storm, which give the TPC/NHC the most accurate measurements of a tropical cyclone's location and intensity.

All weather information is processed and encoded aboard the aircraft, then transmitted by satellite communication directly to the TPC/NHC for input into the national weather data networks. These data are provided freely to all member nations of the WMO.

The first missions in a developing tropical cyclone are often flown between 500 and 1500 feet to determine if the winds near the ocean surface are blowing in a complete, counterclockwise circle, then to find the center of this closed circulation.

As the storm builds in strength, the WC-130s, when tasked, enter a storm at 5000 or 10,000 feet of altitude. Because the tops of the storm clouds may reach up to 40,000 or 50,000 feet, the aircraft do not fly over the storm but go right through the thick of the weather to collect the most valuable information. The *Alpha Pattern* flown through the storm looks like an "X". On each leg, the aircraft flies out at least 105 miles from the center of the storm to map the extent of damaging winds. The alpha pattern provides a pass through the eye every two hours.

The 2005 hurricane supplemental budget provided funding to instrument the fleet of WC-130 aircraft with Stepped-Frequency Microwave Radiometers (SFMRs). For more information on the SFMRs, see section 2.8.2 and table 3-3 below. It is anticipated that the SFMRs will be installed and operational on the entire fleet of 10 aircraft by the 2008 hurricane season.

NOAA WP-3D Aircraft

The two uniquely instrumented WP-3D Orion aircraft, which were manufactured for NOAA in the mid-1970s, are ideally suited to support their operational and research missions. Typically operating at low to mid-levels in the storm environment, these turboprop aircraft are rugged enough to make repeated penetrations of the inner vortex of the storm.

Table 3-2 compares the scientific equipment available aboard these three aircraft types employed in hurricane operations and research. While all three aircraft carry identical dropwindsonde systems, the unique feature of the WP-3D is the wide variety of other scientific systems available to forecasters, scientists, and modelers. Of particular interest are the two radars carried aboard the aircraft. One is a C-band radar that is mounted in the lower fuselage and provides a full 360° depiction of weather around the aircraft, out to a distance of 180 nautical miles. The second radar is a depolarized X-band vertically scanning tail radar, from which three-dimensional horizontal wind vectors can be derived using sophisticated computers aboard the aircraft. Images from these radars, along with meteorological and position data from onboard sensors and vortex, reconnaissance code (recco), and dropsonde data messages, are easily transmitted to TPC/NHC and other ground sites in real time via satellite, using the aircraft's new high-speed satellite communications (SATCOM) system.

Table 3-2. Comparison of Observing Systems aboard Hurricane Aircraft

Science Systems	Agency/Aircraft Type		
	AFRC WC-130J	**NOAA WP-3D**	**NOAA Gulfstream IV**
Nose radar	X-Band	C-Band	C-Band
Flight level meteorological data (pressure, temperature, humidity, winds)	Yes	Yes	Yes
Global Positioning System (GPS) dropwindsonde (also known as Airborne Vertical Atmospheric Profiling System [AVAPS])	4 Channel	4 or 8 Channel	8 Channel
Exterior expendables	No	Yes	No
Free fall chute	Yes	Yes	No
Lower fuselage radar	No	Yes	No
Tail Doppler radar	No	Yes	No *
Cloud physics	No	Yes	No
Air chemistry	No	Yes	Yes
External video	No	Yes	No
Stepped-Frequency Microwave Radiometer (SFMR)	No *	Yes	No *
Radome Gust Probe Systems (e.g., Rosemount and Best Available Turbulence [BAT] sensors)	No	Yes	No
Pyranometers/pyrgeometers	No	Yes	No

* Installation underway, to be completed in 2008.

Other specialized instrumentation aboard the WP-3Ds allows sampling of both in-cloud and ocean environments. Particle measuring systems provide scientists with data for their studies of cloud dynamics, an important aspect of hurricane growth and intensity, while Airborne Expendable Bathythermographs (AXBTs), Airborne Expendable Current Profilers (AXCPs) and Airborne Expendable Conductivity Temperature and Depth (AXCTD) probes may be deployed from the WP-3D aircraft either from external chutes using explosive cads or from an internal drop chute. They activate upon hitting the ocean surface and transmit sea temperature, salinity, and current information via radio back to computers aboard the aircraft. Other instruments aboard are capable of measuring the chemical constituents in the atmosphere, some of which can be used as tracers for air flow studies in storms.

The WP-3D aircraft can serve as a test bed for emerging technologies such as the SFMR, the Imaging Wind and Rain Airborne Profiler (IWRAP), and the Scanning Radar Altimeter (SRA). Table 3-3 provides additional information regarding the instrumentation aboard the WP-3Ds. The NOAA WP-3D aircraft also fly tasked operational missions in situations requiring the use of their SFMR or to augment AFRC tasking when operational fix requirements exceed the capabilities of the DOD aircraft. In such cases, the missions flown are identical to those flown by the AFRC WC-130Js, including reporting data to the TPC/NHC.

Table 3-3. Additional Information on Some of the Specialized Instrumentation Aboard WP-3D Aircraft

Specialized Instrumentation	DESCRIPTION
Nose C-band radar	Weather avoidance radar located in the nose of the aircraft.
Lower Fuselage C-Band Radar	Has a large antenna with a range of 180 nmi located in a large radome under the fuselage.
X-Band Tail Doppler Radar	This vertically scanning radar provides a vertical cross-section of the precipitation concentration and motion. The Doppler radars on the WP-3Ds are used to derive three-dimensional wind fields in regions with scatterers.
GPS Dropwindsondes (AVAPS)	Dropwindsondes are deployed from the aircraft and drift down on a parachute. They measure vertical profiles of pressure, temperature, humidity, and wind as they fall. For additional information regarding the GPS dropwindsondes, see section 2.8.2.
SFMR	The SFMR is a passive radiometer that measures emissivity from the sea surface. The emissivity is essentially a measure of foam coverage, which in turn is related to the surface wind speed. The SFMR instruments were initially installed on the NOAA WP-3D research aircraft, where they demonstrated the capability to remotely sense surface wind speeds along the aircraft track with high temporal resolution (1 Hz). In addition to remotely sensing surface wind speeds, the SFMR measures path-integrated rain rates along the aircraft track. ("Path integrated" means that the SFMR senses the microwave emissions, and therefore brightness temperatures, from the whole rain column from the freezing level to the sea surface.) The SFMR provides independent estimates of rain rates at a horizontal resolution of approximately 10-s (1.5 km) along the flight track. The SFMR-retrieved rain rates are well correlated with airborne radar rainfall measurements.
Air-Deployable Expendable Instruments	Observations of upper-ocean thermal and momentum structure can be made using air-deployable expendable instruments (e.g., AXBTs, AXCPs, and AXCTD profilers) to map background and hurricane-induced oceanic circulation (current shears) and ocean heat content (OHC) variability in an Eulerian sense (Shay et al. 1998). AXBTs and Lagrangian floats provide detailed OHC and upper ocean turbulence measurements (D'Asaro 2003).
IWRAP	This new instrument is the first high-resolution dual-band airborne Doppler radar designed to study the inner core of tropical cyclones. The system is designed to provide high-resolution, dual-polarized, multibeam C- and Ku-band reflectivity and Doppler velocity profiles of the atmospheric boundary layer within the inner-core precipitation bands of tropical cyclones and to study the effects precipitation has on ocean wind scatterometry as it applies to tropical cyclones. Improvements being made to IWRAP could lead to its operational use (see section 4.2.11).
SRA	The NASA-developed SRA provides ocean wave heights and swell motion in the hurricane environment. It measures the energetic portion of the directional wave spectrum by generating a topographic map of the sea surface. The radar altimeter return measures the significant wave height and can resolve low-frequency surface waves—i.e., the ocean swell (Wright et al. 2001).

NOAA Gulfstream IV Aircraft

NOAA's Gulfstream IV SP (Special Performance) jet began operational hurricane surveillance missions in 1997, when it was used primarily for the collection of dropwindsonde data to be assimilated into NCEP's global forecast model to improve track forecasts. These data also support the forecasters at TPC/NHC. The jet, which can fly high, fast, and far with a range of approximately 4,000 nautical miles and a cruising altitude between 41,000 and 45,000 feet, is used to sample the physical nature of the atmosphere from high altitude down to the surface in the region surrounding hurricanes. This sampling is done primarily with GPS dropwindsondes. The objective is to better define the environmental steering flow for potentially landfalling storms. The data are transmitted in real time to NCEP for assimilation into the Global Data Assimilation System (GDAS). The G-IV dropwindsonde data have improved the forecast track from NCEP's Global Forecast System (GFS) by 15–25 percent on average and by as much as 40 percent in individual storm forecast scenarios. For critical landfalling scenarios, the G-IV data, when available, are supplemented by the low-altitude dropwindsonde data collected by NOAA's two WP-3D aircraft and the AFRC WC-130s.

In summary, TPC/NHC forecasters rely heavily on data from reconnaissance and surveillance aircraft. The new airborne technology combination of the SFMR for surface winds, the airborne tail Doppler radar for three-dimensional structure, and GPS dropwindsondes for point vertical profiles—is essential for real-time interpretation of rapidly changing events, especially near landfall (Black et al. 2006). The key is the SFMR capability.

Other Research Aircraft and Instrumentation

In addition to the AFRC WC-130Js, NOAA WP-3Ds, and NOAA G-IV, other aircraft participate in tropical cyclone field experiments, such as those discussed in section 3.5. These aircraft include the following:

- **NASA ER-2.** The ER-2 is a civilian variant of the U-2 reconnaissance plane capable of reaching altitudes as high as 70,00 feet (twice as high as a commercial airliner). The ER-2 carries into the stratosphere dozens of scientific instruments that measure the composition of Earth's ozone layer and gathers data for other weather research projects. The only person on board is the pilot, who must wear a pressurized spacesuit to guard against the dangers of high-altitude flight.
- **NASA-funded DC-8.** NASA's DC-8 research aircraft is used to study both tropospheric and stratospheric weather. In contrast to the ER-2, this research plane carries a team of scientists into the upper troposphere and lowermost stratosphere. Again in contrast to the ER-2 (whose instruments must work autonomously), many of the DC-8 instruments are operated in a "hands on" approach by the investigators.
- **NRL P-3.** A U.S. Navy P-3, located at Naval Air Station Patuxent River (Squadron (VXS-1), participates in some tropical cyclone field experiments. For instance, NRL 154589P-3B was one of five aircraft that participated in the Hurricane Rainband and Intensity Change Experiment (RAINEX) in 2005.
- NSF/NCAR Gulfstream V (G-V). The NSF/NCAR G-V, called the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER), is a new research aircraft. Its first science mission was flown on March 6, 2006. HIAPER is an effective tool for conducting weather and water-cycle research, studying atmospheric chemistry and climate forcing, and monitoring biosphere structure and productivity.

In addition to observational equipment already highlighted earlier in this section, several state-of-the-art remote-sensing instruments have been developed for use in the field experiments. These instruments can help make a significant contribution to the advancement of tropical cyclone knowledge and the processes that drive them. A few of the state-of-the-art sensing instruments are reviewed below.

- **High Altitude MMIC Sounding Radiometer (HAMSR).** This first atmospheric sounder to use receivers based on monolithic microwave integrated circuits (MMICs) was built by NASA's Jet Propulsion Laboratory (JPL) to demonstrate and validate new miniature technology and advanced design concepts (Lambrigtsen et al. 2002). HAMSR was the first aircraft microwave sounder with both temperature and humidity sounding capabilities in a single package and a common field of view. It was one of the first complete instrument developments that emerged from NASA's Earth Science Technology Office Instrument Incubator Program.
- **Advanced Microwave Precipitation Radiometer (AMPR).** The AMPR remotely senses passive microwave signatures of geophysical parameters. AMPR is flown on the NASA's ER-2 or DC-8 aircraft. The instrument can provide multifrequency microwave imagery with high spatial and temporal resolution. AMPR data are collected at a combination of frequencies (10.7, 19.35, 37.1, and 85.5 GHz), unique to current NASA aircraft instrumentation, that are well suited to the study of rain cloud systems and various ocean and land surface processes.
- **Airborne Precipitation Radar-2 (APR-2).** In support of NASA's rain measuring missions, the radar group at JPL designed and built the Airborne Rain Mapping Radar (ARMAR) in the early 90's. In 2001, the group completed the second-generation Airborne Precipitation Radar (APR-2). While ARMAR was a single-frequency system, APR-2 is a dual-frequency radar. APR-2 participated in the fourth Convection and Moisture Experiment (CAMEX-4) campaign in 2001 on board NASA's DC-8 aircraft, marking the first time a dual-frequency polarimetric Doppler radar was flown over precipitating systems.
- **ER-2 Doppler Radar (EDOP).** The EDOP is an X-band (9.6 GHz) Doppler radar with dual 3-degree beamwidth antennas fixed at nadir and 30 degrees forward of nadir. The radar maps out Doppler winds and reflectivities in the vertical plane along the aircraft's motion vector.
- **Other Instruments.** Considerable instrumentation is available for use in research aircraft and provides vital data sets for scientists. Details on each of these instruments are beyond the scope of this plan. Among these research instruments are NASA-developed systems such as the Cloud Radar System, second-generation Lightning Instrument Package, Microwave Temperature Profiler, and MODIS Airborne Simulator.

3.1.2 Satellite Platforms, Instruments, and Data Streams

Satellite observations play a critical role at all tropical cyclone warning centers. As mentioned above, aircraft observations are only routinely available in the Atlantic Basin for storms threatening land and in the Pacific for storms threatening Hawaii. Thus, satellite data are the primary source of tropical cyclone information for the majority of tropical cyclones around the globe that are out of range of coastal radars (270 km/150 nmi.). Satellite data are used in two primary ways. First, the data are used for tropical cyclone monitoring including estimation of current position and intensity, projection of short-term trends in position and intensity, wind structure, rainfall rate and inner-core structure analysis, and storm-environment analysis. Second, the satellite observations are assimilated into numerical forecast models to obtain more accurate estimates of the initial values for the model state variables.

Environmental satellites can be classified into two basic types, geostationary and low Earth-orbiting (including polar-orbiting). The geostationary satellites are operational systems that measure radiation in the visible and infrared (IR) portions of the electromagnetic spectrum. All tropical cyclones around the globe have geostationary coverage from systems maintained by the United States (the Geostationary Operational Environmental Satellite [GOES] System), the European Space Agency (Meteosat), Japan (Multifunctional Transport Satellite [MTSAT] series), and China (FY-series satellites). The polar-orbiting satellites, some of which are operational missions while others are experimental, measure the microwave portion of the spectrum in addition to the visible and IR. There are also specialized satellite systems that contain active or passive microwave instruments for estimating the surface wind speed and the height of the ocean surface. The microwave measurements are of great utility for tropical cyclone analysis because they provide information below the cloud tops that are normally present over tropical cyclones. The geostationary satellites provide near-continuous temporal coverage from the equator to about 65^{o} north latitude, while the polar systems generally provide about two passes per day over a fixed point on the earth (more near the poles, less near the equator). The satellite instruments include imagers, which generally have higher horizontal resolution with fewer spectral channels, and sounders (IR and microwave), which have lower resolution but more and spectrally narrower channels. The imagers are utilized for feature analysis, while the sounders provide vertical profiles of temperature and moisture. Some quantitative analysis is also performed with the imagers, such as rainfall and wind estimation.

Satellite Data in Tropical Cyclone Analysis

Once an area of persistent convection is identified in the tropics or subtropics, satellite analysts use scatterometer data to assess the low level circulation of the system. The primary tool for this analysis is data from the SeaWinds sensor on the NASA QuikSCAT satellite. SeaWinds is a specialized microwave radar that measures oceanic near-surface wind speed and direction. When available, data on surface wind speed and direction are also analyzed from the WindSat polarimetric radiometer aboard the Coriolis satellite, which is jointly sponsored by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO), the DOD Space Test Program, and NASA. Both scatterometers and polarimetric radiometers provide valuable information about developing tropical cyclones. However, limitations of both sensors prevent wind retrievals at higher wind speeds and in deep convection, limiting the use of these data for hurricanes and typhoons of sufficient intensity, especially near the inner-core.

Once a disturbance is classified as a tropical cyclone, satellite data are routinely used to estimate the position and intensity of the storm, referred to as a “fix” on the storm. Animations of the visible and IR imagery are especially useful for center determination. The Dvorak technique has been the cornerstone for intensity estimation from satellites for more than three decades and includes visible and IR methods. The IR technique is generally more objective than the visible method for stronger hurricanes but less objective for weaker storms. The Dvorak intensity estimates are provided by four operational agencies: the Tropical analysis and Forecast Branch (TAFB) of the TPC/NHC, the NESDIS Satellite Analysis Branch, the JTWC, and the Air Force Weather Agency (AFWA). The TAFB fixes are limited to the Atlantic and to the northeast Pacific east of 140º W latitude. The CPHC produces Dvorak intensity estimates for the Central Pacific Basin.

The Dvorak technique relies on image pattern recognition along with analyst interpretation of empirically based rules regarding the vigor and organization of convection surrounding the storm center. The subjectivity of the Dvorak technique is well documented, and an accurate analysis depends largely on the skill and experience level of the satellite analyst. The Dvorak technique is the main tool for determining tropical cyclone strength when it is out of range of reconnaissance aircraft. As mentioned in section 3.1, TPC/NHC forecasters rely heavily on data from reconnaissance aircraft to determine tropical cyclone position and intensity. The SFMR for surface winds, airborne tail Doppler radar for three-dimensional structure, and GPS dropwindsondes for vertical profiles at a single point are valuable for real-time interpretation of rapidly changing events.

With a process called composite fixing, forecasters use data from multiple fixing agencies when positioning tropical cyclones. For a composite fix, the forecasters subjectively weight the available data based on a confidence interval assigned by the satellite analyst and use the weighted data to estimate the position of each tropical cyclone. For example, during 2005 satellite analysts at JTWC produced 7,988 position and intensity fixes within the Central and Western North Pacific, South Pacific, and Indian Ocean basins. They processed an additional 6,102 fixes produced by other agencies. Figure 3-1 analyzes the JTWC satellite fixes in 2005 by platform from which satellite data were used. JTWC satellite analysts created 3,781 position and intensity fixes from multispectral (combined visible and infrared) and enhanced infrared geostationary imagery during 2005; the remaining fixes were determined from microwave imagery, which supplement the information from the geostationary satellites, as described below.

Satellite analysts also assess tropical cyclones in real time for operational forecasting using imagery from microwave imagers and sounders. This imagery may come from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMI/S) instruments, from NOAA Advanced Microwave Sounding Unit (AMSU-B) instruments, from the NASA Aqua Advanced Microwave Scanning Radiometer-Enhanced (AMSR-E) or NASA Tropical Rainfall Measurement Mission (TRMM) Tropical Microwave Imager (TMI), or from the Coriolis WindSat. The satellite analysts assess tropical cyclone position using imagery collected at frequencies of 85–89 GHz and 36–37 GHz, as

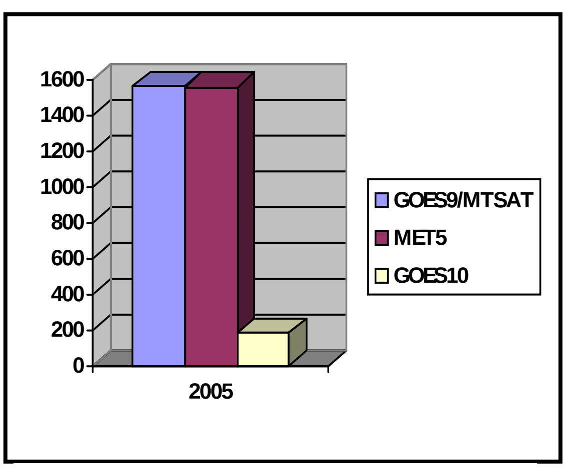


Figure 3-1. Geostationary satellite position and intensity fixes by JTWC during 2005.

well as several derived images created by NRL-Monterey and FNMOC. Valuable information about tropical cyclone structure and developmental stage can also be inferred from these images. For example, analysts at JTWC produced 4,207 tropical cyclone position fixes from microwave imagery during 2005. Figure 3-2 shows the source of JTWC microwave fixes by platform.

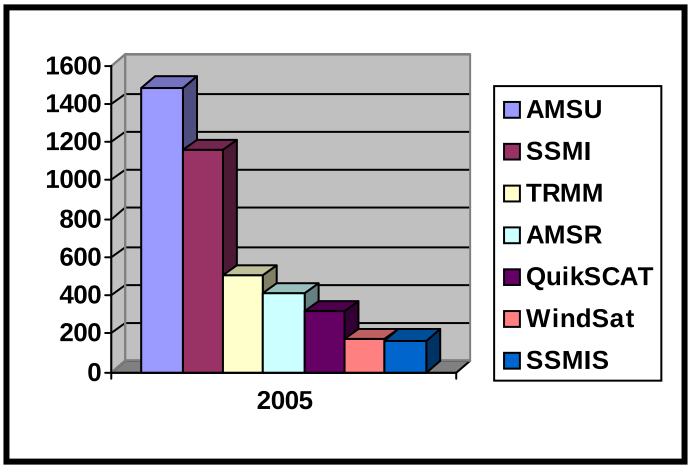


Figure 3-2. Microwave position fixes by JTWC during 2005.

The original Dvorak technique was developed more than three decades ago. More recently, the Advanced Dvorak Technique (ADT), developed by UW-CIMSS, creates an automated tropical cyclone position and intensity analysis using enhanced infrared satellite imagery. This robust computer algorithm first determines the position of the tropical cyclone and then applies a series of subroutines to determine tropical cyclone intensity. Finally, the Dvorak constraints are applied to ensure that the storm's intensity is not increased or decreased too quickly. Whereas manual application of the Dvorak technique yields a position estimate every three hours and an intensity analysis every six hours, ADT estimates can be generated hourly or half-hourly, depending on how frequently new imagery is received. Assessments conducted by the Satellite Analysis Branch of NOAA/NESDIS, in the Operations Directorate of AFWA (AFWA/XOGM), and at JTWC have concluded that the ADT performs well for well-defined systems with a clear, visible eye. Continued improvements are required before this tool can be integrated into operations.

The AMSU instrument on NOAA polar-orbiting satellites provides a direct measure of the storm warm core from temperature and moisture soundings, which can be related to the storm intensity. AMSU-based intensity estimation techniques have been developed by UW-CIMSS (Brueske et al. 2002) and by CIRA (Demuth et al 2004) and are routinely applied by operational forecasters. The horizontal resolution of the AMSU instrument (50 km near nadir) limits the usefulness of this method for small, very intense storms, but the techniques provide fairly reliable intensity estimates in most cases.

UW-CIMSS and NRL-Monterey have collaborated to develop a multiplatform, weighted position and intensity fix for use in tropical cyclone operations. This satellite consensus, or SATCON, includes inputs from AMSU, ADT, and the UW-CIMSS infrared core winds analysis. An algorithm applies a relative weight to each component, based on the known strengths and weaknesses and past performance of each automated method. As described above, the ADT works best for strong storms, while the AMSU technique is better for weaker systems, so the SATCON method can take advantage of these complementary techniques. This product has not yet been released for operational assessment.

For purposes of community evacuation, general protection of life and resources, and safe maritime operations, it is important to determine (analyze) and forecast the structure (wind radii) of tropical cyclones. Recent improvements in microwave imagery analysis and automated interrogation programs have provided new data sources and methods for estimating tropical cyclone structure. Each method has its own strengths and shortcomings. Satellite-based microwave scatterometers generally perform best in low wind speed and low precipitation environments (Zeng and Brown 1998; Weissman et al. 2002; Yueh et al. 2003) and thus are most useful for estimating surface winds in the tropical cyclone outer core away from the high-wind and high-precipitation eyewall region. Satellite-based passive microwave instruments such as the SSM/I are routinely applied to the estimation of surface winds over open water, but are also limited to the tropical cyclone outer core when estimating tropical cyclone winds (Goodberlet et al. 1989). Similarly, geostationary satellite cloud-track winds (e.g., Velden et al. 2005) can be deduced in the outer core away from the obscuring effects of the cirrus shield that typically resides over the inner core. The underlying surface winds can then be estimated by reducing the cloud-track winds to the surface (Dunion et al. 2002; Dunion and Velden 2002). The CIRA version of the AMSU intensity estimation technique also provides information on wind structure through the use of statistically adjusted wind retrieval techniques based upon pressure-wind balance approximations.

Automated methods to combine information on wind distribution from multiple satellite platforms both in and around tropical cyclones have been developed by CSU-CIRA and UW-CIMSS. The CIRA method, first tested operationally in 2005, fuses several different satellite-derived data sets, including QuikSCAT, infrared core winds from IR data (Mueller et al. 2006), and AMSU position and wind distribution, to develop a wind distribution profile every six hours. The CIMSS method isolates infrared core winds from geostationary imagery and uses them to derive a maximum wind speed and radius of maximum wind estimate. This multiplatform wind product is still under development.

As mentioned previously, AMSU-A microwave sounder imagery provides forecasters with information regarding both the vertical thermal structure and horizontal wind distribution (derived from the thermal analysis and balance relationships) of a tropical cyclone, in addition to its position and intensity. Accurate structural analysis of a tropical cyclone enables the forecaster to more precisely assess initial and short-term changes. Unfortunately, these data are available only when the AMSU-A sensor flies over a tropical cyclone which can be at very irregular intervals due to the combination of swath width, satellite orbit, and storm motion. The relatively coarse spatial resolution of the sensor also limits analysis. For example, the tropical cyclone warm core is not well sampled because of its small size, and data become less reliable along the edges of the swath due to increased incidence angle.

Tropical cyclone forecasters and satellite analysts conduct continuous global monitoring using animated water vapor imagery. Uses for these animations include the following:

- Monitor tropical cyclone steering and outflow patterns
- Assess the relative positions of the polar front and subtropical jet streams, subtropical ridge axis, and cyclonic cells within the Tropical Upper Tropospheric Trough (TUTT)
- Evaluate how these features may impact both the development and movement of tropical cyclones
- Identify potential developing cloud clusters that warrant further interrogation

In addition to intensity, wind structure, and synoptic analysis, satellite data are also useful for estimating the rainfall rate. Microwave data from the polar-orbiting satellites and the geostationary IR data are both utilized for this purpose (e.g., Scofield 2001). Extrapolation techniques provide short-term rainfall forecasts from the satellite rain-rate estimates (Ferraro et al. 2005).

Microwave sensors are also applied to ocean analysis and forecasting. For example, the Topex/Poseidon satellite, a U.S.-French venture, uses an altimeter to measure ocean wave height and wind speed, from which water temperature and salinity can be inferred. Topex/Poseidon flies in constellation with Jason-1. (Jason-1 is the follow-on to Topex/Poseidon.) Together, their altimeters measure the Earth's sea level every 9.9 days along a repeat ground-track spaced 3^{o} longitudinally at the equator. Two other space-based altimetry programs, the ERS-2 mission and NOAA Geosat Follow-On (GFO) missions, have repeat tracks of 35 and 17 days, respectively. The importance of altimetry data is further discussed in section 3.1.3.

Satellite Data in Tropical Cyclone Forecasting

During the 1990s, NWP modeling centers made significant advances in assimilating satellite data for analyses of the tropical cyclone environment. For example, 99 percent of the data assimilated in NCEP models is currently derived from satellites. The assimilation of satellite data has led directly to improvements in NWP tropical cyclone track guidance, as discussed in section 3.3.4, Data Assimilation Capability. The satellite data used in NCEP's operational data assimilation systems are summarized in appendix A.

As discussed in section 2.4.6, 2 years of preparation time was required previously for the data from each new satellite-based instrument to be used operationally. This lag time represents 40 percent of the design lifetime for many new instruments. NOAA, NASA, and the DOD formed the Joint Center for Satellite Data Assimilation (JCSDA) to expedite the assimilation of satellite data in operational models. Currently, satellite observations are used only indirectly in the high resolution, limited-area tropical cyclone prediction models. The satellite data are assimilated into the global models, which provide the background field and boundary conditions for the regional models. However, the satellite data are not used by the regional models to refine the analysis in the inner core. The next generation regional tropical cyclone models will include the capability to assimilate satellite, radar, and in situ observations of the inner core.

3.1.3 Ocean Observations

Hurricanes develop from and are maintained by heat and moisture they receive from the sea surface. The higher the sea-surface temperature (SST) below the hurricane, the more energy is available to the hurricane (e.g., Emanuel 1986; 1999b). Wind-induced mixing of the upper ocean by a hurricane can lower the SST via entrainment of cooler water into the oceanic mixed layer (OML) from below (e.g. Shay et al. 1992; Ginis 2002). Therefore, the future intensity (and perhaps track) of a given hurricane depends not only on the initial SST below the hurricane, but also on the magnitude of the wind-induced cooling in the region that is still providing heat and moisture to the overlying hurricane (Bender and Ginis 2000; Shay et al. 2000; Cione and

Uhlhorn 2003). The magnitude of the wind-induced cooling depends on the magnitude of the surface wind stress, the depth of the OML, and the temperature gradient at the base of the OML.

Improving Observations of Ocean Thermal Structure

The SST under and around the hurricane is a parameter that influences the evolution and strength of a hurricane. In general, the temperature at the sea surface is decreased by turbulent latent and heat fluxes and by vertical motions (Ekman pumping) associated with hurricane high-wind conditions. In zones of horizontal divergence, relatively colder water is brought to the surface. Under strong cyclonic wind stirring and induced cyclonic ocean inertial motions, divergence conditions are favored on the right side of an advancing storm. The pattern of a stronger cooling on the right side of the storm is often observed.

Although the turbulent and mechanical stirring contributions to upper-layer ocean cooling are generally of the same order of magnitude; the latter can be two to four times larger. The decrease in the SST provides a negative feedback to hurricane strength. The strength of this feedback depends upon the exposure of the hurricane to the cooling—a fast moving storm feels less of its own cooling than a slower moving storm—and the strength of the cooling (Emanuel 1989). The amount of cooling due to the horizontal divergent flow depends upon the vertical structure of the upper ocean under the influence of stirring. The structure can be described in terms of the temperature and depth of the mixed layer and the strength of the thermocline (i.e., dT/dz). These effects can be represented properly in ocean numerical simulation if the upper-layer thermal structure down to the seasonal thermocline is well approximated and vertical motions are well resolved. In general, the upper-layer thermal structure variability is due to non-adiabatic processes and evolving internal structures that induce, among other things, the relative lifting and sinking of isopycnals. This lifting or sinking contributes to lower or higher temperatures, respectively, in the upper thermocline. The sea surface height (after filtering for the effects of tides, winds, and atmospheric pressure) is related in part to the density distribution of the water column. Over lifted/depressed isopycnals, the sea level is depressed/raised. This property allows estimation of dT/dz from the height of the sea surface as observed with satellite altimeters.

The integrated thermal structure (ocean heat content, OHC) is a more effective measure of the ocean's influence on storm intensity than just SST (Brewster and Shay 2006; see figure 3-3). In regions where the OML is deep, the SST cooling due to upwelling and mixing tends to be reduced, so there is considerably more thermal energy available to be transferred to the atmosphere than in areas where a very shallow layer of warm water exists (Mainelli et al. 2002). In this context, upper ocean structure must be accurately accounted for in the models, as discussed in section 3.3.3**,** under the heading "New Ocean Model Initialization Method" (Yablonsky et al. 2006; Bender and Ginis 2000). It has been demonstrated that sudden unexpected intensification in tropical cyclones often occurs as they pass over warm oceanic regimes such as the Gulf Stream, Florida Current, Loop Current, or large, warm core rings (WCRs) in the western North Atlantic Ocean and Gulf of Mexico (Shay et al. 2000).

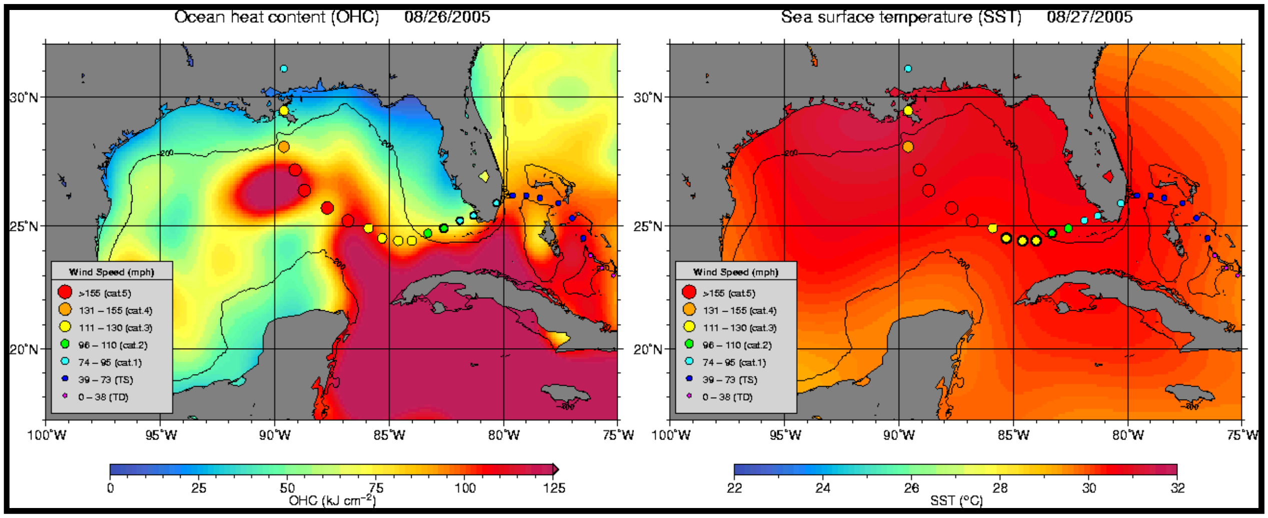


Figure 3-3. Comparison of altimeter-derived estimates of ocean heat content (left) and satellite-derived sea surface temperature (right). The circles of different colors indicate the track and intensity of Hurricane Katrina (Mainelli et al. 2006).

The OHC can be estimated using a combination of sea surface temperature and ocean altimeter measurements. As an example, NOAA/AOML provides four daily maps on its website:[1] (1) sea surface temperature, (2) sea height anomalies, (3) altimeter-based estimate of the depth of the 26^{o}C isotherm, and (4) tropical cyclone heat potential (TCHP). The sea surface temperature is obtained from TRMM/TMI fields. The sea height anomaly represents the deviation of the sea height with respect to its mean. Sea height anomaly fields from three satellite altimeters—JASON-1, ERS-2, and GFO—are used in the analysis. The TCHP is a measure of the integrated vertical temperature between the SST and the estimate of the depth of the 26^{o}C isotherm (Shay et al. 2000). *Thus, satellite altimetry is fundamental for real-time upper-ocean analysis.* The ability of satellite altimetry to aid forecasters in identifying regions of hurricane intensification is discussed in further detail by both Goni and Trinanes (2003) and Goni et al. (2003). The maps can be used to identify warm anticyclonic features—usually characterized by sea height anomalies and a depth of the 26^{o}C isotherm greater than in surrounding waters—and to monitor regions of very high (usually larger than 90 kJ cm^{-2}) TCHP. These regions have been associated with sudden intensification of tropical cyclones.

Real-time OHC analysis was implemented at the TPC/NHC in 2002 by M. Mainelli and N. Shay (Mainelli et al. 2006). OHC was added as a predictor in the TPC/NHC operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) beginning in 2004. For JTWC operations, forecasters have access to the AOML-produced TCHP. Also, OHC was implemented in the Statistical Typhoon Intensity Prediction Scheme (STIPS) in August 2005 and is still being evaluated for potential operational use. A coordinated effort to improve oceanic observations, both in situ (e.g., AXBT, XBT, drifters) and from altimeters (e.g., from satellites such as JASON-1, ERS-2, and GFO), and to continue development of a coherent ocean data assimilation system will increase the accuracy and resolution of modeling data for the upper-ocean layer structure. In this strategy, satellite altimeter data are essential for improvement because of the need to observe the ocean over large regions where in situ data are unavailable.

[1] http://www.aoml.noaa.gov/phod/cyclone/data/

In Situ Ocean Observations

Section 3.1.1 discussed air-deployable expendable instruments/sensors for ocean observations (e.g. AXBTs, AXCPs, and AXCTDs). Another source of important oceanic observations comes from *moored buoys* and from *Coastal Marine Automated Network (C-MAN) stations.* The National Data Buoy Center (NDBC) operates and maintains a network of approximately 90 moored buoys and C-MAN stations in the Gulf of Mexico and in the Atlantic and Pacific Oceans. The NDBC provides hourly observations of wind speed and direction, gusts, barometric pressure, and air temperature from this network. In addition, some platforms measure wave height. Data from the buoys, some of which are as large as 12 m wide, are also used to calibrate and validate the quality of measurements and estimates obtained from remote-sensing instruments onboard reconnaissance aircraft and satellites, as well as to validate NOAA/NWS forecasts. In 2005, the NDBC launched six new weather data buoy stations that were designed to enhance hurricane monitoring and forecasting. The buoys have been deployed in key locations in the Caribbean, Gulf of Mexico, and Atlantic Ocean. The center also deployed a seventh buoy off the coast of Pensacola, Florida, to re-establish a former station.

Another oceanic observation capability comes from *drifting buoys* (drifters), which aim to follow the ocean current while measuring both near-surface atmospheric and upper-ocean properties. A small surface float supports a much larger drogue centered at 15 m depth. The large drogue causes the drifter to nearly follow the horizontal water motion at approximately 15 m depth. A transmitter in the surface drifter sends data to the Argo satellite system (see below). The same signals are used to track the drifter. The standard drifter measurements are position and near-surface temperature. Minimet drifters are also designed to estimate wind speed using the sound level at 8 KHz and wind direction using a vane on the surface float. Evaluation of the accuracy of this approach at hurricane wind speeds is still under way. Autonomous Drifting Ocean Station (ADOS) drifters measure the temperature profile to 100 m depth using a thermistor chain.

Argo is an international program that calls for the deployment of 3,000 free-drifting profilers, distributed over the global oceans, to measure the temperature and salinity in the upper 1,000 to 2,000 m of the ocean. When fully implemented, Argo will provide 100,000 temperature and salinity profiles and reference velocity measurements per year (figure 3-4) and will serve as a major component of the ocean-observing system. Argo has two specifically hurricane-related objectives:

- Argo data will be used for initializing ocean and coupled ocean-atmosphere forecast models, for data assimilation, and for model testing.
- The data will enhance the value of the Jason satellite altimeter data (discussed in the next section) through measurement of subsurface temperature, salinity, and velocity, with sufficient coverage and resolution to permit interpretation of altimeter-measured sea-surface height variability.

The Global Drifter Program (GDP) is the principal component of the Global Surface Drifting Buoy Array, a branch of NOAA's Global Ocean Observing System (GOOS). GDP has the following objectives:

- Maintain a global 5x5 degree array of 1,250 Argo-tracked surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations of mixed layer currents, sea surface temperature, atmospheric pressure, winds, and salinity
- Provide a data processing system for scientific use of these data

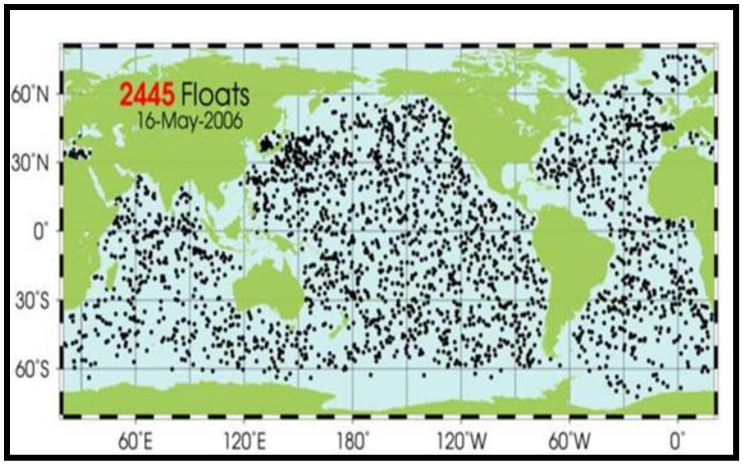


Figure 3-4. The Argo array.

NOAA/AOML's contribution to the GDP consists of the Drifter Operations Center and the Drifter Data Assembly Center (DAC). The Drifter Operations Center manages global drifter deployments, using research ships and aircraft, plus ships participating in the Voluntary Observing Ship (VOS) program. The DAC verifies that the drifters are operational, distributes the data to meteorological services via the Global Telecommunications System, assembles and quality-controls the data, makes the data available on the Internet, and offers drifter-derived products. For the Atlantic tropical cyclone forecast and warning program, the major drawback of Argo is the lack of observations in the Gulf of Mexico and the Caribbean, as shown in figure 3-4.

Ships at sea are another important source of observations. The WMO's VOS program is an international activity through which ships plying the oceans and seas of the world are recruited by national meteorological services to take meteorological observations and transmit the data to the meteorological services. At present, the contribution that VOS meteorological reports make to operational meteorology, marine meteorological services, and global climate studies is unique and irreplaceable. During the past few decades, the increasing recognition of the role of the oceans in the global climate system and for tropical cyclone forecasting has placed even greater emphasis on the importance of marine meteorological and oceanographic observing systems.

One of the major continuing problems facing meteorology is the scarcity of data from vast areas of the world's oceans (the "data sparse areas") in support of basic weather forecasting, the provision of marine meteorological and oceanographic services, and climate analysis and research. While the new generation of meteorological satellites helps to overcome these problems, data from more conventional platforms, in particular the VOS, remain essential. These ship observations provide: (1) ground truth for the satellite observations; (2) important information on conditions that the satellites cannot observe; (3) essential contributions to the data input for NWP models; (4) and real-time reports that can be used operationally in the preparation of forecasts and warnings, including those for the Global Maritime Distress and Safety System, which are issued specifically for the mariner. Thus, without VOS observations, reliable and timely services for mariners cannot be provided.

A peak in the number of vessels participating in the VOS program was reached in 1984–1985 when about 7,700 ships worldwide were on the VOS fleet list. The number of participating ships has declined since then and is currently estimated at about 4,000. As one would expect, real-time reports from VOS are heavily concentrated along the major shipping routes, primarily in the North Atlantic and North Pacific Oceans. Ships contribute to the global observing program and consequent enhancement of the forecast and warning services to the mariner. Since VOS reports are part of a global data capture program, they are of value from all the oceans and seas of the world, but even the well-frequented North Atlantic and North Pacific Oceans require more observational data.

U.S. Navy ships also provide timely and accurate weather observations. Since the U.S. Navy may be committed to operations anywhere in the world, total global observations of meteorological and oceanographic conditions are required. Ships in port are required to make regular weather observations and to report by electronic means unless there is a nearby U.S.-manned weather-reporting activity. When out of port, Navy ships provide observations through U.S Navy communications channels. Weather observations and reports of guard ship arrangements may be used for groups of ships at the discretion of the senior officer present.

3.1.4 Land-Based Surface Systems

The Automated Surface Observing Systems (ASOS) program is a joint effort of NOAA/NWS, the Federal Aviation Administration (FAA), and the DOD. The ASOS systems serve as the nation's primary surface weather observing network. ASOS is designed to support weather forecast activities and aviation operations; it also supports the needs of the meteorological, hydrological, and climatological research communities. The ASOS network has more than doubled the number of full-time surface weather observing locations. ASOS observations are provided every minute, 24 hours a day, every day of the year.

Each ASOS unit observes, formats, archives, and transmits observations automatically. ASOS observations are disseminated hourly, with both hourly and special observations being disseminated via networks. ASOS transmits a special report when conditions exceed preselected weather element thresholds (e.g., the visibility decreases to less than 3 miles). In addition, ASOS routinely and automatically provides computer-generated voice observations directly to aircraft in the vicinity of airports using FAA ground-to-air radio. These messages are also available via a telephone dial-in port.

A major issue with the ASOS observations, documented in a number of recent post-storm service assessments, is their failure during tropical cyclone landfall. A major cause of these failures is a loss of power when the electric power grid fails. As a solution, NOAA has instituted the use of backup power for ASOS sites affected by hurricane landfall.

Another observational capability from a land-based surface instrument is weather radar, specifically the Weather Service Radar 1988-Doppler (WSR-88D) radar network. Radar has played an important role in studies of tropical cyclones since it was developed in the 1940s. In the past 15 years, the operational WSR-88D radar network and technological improvements such as the Doppler radar deployed in the tail of NOAA WP-3D aircraft have produced new tropical cyclone data whose analysis has provided an unprecedented opportunity to document and understand the dynamics and rainfall of tropical cyclones. Data from the WSR-88D Doppler radar network have improved understanding of: (1) severe weather events associated with landfalling tropical cyclones; (2) boundary layer wind structure as the storm moves from over the sea to over land; and (3) spatial and temporal changes in the storm rain distribution. The WSR-88D data have also been instrumental in developing a suite of operational single Doppler radar algorithms to analyze the tropical cyclone wind field objectively by determining the storm location and defining its primary, secondary, and major asymmetric circulations.

A recent addition to surface observation capability is the use of relocatable observing platforms to provide measurements in the potential damage area of landfalling tropical cyclones. For example, miniaturized Doppler radars mounted on trucks, originally developed for tornado observations, were first deployed in Hurricane Fran in 1996 and provided very high resolution measurements of boundary layer structure. Since then, portable radar wind profilers and rapidly deployable ASOS units have been set up in a network in advance of a number of landfalling hurricanes.

3.1.5 Adaptive (Targeted) Observation Strategies

Adaptive observations have a relatively long history within NOAA. The initial Hurricane Reconnaissance program, in which NOAA and Air Force planes were first tasked to collect critical information on the location and intensity of hurricanes, started in 1947. In 1982, NOAA's National Hurricane Research Laboratory (now NOAA/OAR/HRD, see section 2.2.1) began research flights around tropical cyclones in the data-sparse regions to improve NWP forecasts of their tracks. Papers dating back to 1920 (Gregg 1920; Bowie 1922) suggest that observations to the northwest of the tropical cyclone center are most important for subsequent forecasts (Franklin et al. 1996). This was confirmed during subjectively planned synoptic flow missions. Burpee et al. (1996) found that such flights led to an improvement in hurricane track forecasts of approximately 25 percent. As a result, NOAA procured the G-IV aircraft for operational synoptic surveillance flights for hurricanes threatening landfall in the United States and its territories east of the International Dateline.

Hurricane-related adaptive observational work has been limited to the tropics and subtropical areas and until recently has been based on subjective techniques. Objective targeted observational techniques were first developed for extratropical use in the Fronts and Atlantic Storm-Track Experiment (FASTEX) field program (Joly et al. 1997). Following a workshop (Snyder 1996), various groups developed and applied targeted observational strategies that were later used in FASTEX and subsequent field programs (Buizza and Montani 1999; Gelaro et al. 1999; Bergot et al. 1999; Szunyogh et al. 1999).

Adaptive observation strategies in numerical weather prediction aim to improve forecasts by exploiting additional observations at locations that are optimal with respect to characterizing the current state of the atmosphere. The objective is to take the observation that is most likely to yield maximum information relative to some forecast goal. Of most use for targeted observations are platforms that can provide observations at controllable locations. Examples of such platforms are unmanned aircraft systems (discussed in section 4.2.8), energy-intensive satellite observations (such as the proposed lidar wind measurements), and dropwindsondes released from manned aircraft. To date, only the dropwindsonde technique has been employed for targeted observations.

The final step in a targeted observation system is the assimilation of the targeted data, along with data available from the regular and opportunity-driven part of the observing network, into a NWP model. The impact of the data is usually evaluated by running a control analysis/forecast cycle in parallel with the operational cycle and differing from it only in excluding the targeted observation data. The difference between the operational and control fields reveals the effect of the targeted data. Although the principles are well established, extracting useful information from geographically localized data is a demanding task for current analysis systems. Further improvements in automating the assimilation and analysis processes are necessary before the full potential of targeted observations can be realized in operations.

3.1.6 Observations of the Tropical Cyclone Inner Core

Observations in the tropical cyclone inner core are essential for tropical cyclone analysis and the initialization of the tropical cyclone vortex in operational, high resolution, next generation NWP models. As mentioned in section 3.1.2, satellite-based scatterometers and polarimetric radiometers provide valuable information, but the limitations of both sensors prevent wind retrievals at higher wind speeds and in deep convection (i.e., heavy precipitation), limiting the utility of these sensor types for hurricanes and typhoons of sufficient intensity, especially near the inner core. Also described in section 3.1.2 are techniques to indirectly estimate inner-core winds from AMSU temperature retrievals and IR imagery. However, the AMSU instrument lacks the horizontal resolution to properly resolve the inner core, and the IR technique provides winds based upon statistical relationships with the cloud top structure. The satellite techniques are more reliable for estimation of the outer-core structure. As to the importance of inner-core observations, the report from the May 2005 Air-Sea Interactions in Tropical Cyclones Workshop stated:

> *By providing better initial ocean conditions, and improving air-sea parameterization schemes in the coupled models, we may expect improved forecast of the tropical cyclone surface wind field, the ensuing storm surges and the inland flooding, which accounts for a majority of the Nation's hurricane-related fatalities. To meet the above forecast challenges, significant advances must concurrently occur in advanced observations, data assimilation techniques and model development for both the hurricane environment and the hurricane core.*

Given the current limitations in satellite observations, the only inner-core wind data routinely available—derived from the SFMR (surface winds), airborne tail Doppler radar (three-dimensional structure), and GPS dropwindsonde (point vertical profile)—are collected by aircraft reconnaissance (NOAA WP-3D and U.S. Air Force WC-130). As detailed in section 3.1.1, TPC/NHC forecasters rely heavily on data from reconnaissance aircraft. The combination of SFMR, airborne tail Doppler radar, and GPS dropwindsonde is essential for real-time interpretation of rapidly changing events, especially near landfall (Black et al.2006). The SFMR capability is especially critical to the forecasters.

To obtain the inner-core data, the reconnaissance aircraft typically fly radial flight-legs toward and away from the tropical cyclone center. Most of the radial legs are flown at an altitude of 3 km and the wind at that level is sampled by instrumentation onboard the aircraft. The flight-level wind data are then extrapolated to surface wind values using empirically derived relationships (e.g., Franklin et al. 2003). In addition to these flight-level measurements, dropwindsondes are regularly deployed from the WP-3D and WC-130 aircraft. Surface winds below a WP-3D aircraft are estimated along its flight path by the SFMR, a passive microwave sensor (Uhlhorn and Black 2003). In addition to the onboard wind sensors, the WP-3D aircraft are equipped with a tail radar that can be operated in dual-Doppler mode to measure the three-dimensional wind structures (above the near-surface region) in the inner core when precipitation is present (Reasor et al. 2000; Marks 2003).

As previously presented in Table 3-2, NOAA is in the process of procuring an airborne Doppler radar along with an SFMR to be installed on its G-IV aircraft, which will be tasked to provide initial conditions in the hurricane core for the operational initialization of NOAA's new high-resolution hurricane model, HWRF. HWRF is slated to become operational in 2007 (Surgi et al. 2006; Surgi et al. 2004). The airborne Doppler radar, which is similar to those on the WP-3D aircraft, is expected to become operational on the G-IV in 2009. It will provide far better observations of the three-dimensional structure of the hurricane vortex from the hurricane outflow layer. These observations, along with the data from the SFMR and dropwindsonde, will provide a unique initial description of the hurricane core circulation, for use in the HWRF, ranging from top to bottom of the storm. Storm observations derived from airborne instruments will increasingly become assimilated into hurricane computer models, which will lead to improved forecasts. Specifically, observations from the airborne Doppler radars, the SFMRs, and AXBTs are planned for assimilation into the HWRF model.

At present, sampling of the inner core of hurricanes by aircraft is performed routinely only in the Atlantic Basin. Because of range limitations of the aircraft, westward-tracking hurricanes in the Atlantic are not measured until they are close enough to land-based air bases. Storms that are far out to sea but still pose a threat to shipping and marine interests are therefore not sampled by aircraft. Information about their inner-core wind is often unavailable for many days. Aircraft reconnaissance in the eastern Pacific is occasionally tasked at the discretion of the TPC/NHC, and the CPHC can request reconnaissance flights for tropical cyclones west of 140^{o} W longitude. In all other basins prone to tropical cyclones, in situ information about inner-core winds is based entirely on occasional serendipitous sources such as ships, buoys, and island-based meteorological measurements.

3.2 Statistical Analysis and Prediction Techniques

Many of the analysis procedures discussed so far are statistically based. Statistical methods are used to provide forecasts of various tropical cyclone parameters including track, intensity, rainfall, and wind radii. The algorithms that provide future predictions of parameters, rather than only a diagnosis of current conditions, are referred to as statistical forecast models.

Statistical forecast models have two primary applications. First, they can provide a useful forecast for situations where physically based NWP modeling approaches are difficult. A second application is for use as a benchmark for evaluating the skill of more general techniques. At present, the statistical track forecast models are primarily used for benchmark purposes, but statistical intensity and rainfall models serve both purposes.

The history of statistical track forecast models for the Atlantic basin was described by DeMaria and Gross (2003). The earliest objective track guidance models employed by TPC/NHC (beginning in the late 1950s) used empirical relationships between future storm motion and various parameters such as previous storm motion, Julian Day, and current position. These techniques were later generalized to "statistical-dynamical" models, where additional predictors of storm motion were obtained from the output from NWP models. The statistical-dynamical models continued to improve through the 1980s and generally remained the most skillful until that time. Beginning in the 1990s, the NWP model track forecasts improved to the point that they were much more accurate than forecasts from the statistical models. The NWP forecasts are now the primary tools used by TPC/NHC for official track forecasts. The JTWC track models followed a similar history. Additional information concerning this history is contained in appendix B.

One of the simplest statistical track forecast models is the CLImatology and PERsistence (CLIPER) model. The climatology and persistence input is simply the initial storm position and intensity, their time tendencies, and the Julian Day. The errors from the CLIPER model are commonly used as a benchmark for track forecast skill by TPC/NHC and JTWC. To attain forecast skill, the average track errors from a particular technique must be smaller than the corresponding CLIPER errors.

Intensity forecast models that use simple climatology and persistence input are also available, such as the Statistical Hurricane Intensity FORecast (SHIFOR) model. The SHIFOR forecasts are the basis for evaluating intensity forecast skill from other methods. More-general statistical-dynamical intensity models are also available to TPC/NHC and the JTWC, including SHIPS, which is used for the Atlantic and the eastern and central North Pacific, or STIPS, used for the West Pacific, Indian Ocean, and southern hemisphere.

In contrast to track forecasting, for which the NWP models are now the most skillful, the SHIPS and STIPS models have continued to provide the most skillful intensity forecasts over the past several years. However, as shown by DeMaria et al. (2005), the skill of these recent intensity forecasts is 2 to 3 times less than the skill for track forecasts.

In recent years, tropical cyclone rainfall and wind radii forecasts from NWP models have begun to be verified (e.g., Marchok et al. 2006; J. Franklin, personal communication). Simple CLIPER-type statistical rainfall and wind radii techniques have also been recently developed to provide skill baselines for the operational models. More-general statistical rainfall models are under development. It remains to be seen whether the generalized statistical or NWP approach will provide the most accurate predictions for tropical cyclone rainfall and wind radii. Section 3.4.5 provides additional details on precipitation forecasting methods and capabilities.

3.3 Numerical Models

Significant improvements in hurricane track forecasting occurred over the past two decades primarily through major advances in global and regional operational NWP modeling systems for which high quality satellite observations were routinely available, through development of sophisticated data assimilation techniques and improved representation of model physics, and through major investments in supercomputing at operational NWP centers.

In contrast to improved track forecasting, intensity forecasts have improved only modestly, as discussed in the previous section. Tropical cyclone intensity prediction continues to be a challenging scientific problem because of complex, nonlinear processes occurring in the ocean, the tropical cyclone boundary layer, convective structures, and environmental forcing. The modest improvement in the intensity forecasts may reflect deficiencies in the current prediction models, including such factors as inadequate initialization of the hurricane vortex and inadequate representation of the atmosphere-ocean boundary layer (Ginis et al. 2006a and 2006b).

How the tropical cyclone vortex is initialized in operational, high resolution, next generation models is critical to improving tropical cyclone intensity and structure forecasts. At present, most models employ a bogusing technique for the storm initialization. These techniques often fail to capture a realistic storm structure in all spatial dimensions of the model analyses. The bogusing techniques are particularly inadequate in describing the asymmetries of the core circulation associated with storms that are less mature than very strong, mature storms. To replace the traditional bogusing system, observations of tropical cyclone inner core (see section 3.1.6) and development of an advanced data assimilation capability are required.

Tropical cyclones draw energy from the ocean surface, thereby cooling the ocean, by wind-induced surface fluxes and vertical mixing. The extreme winds, heavy rainfall, huge ocean waves, and profuse sea spray of such storms push the surface-exchange parameters for temperature, water vapor, and momentum into untested new regimes. Due to limited observations, the air-sea interaction in the eyewall region is largely unknown. The momentum and enthalpy exchange coefficients under high-wind conditions are difficult to determine. Continued research is required to better understand the physical processes that contribute to tropical cyclone intensity and structure changes. This research priority is characterized further in Chapter 5.

High-quality, high-resolution observations are necessary to advance model parameterizations for atmospheric, oceanic, or coupled processes. Aircraft and buoy technology has improved to the point where air-sea interactions during tropical cyclone extreme events can be quantified with movable observing strategies (Shay et al. 2000). These measurements will allow coupled models to be tested to identify deficiencies in their parameterizations. They will help to advance new ideas and isolate physical processes involved in air-sea interactions (Hong et al. 2000). Together with parallel improvements in modeling, the improved observations will provide important insights into the ocean's role in modulating tropical cyclone intensity change (Marks et al.1998). Field experiments, another source of NWP model improvements, are discussed in section 3.5.

The following three sections will discuss global models, high-resolution regional models, and ocean and wave models that are currently operational, including recent improvements to these models. A storm surge model, the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, is discussed in section 3.4.4. Appendix B reviews the history of important upgrades to the global models and of the operational use of high-resolution regional models—advances that have greatly improved tropical cyclone forecasting.

3.3.1 Global Models

Over the past two decades, advances in global models such as NOAA/NCEP's GFS (formerly the Aviation/Medium Range Forecast model, AVN/MRF), the Navy Operational Global Atmospheric Prediction System (NOGAPS) run at FNMOC, and the United Kingdom Meteorological Office global model (UKMO) have culminated in state-of-the-art forecast skill in predicting tropical cyclone track. This skill has been confirmed during the past several hurricane seasons. The modeling advances included improvements to data assimilation techniques, which allowed better use of observations; improvements to model physics; improvements in the initialization of the hurricane vortex; and increases in model resolution. To illustrate some of these advances, tables 3-4 and 3-5 summarize significant improvements made to the GFS and NOGAPS models, respectively.

Section 3.3.4 will illustrate the positive impact on tropical cyclone track forecasts from assimilating satellite data into NWP models. Experiments were conducted from August 14 to September 30, 2004, to determine the impact of improvements to the NOGAPS global spectral model on NOGAPS tropical cyclone track forecasts (Goerss and Hogan 2006). This was a particularly active period with 12 hurricanes (including Charley, Frances, Ivan, and Jeanne), 5 typhoons, and 7 tropical storms. For the first experiment, the configuration of NOGAPS using the NRL Atmospheric Variational Data Assimilation System (NAVDAS) was T79L18 with relaxed Arakawa-Schubert convective parameterization. For the second experiment, the model resolution was increased to T159L24. The relaxed Arakawa-Schubert convective parameterization was replaced with the Emanuel convective parameterization in the third experiment (T159L24E). The control run was T239L30 model resolution with Emanuel convective parameterization.

The results of these experiments are summarized in figure 3-5, which shows the percentage improvement with respect to the control experiment. The numbers of forecasts, by forecast length, were 288 (24-hour), 249 (48-hour), 210 (72-hour), 169 (96-hour), and 133 (120-hour). The overall improvement in tropical cyclone track forecast due to model improvements was 15 percent at 24 hours, 22 percent at 48 hours, 25 percent at 72 hours, 34 percent at 96 hours, and 44 percent at 120 hours. The improvements were statistically significant at the 99 percent confidence level for all forecast lengths.

- Except for the 24-hour forecast length, the largest improvement was seen when the resolution was changed from T79L18 to T159L24, and the improvement increased with increasing forecast length: 12 percent at 48 hours, 20 percent at 72 hours, 25 percent at 96 hours, and 30 percent at 120 hours. These improvements were all statistically significant at the 99 percent confidence level.

Table 3-4. Upgrades to the GFS Model and its Predecessor AVN and MRF Models

Year	Operational Upgrades to the GFS (AVN/MRF)
Pre-1991	• MRF model resolution increased to T80L18 (~165 km horizontal resolution, 18 vertical levels). • Physics from the Geophysical Fluid Dynamics Laboratory model (GFDL) incorporated.
1991	• Model resolution increased to T126L18. • Develop improved data assimilation technology—the Spectral Statistical Interpolation (SSI).
1993	• Arakawa-Schubert convective parameterization scheme. • Vertical resolution increased to 28 levels.
1995	• Direct assimilation of satellite radiances and assimilation of ERS-1 winds. • Assimilation of SSM/I precipitable water.
1996	• Adjustments made to planetary boundary layer (PBL) physics and convection scheme.
1998	• Numerous changes—see Technical Procedures Bulletins (TPB) at: http://www.nws.noaa.gov/om/tpb/449.htm and http://www.nws.noaa.gov/om/tpb/450.htm
1999	• Introduction of high-resolution data—radiances from the AMSU-A and HIRS-3 instruments—from NOAA-15 satellite.
2000	• MRF model resolution increased to T170L42 through day 7, then to T62L28 through day 16. The AVN is run at T170L42 out to 84 hours four times a day. • Hurricanes and tropical storms in the model's guess field are relocated to the official TPC/NHC position in each 6-hour analysis cycle. Procedure yielded dramatic improvement in hurricane track forecasts not only in the global model suites (MRF and AVN), but also in the GFDL model, which uses initial conditions from the global suite.
2001	• Numerous changes - see TPB at http://www.nws.noaa.gov/om/tpb/484.htm.
2002	• Assimilation of QuikSCAT surface winds added. • MRF is replaced by the 00Z AVN model. • Name changes: The AVN is now referred to as the Global Forecast System model (GFS). • Assimilation of AMSU-A channels 12 and 13 from NOAA-15 and NOAA-16 and HIRS from NOAA-16.
2003	• QuikSCAT winds superobbed at 0.5 degrees • Package of minor analysis changes—see http://wwwt.emc.ncep.noaa.gov/gmb/para/paralog.analy2003.html.
2004	• Ensemble run four times daily. Horizontal resolution of ensemble run is T126 from 0–180 hours, then T62 to 384 hours.
2005	• Amount of assimilated radiance data increases substantially with the addition of Aqua AIRS and Aqua AMSU-A data. • GFS land-surface model component was substantially upgraded from the Oregon State University (OSU) land surface model to NCEP/EMC's new Noah Land Surface Model (Noah LSM). • GFS model resolution increased to T382L64 out to 180 hours, T190L64 out to 384 hours
2006	• GFS ensembles composed of 14 members are run four times daily.

Table 3-5. Upgrades to the NOGAPS Model

Year	Operational Upgrades to the NOGAPS
Pre-1991	• NOGAPS spectral model resolution increased to T79L18 (~165 km horizontal resolution, 18 vertical levels). With this increase in resolution, it was found that NOGAPS had tropical cyclone track forecast skill (Hogan and Rosmond 1991). • Assimilation of synthetic tropical cyclone observations into NOGAPS (Goerss and Jeffries 1994).
1994	• Model resolution increased to T159L18 (~110 km horizontal resolution).
1996	• Assimilation of high-density multispectral feature-track winds from geostationary satellites (Goerss et al. 1998).
1997	• Assimilation of SSM/I precipitable water.
1998	• Model resolution increased to T159L24 (24 vertical levels).
2000	• Emanuel convective parameterization scheme replaces relaxed Arakawa-Schubert scheme (Peng et al. 2004).
2002	• Model resolution increased to T239L30 (~55 km horizontal resolution, 30 vertical levels) and improvement made to Emanuel convective parameterization scheme.
2003	• NRL Atmospheric Variational Data Assimilation System (NAVDAS), a 3D-VAR data assimilation system, replaced MVOI system (Daley and Barker 2001).
2004	• Direct assimilation of AMSU-A radiances replaces assimilation of NESDIS ATOVS retrievals. • Assimilation of Moderate Resolution Imaging Spectroradiometer (MODIS) polar winds from NASA satellites Aqua and Terra. • Assimilation of QuikSCAT and ERS-1 scatterometer winds.
2005	• Assimilation of synthetic tropical cyclone observations improved.

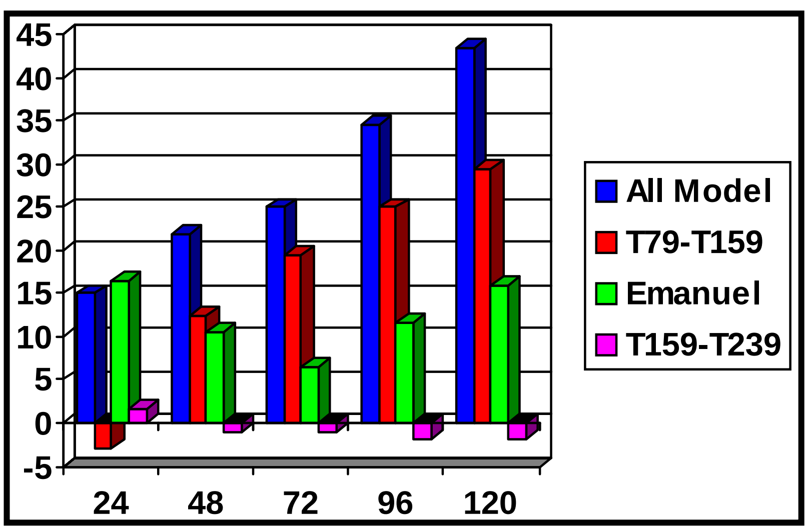


Figure 3-5. Percentage improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004.

- The improvements due to implementing the Emanuel convective parameterization were 16 percent at 24 hours, 10 percent at 48 hours, 6 percent at 72 hours, 12 percent at 96hours, and 16 percent at 120 hours. With the exception of 72-hour forecast length, these improvements were all statistically significant at the 95 percent confidence level.
- While increasing the model resolution to T239L30 improved forecast performance in the extra-tropics (not shown), it resulted in degradations in tropical cyclone track forecasts (not statistically significant) at all forecast lengths except 24 hours.

Similar to the above NOGAPS experiments, NCEP/EMC performed tests of the new GFS after the substantial upgrades in 2005. Table 3-6 displays the results of the retrospective runs, using data from the 2004 Atlantic tropical cyclone season, compared with the results of the GFS version run operationally during the 2004 season. The 2005 version of the GFS had substantially reduced track forecast errors for the sample cases at all forecast verification times.

Table 3-6. Mean 2005 GFS Track Errors (in nautical miles) for a Sample of Cases from 2004

	00 h	12 h	24 h	36 h	48 h	72 h	96 h	120 h
Operational GFS	12.4	35.1	52.1	72.2	88.0	140.2	204.3	275.5
New (T382) GFS	11.7	31.8	45.4	61/3	76.7	115.1	161.6	218.0
Reduction of Error With New GFS	5.7%	9.3%	12.9%	15.1%	12.8%	17.9%	20.9%	20.9%
# of Cases	61	59	57	55	53	50	43	35

Continued improvements in global models will provide fundamentally important contributions toward improving track skill. Five-day global model track forecasts are currently as skillful as the three-day track forecasts were 10 years ago. Not far in the future, demand for skillful seven-day forecasts will be forthcoming. However, the challenge remains to increase track forecast skill for erratically moving storms: the outliers of nature such as stalling storms, looping and zigzagging storms, and rapidly accelerating storms (examples in figure 3-6). Furthermore, continued improvements in track forecasts are fundamentally important to improving forecasts of storm intensity and rainfall.

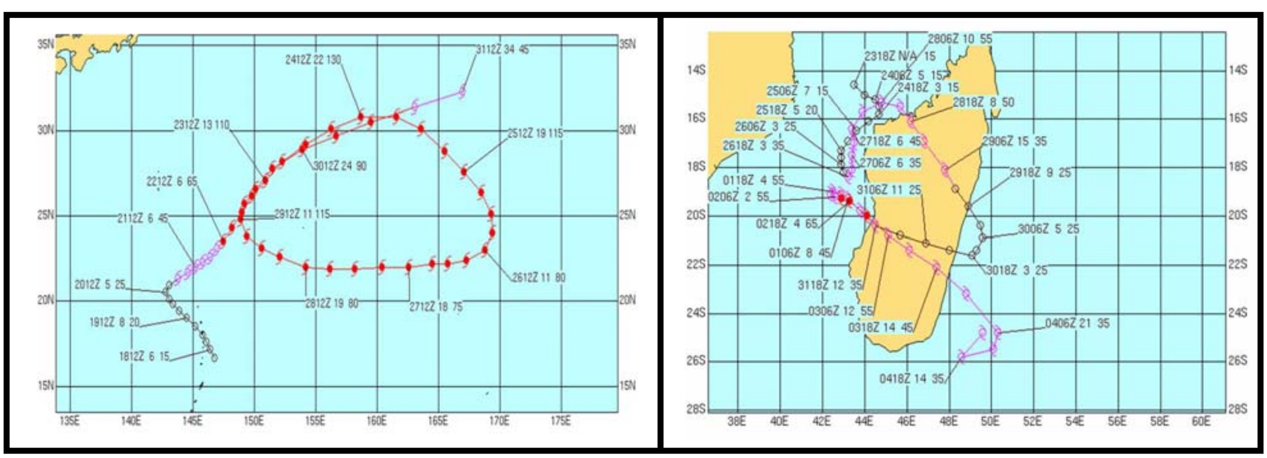


Figure 3-6. Two examples of erratically moving storms. Left: Tropical Cyclone Parma, October 18–31, 2003; Right: Tropical Cyclone Elita, January 23–February 5, 2004. Credit: JTWC.

The contributions from the operational global modeling community remain critical to meeting this challenge, as this community has long-term expertise and experience in improving tropical cyclone forecasts.

3.3.2 High-Resolution Regional Models

While global and regional-scale NWP models have proven highly successful at forecasting tropical cyclone tracks, models with much higher resolution appear necessary to make strides in forecasting tropical cyclone intensity. Over the past 20 years, NWP track forecasts have improved so much that today's 5-day forecasts are more accurate than the 3-day forecasts from the 1980s. As higher-resolution, coupled NWP forecast systems are developed and improved, the expectations are that forecast intensity guidance from these advanced model systems will improve enough to outperform the predictions from statistical models.

After the devastation of Hurricane Andrew in 1992, the tropical cyclone research community experienced a resurgence in developing high-resolution dynamical hurricane models. As described in appendix B, this development objective became a focus not only for improving track forecasts but also to realize the potential to provide the higher resolution necessary to improve intensity forecasts. The pioneering effort of Yoshio Kurihara in the mid 1970s at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) had led to the development of a hurricane model with a movable nested grid (Kurihara and Bender 1980). During the next two decades, this GFDL model was used as a research tool to study such topics as hurricane structure, mechanisms for decay at landfall, hurricane genesis, and effects of topography. A multiyear effort started in the late 1980s to develop a new lateral boundary scheme (Kurihara et al. 1989) and initialization scheme (Kurihara et al. 1993 and 1995) for the GFDL model. The improved GFDL model was successfully transitioned into NCEP operations in time for the 1995 hurricane season. Since then, it has been one of the most reliable models for hurricane track (Kurihara et al, 1998). The GFDL Hurricane Prediction System—Navy version (GFDN) is a version of the GFDL model that is run at FNMOC. It became operational in May 1996 (Rennick 1999).

Recent Improvements to the NOAA/NCEP GFDL Model

To investigate the effect of tropical cyclone–ocean interaction on the intensity of observed hurricanes, the GFDL atmospheric model was coupled with a high-resolution version of the Princeton Ocean Model (POM) (Bender and Ginis 2000). (For more information on the POM, see section 3.3.3.) Substantial improvements to this coupled model over the past decade are summarized in table 3-7. During the 1995 to 1998 hurricane seasons, this coupled GFDL model was run on 163 forecasts. Coupling the atmospheric and ocean models improved intensity forecasts; the mean absolute error in the forecast of central pressure was reduced by about 26 percent compared with the noncoupled GFDL model. The results of these tests confirmed that tropical cyclone–ocean interactions are an important physical mechanism in the intensity of observed storms. The coupled GFDL model became operational at NCEP in 2001.

The GFDL currently has a horizontal resolution of about 8 km with 42 vertical levels and is coupled to a modified version of the POM (Bender and Ginis 2000). These improvements led to

Table 3-7. Upgrades to the GFDL Forecast System since 1998

Year	Operational Upgrades to the GFDL Forecast System
1998	• Beta-gyre in specified vortex is replaced by asymmetries obtained from previous 12-hour forecast. • Vertical distribution of target wind in vortex spin-up made a function of storm intensity.
2001	• Atmospheric model coupled to a high-resolution version of the POM. • Vertical diffusion upgraded from 2.0 to 2.5 Mellor & Yamada Closure.
2002	• Horizontal resolution in outer nest increased from one degree to one-half degree. • Region covered by finest mesh expanded from 5-degree square domain to 11 degrees. • Filter to remove global vortex in vortex initialization modified to enable more small-scale features in the global analysis to be retained. • Vortex removal algorithm in initialization improved (less distortion of environmental fields).
2003	• Vertical resolution increased (number of vertical levels increased from 18 to 42). • Kurihara cumulus parameterization replaced by simplified Arakawa-Schubert (SAS). • Mellor and Yamada 2.5 diffusion replaced by Troen and Hahrt nonlocal scheme. • Mass initialization improved for temperature and sea-level pressure (reduced noise over mountains). • Pressure gradient computation improved to use virtual temperature. • Effect of evaporation of rain added. • Further refinements made to vortex removal algorithm in initialization. • More consistent target wind in vortex initialization. • Ocean coupling expanded to entire ocean domain. • Gulf stream assimilation added to ocean initialization.
2005	• Third nest added with one-twelfth degree resolution. • Vortex spin-up improved with model physics consistent with 3D model. • Mass initialization step eliminated.
2006	• Large-scale condensation scheme replaced with Ferrier Micro-physics package. • Effect of dissipative heating added. • Momentum flux parameterization improved for strong wind conditions. • Assimilation of Loop Current in Gulf of Mexico added to ocean initial condition.

the GFDL becoming the primary hurricane guidance to TPC/NHC forecasters. In 2003 the GFDL model was upgraded to 42 levels and the GFS deep convection and boundary layer physics were adopted. In 2005 the resolution of the inner nested grid was doubled.

The upgrades of the GFDL over the past 5 years have steadily improved its intensity skill (figure 3-7), and the latest version is now competitive with the statistical models (figure 3-8). In the 2006 version of the GFDL model, the large-scale condensation package was replaced with EMC's Ferrier microphysics package. An improved formulation of the surface drag (Moon et al. 2007) became operational, and the effect of dissipative heating was added. Also, further improvements in the ocean initialization were made to include a realistic representation of the Loop Current. These upgrades were tested on 172 selected cases from the 2003, 2004, and 2005 hurricane season, and the results suggest that further improvements in intensity skill are likely, compared with the 2005 GFDL version (figure 3-8). Both the ocean initialization and the improved momentum flux parameterization are described below.

Improving the GFDL Air-Sea Momentum Flux Parameterization

In previous versions of the GFDL hurricane model, the air-sea momentum flux (the Charnock drag coefficient C_d) was parameterized with a constant non-dimensional surface roughness regardless of wind speeds or sea states. This parameterization assumed a continual increase in C_d with wind speed. However, results from a number of studies (CBLAST-DRI and others) suggest that the value of C_d depends on the sea state represented by the wave age.

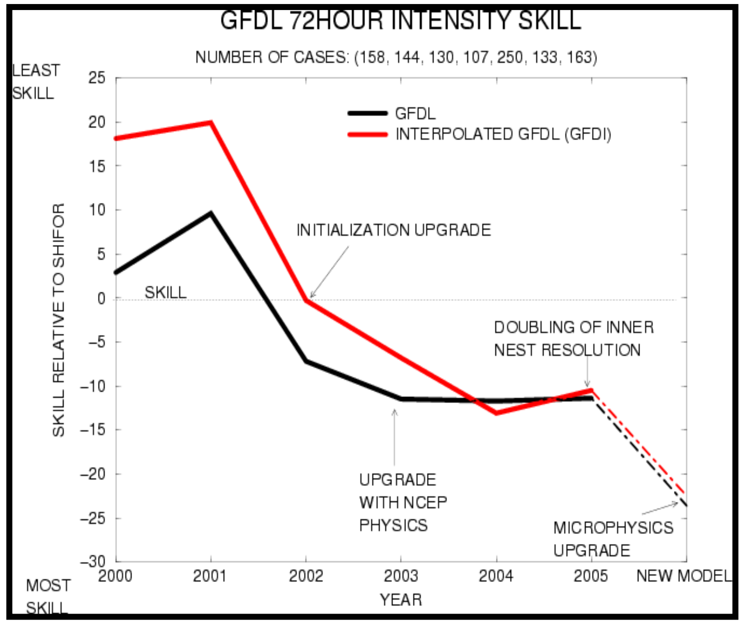


Figure 3-7. GFDL intensity skill (Atlantic basin) relative to SHIFOR since 2000. Also plotted is the intensity skill for 163 cases run with the 2006 version of the GFDL model (NEW MODEL).

Lively debate continues in the research community over the relationship between the Charnock drag coefficient and sea state. A major reason for the discrepancies among different studies of the relationship is the paucity of in situ observations, especially in high wind speeds and young seas.

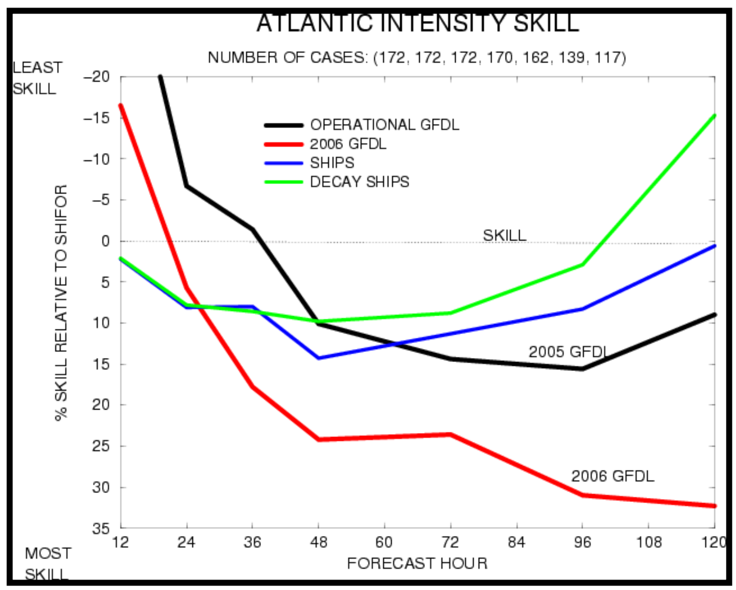


Figure 3-8. Comparison of intensity skill (Atlantic basin) between the 2005 operational GFDL model, the GFDL model made operational in 2006, and the statistical intensity models (SHIPS and DECAY SHIPS), run for select cases from the 2003-2005 hurricane seasons.

The Charnock coefficient under hurricane conditions was also examined using a coupled wind-wave model that includes the spectral peak in the surface wave directional frequency from WAVEWATCH III and a parameterized high frequency part of the wave spectrum using a recently developed model. The wave spectrum was then introduced in the wave boundary layer model to estimate the Charnock coefficient at different wave evolution stages. In this simulation system, the drag coefficient leveled off at very high wind speeds, which is consistent with recent field observations. The most important finding from this study was that the relationship between the Charnock coefficient and the input wave age (wave age determined by the peak frequency of wind energy input) varies but does show a strong dependence on wind speed. The regression lines between the input wave age and the Charnock coefficient have a negative slope at low wind speeds and a positive slope at high wind speeds. This behavior of the Charnock coefficient in high winds provides a plausible explanation for why the drag coefficient under tropical cyclones—where seas tend to be extremely young—may be significantly reduced in high wind speeds.

Improving the GFDL Air-Sea Heat and Humidity Flux Parameterization

Heat and humidity flux parameterizations are a crucial factor in hurricane-ocean coupling. In high wind conditions, the heat and humidity exchange coefficients (C_h and C_e) can be directly related to the roughness lengths of temperature and water vapor (Z_T and Z_q). Isaac Ginis has tested various parameterizations of Z_T and Z_q in the GFDL hurricane model and found that, for simulations of very intense hurricanes with maximum wind speeds exceeding 50 $m \cdot s^{-1}$, large values of C_h are necessary, with C_h/C_d greater than 1. For example, testing the parameterization of Z_T and Z_q used in the GFS model for Hurricane Isabel (2003) indicates that the storm should not have intensified beyond 50 $m \cdot s^{-1}$, but the maximum winds actually reached about 70 $m \cdot s^{-1}$. Theoretical results suggest that this ratio needs to exceed 1 for tropical cyclones to intensify (Emanuel 1995). However, recent observations from CBLAST suggest that, in strong winds, this ratio may be less than unity. Certainly these results indicate that more research and study of this important topic are needed. It is possible that sea spray, which is neglected in these numerical experiments, may provide an additional heat and moisture source (Andreas and Emanuel 2001).

Preparing for the Next Generation of Hurricane Models

The air-sea momentum flux parameterization and the air-sea heat and humidity flux parameterization in GFDL are examples of critical physical processes that need to be better understood and more realistically represented in the next generation hurricane models (e.g., the HWRF Air-Sea-Land Hurricane Prediction System and the next generation COAMPS system described in section 4.4). Chapter 5 includes these parameterizations as a research priority.

DOD's High-Resolution Regional Models

A version of the GFDL run operationally at FNMOC since 1996 is the GFDN. Improvements made to the GFDL model at NCEP make their way into the GFDN at FNMOC with typically a 1-2 year lag time. For example, the GFDN run at FNMOC for the 2005 season was essentially the GFDL model run at NCEP for the 2004 season.

In 1999, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®)[2] was implemented at FNMOC for several regions that periodically experience tropical cyclones. Among those regions were the western Atlantic, the Caribbean, and the eastern and western North Pacific. Forecasters at the Naval Atlantic Meteorology and Oceanography Center and at the JTWC used the COAMPS forecast fields as an additional guidance product in their operational decisionmaking process. COAMPS forecast tracks were made available on the Automated Tropical Cyclone Forecasting System (ATCF) to JTWC forecasters in 2000 and to TPC/NHC forecasters in 2001. In 2001, COAMPS forecast tracks for the western North Pacific

[2] COAMPS® is a registered trademark of the Naval Research Laboratory (Hodur 1997).

were used in consensus guidance generated on the ATCF for use by JTWC forecasters. Consensus guidance is further discussed in section 3.4.

AFWA has an automated tropical cyclone track and intensity forecast capability that provides bulletins for use by JTWC tropical cyclone forecasters during their forecast process. These bulletins are based on 45 km windows from the fifth generation Pennsylvania State University/NCAR nonhydrostatic atmospheric mesoscale model (MM5) run at AFWA. AFWA also has the ability to activate 15 km and 5 km MM5 windows that follow tropical cyclones. Products and data are routinely available through AFWA's Joint Air Force and Army Weather Information Network (JAAWIN), whose website is https://weather.afwa.af.mil.

3.3.3 Ocean and Wave Models

Ocean Model

The ocean component of the GFDL model is the Princeton Ocean Model (POM). It is a three-dimensional, primitive equation model with complete thermohaline dynamics, sigma vertical coordinate system, and a free surface (Blumberg and Mellor 1987). The specific model details and design of the coupling between GFDL and POM models have been outlined extensively in Bender and Ginis (2000). The POM configuration includes two computational domains in the Atlantic basin (East Atlantic and West Atlantic) selected automatically, depending on the location of the forecast storm. The horizontal grid resolution of each domain is $1/6^{o}$ with 23 sigma levels. Most of the Atlantic basin in which the TPC/NHC has forecast responsibility is covered by one of the two model domains.

In 2004, the GFDL model was coupled with a one-dimensional ocean model for the eastern Pacific derived from the three-dimensional POM. The eastern Pacific ocean model is configured on a 40º x 40º relocatable grid with a horizontal resolution of one-sixth of a degree and 16 sigma levels. The center of the grid coincides with the center of the GFDL hurricane model's outer mesh, which is determined at the beginning of each forecast.

New Ocean Model Initialization Method

The importance of the integrated thermal structure (OHC) as a more effective measure of the ocean's influence on storm intensity than just SST was discussed in section 3.1.3. In the Gulf of Mexico, the deepest areas of warm water are associated with the Loop Current and the rings of current that have separated from the Loop Current, commonly called Loop Current eddies. A new ocean data assimilation and initialization package has been developed to improve simulations of the Loop Current in the GFDL operational coupled hurricane prediction system (Yablonsky et al. 2006). The initialization procedure is based on feature modeling and involves cross-frontal "sharpening" of background temperature and salinity fields according to data obtained in specialized field experiments. It allows the position of the Loop Current in the Gulf of Mexico and the location of the primary warm core rings to be specified using real-time SST and sea surface height data. The initialization procedure is outlined in detail in Bender and Ginis (2000).

Experiments carried out with Hurricanes Katrina and Rita with the new initialization indicated improved forecasts of intensity in the GFDL model (figure 3-9), and the procedure was made operational in 2006. In the current implementation, the file describing the location of the Loop Current and the primary warm-core ring is updated at least once a week.

Wave Model

Both FNMOC and NCEP run the WAVEWATCH-III wave model globally. Since 2001, NCEP has provided operational hurricane wave forecasts for maritime operations with WAVEWATCH-III using blended winds from NCEP's GFS and the GFDL hurricane model (Chao et al. 2005). These wave models consist of large regional grids for the western North Atlantic and for the eastern North Pacific, with spatial resolutions of approximately 25 km. Operational forecasts provided with these models have shown excellent results (e.g., Tolman et al. 2005). However, recent major landfalling hurricanes have exposed two shortcomings of these models. First, the 25 km resolution is grossly inadequate to resolve coastal wave conditions. Second, even at the coarse resolution of 25 km, surf-zone conditions where wave heights become of the same order as the water depth can be observed in the wave model grid. Because the model does not incorporate surf-zone physics, near-coast wave conditions can be highly unrealistic (gross overestimation of wave heights).

NCEP is presently developing a new multi-grid version of WAVEWATCH-III with a telescoping nest following the hurricane and with full two-way interaction between nested grids. This model version is particularly suitable for incorporation into the HWRF model (Tolman 2005, Ginis et al. 2006). Apart from following hurricanes, this modeling approach will allow high-resolution grids at the coast and hence will render the present large regional models obsolete. With this approach and sufficient funding, a 5 km coastal resolution for operational modeling could be implemented for the entire U.S. coastline. With this dramatic increase in

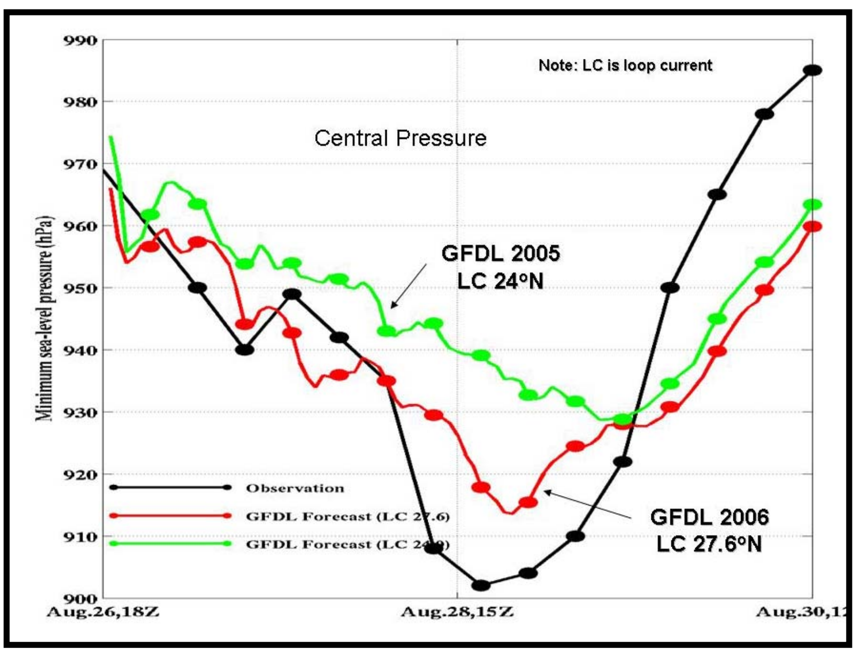


Figure 3-9. Positive impact of improved Loop Current initialization in the 2006 GFDL compared with the operational 2005 GFDL for Hurricane Katrina.

coastal resolution, the need for surf-zone physics in the wave model would become even more urgent. The need for surf-zone physics and other improvements to WAVEWATCH-III is discussed in section 4.4.2.

3.3.4 Data Assimilation Capability

NCEP/EMC continues to develop improved data assimilation technology for both global and regional applications. For atmospheric data assimilation, the current three-dimensional variational (3D-VAR) technology at NCEP/EMC, known as the Spectral Statistical Interpolation (SSI), became operational with the GFS model in 1991 and continues to produce excellent results. The SSI, which was the first operational global 3D-VAR system, has evolved in the intervening 15 years through periodic incremental upgrades to improve accuracy, adapt to using new observations as they became available, and improve efficiency. During this 15-year period, ground-breaking work was also done in the following areas:

- First direct inclusion of polar-orbiting satellite measured radiances
- First direct inclusion of geostationary satellite measured radiances
- Three-dimensional ozone analysis and assimilation
- Improved techniques for specifying forecast errors used in the European Center for Medium-Range Weather Forecasting (ECMWF) and NCEP assimilation systems
- First direct incorporation of Doppler radial winds
- First 3D-VAR system to perform analysis at the same resolution as the forecast model

When it was implemented in 1998, the NCEP 3D-VAR regional analysis, which supports the North American Model (NAM) run, was also the first operational mesoscale 3D-VAR system. However, this 3D-VAR code differs in many details from the SSI, since it is applied to a gridpoint model rather than a spectral model.

Recently, a new analysis code called the Gridpoint Statistical Interpolation (GSI) has been developed at EMC for both global and regional applications. Although closely related to the SSI, this code performs calculations in gridpoint space and therefore has the following advantages:

- Concentration on one code for both global and regional applications decreases code maintenance costs and improves development efficiency.
- The scalability to large numbers of processors is increased.
- Time- and space-varying background errors can be used.

One very positive outcome of the GSI development has been adoption of the code by the NASA Global Modeling and Analysis Office (NASA/GMAO), which paves the way for increased collaboration and leverage of NCEP's Data Assimilation Team.

For ocean modeling, the Marine Modeling and Analysis Branch at NOAA/NCEP has implemented the Real Time Ocean Forecast System (Atlantic) (RTOFS [Atlantic]). RTOFS will provide the foundation for the initial and boundary conditions for the ocean component of NOAA's HWRF Air-Sea-Land Hurricane Prediction System, as well as the high-resolution regional models for environmental and ecosystem management, safety of marine transportation, and coastal flooding. Future RTOFS development is focused on increasing the domains, observations ingested, and products/services provided by the RTOFS. The new domains include a global domain and the eastern North Pacific Basin. The dynamical ocean model in RTOFS (Atlantic) is the Hybrid Coordinate Model (HYCOM); for more information on HYCOM, refer to section 4.4.2.

As noted in table 3-5, the NAVDAS was implemented in operation at FNMOC for NOGAPS in 2003. NAVDAS is an observation-space 3D-VAR system that can be run both globally and for regional applications. Prior to the NAVDAS implementation, a global multivariate optimum interpolation (MVOI) analysis system was used for NOGAPS data assimilation. Over the years, data from new observing systems have been assimilated into NOGAPS. Some of the more notable milestones (table 3-5) with respect to tropical cyclone forecasting were the assimilation of synthetic tropical cyclone observations in 1990, the ground-breaking assimilation of high-density multispectral feature-track winds from geostationary satellites in 1996, the assimilation of SSM/I precipitable water in 1997, and the direct assimilation of AMSU-A radiances in 2004.

The assimilation of satellite data has led directly to improvements in NWP tropical cyclone track guidance. This is clearly illustrated in figure 3-10, which shows the results of a JCSDA project funded by the NPOESS IPO, with the work performed with the NCEP GFS model by Dr. Tom Zapotocny (University of Wisconsin) and Dr. James Jung (JCSDA). In another example, the impact of the assimilation of satellite data upon the NOGAPS tropical cyclone track forecasts from the NOGAPS experiments described in section 3.3.1 (Goerss and Hogan 2006) is illustrated in figure 3-11. The current operational configuration (T239L30 with Emanuel convective parameterization) was used in these assimilation experiments. At all forecast lengths except 120 hours, the feature-track winds had the most impact on the NOGAPS forecasts. At 120 hours, the assimilation of AMSU-A radiances had the largest impact. The overall impact of satellite data assimilation on NOGAPS tropical cyclone forecasts is about 15–25 percent improvement

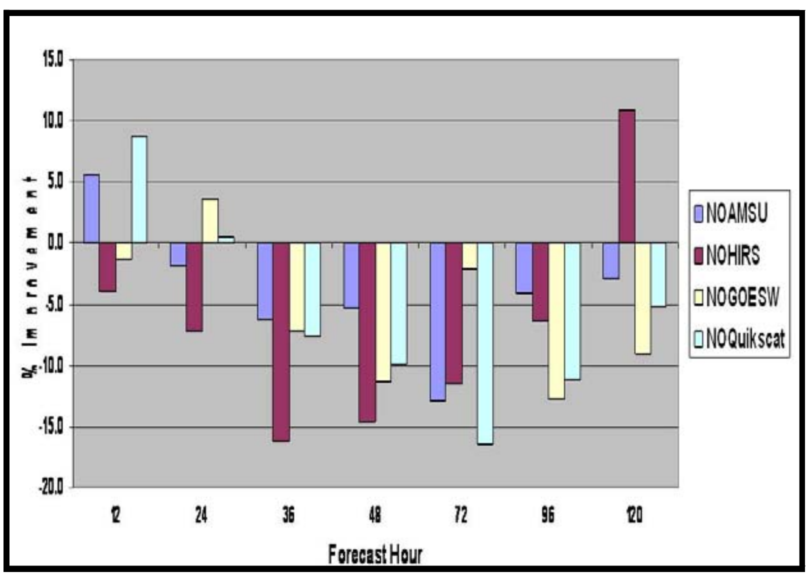


Figure 3-10. Negative impact of removing AMSU, HIRS, QuikSCAT surface wind data from the hurricane track forecast guidance in the Atlantic basin in 2003 (34 cases).

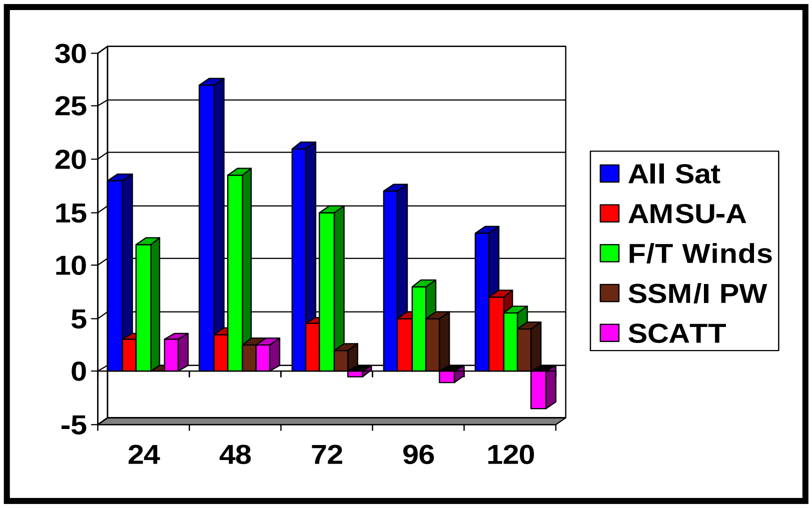


Figure 3-11. Percent improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004.

(compare the 15–45 percent improvement shown in figure 3-5 due to improvements in the global spectral model).

3.3.5 Use of Research Models

In addition to the models used by the operational centers, other global and high-resolution regional models are used by members of the research community (e.g., NCAR, NASA, and universities) for the purposes of conducting basic and applied research related to hurricanes. This research includes studies of the dynamics and physics of hurricane genesis, motion, intensity change, precipitation, environmental interactions, intraseasonal and interseasonal variability, and climate-hurricane interactions. These models are also used as experimental real-time forecasting systems that provide tools for testing new numerical schemes, physical parameterizations, data assimilation techniques or data sources, and ensemble forecasting techniques. The advantages of these modeling systems are that they are generally not bound by operational time constraints, so they can be run at higher resolution or with more detailed but time-intensive model physics. They also increase the diversity of modeling approaches, configurations, and physics. A disadvantage is that they often do not provide a stable model configuration over multiple seasons that allows for evaluation of forecast skill. Also, techniques or model physics developed for these models generally cannot be, and have not been, readily transferred to operational models. For a review of research models, see appendix C.

3.4 Forecasting and Warning

As mentioned in Chapter 1, hurricane forecasts and warnings originate at one of the tropical cyclone forecast and warning centers. For information regarding precipitation forecasts, refer to section 3.4.5. For civil operations, the NWS WFOs tailor the tropical cyclone forecasts to conditions in their area of responsibility. The TPC/NHC's TAFB and NCEP's Ocean Prediction Center (OPC) provide forecasts to mariners at sea (section 1.4.4). The U.S. military also contributes to the forecast process through its own forecasting operations and through reconnaissance by aircraft and satellites. The military uses forecasts (TPC/NHC, CPHC, or JTWC forecasts depending on the theater of operations) to keep ships, aircraft, and other assets out of harm's way. In addition, state and local emergency managers order evacuations and other preparations based on NWS forecasts, and municipalities, business enterprises, and individual citizens respond in a variety of ways.

Numerous objective forecast aids (guidance models) are available to help the TPC/NHC, CPHC, and JTWC tropical cyclone forecasters in the preparation of their official track and intensity forecasts. Guidance models are characterized as being either early or late, depending on whether or not they are available to the hurricane forecaster during the forecast cycle.

Multilayer dynamical models are generally, if not always, late models. An estimation technique is used to adjust the forecast from the most recent run of a late model for the current synoptic time and initial conditions. This adjustment process creates an "early" version of that model for use in preparing forecasts, ensemble forecasting, etc. These adjusted versions of late models are commonly called "interpolated models."

Appendix D lists the individual models used by the TPC/NHC and CPHC during 2005. For each model, its model type is given. Appendix E contains a similar list of the models used by the JTWC, with their model type. The model types in operational use include: (1) dynamical models, which solve the physical equations governing motions in the atmosphere; (2) statistical models, which do not consider the physics of the atmosphere but instead are based on empirical relationships between storm behavior and various other parameters derived from historical data sets; (3) statistical-dynamical models, which use output from dynamical models as well as historical data; and (4) consensus models, which are not true forecast models per se but merely weighted combinations of the forecasts from other models. Consensus forecasting is discussed further in section 3.4.2.

3.4.1 Track

Tropical cyclone forecasters use more than one model to track and predict hurricane movement and intensity. This can be an advantage because each type of model has particular strengths. The tropical cyclone forecasters have to interpret the results from the different models to arrive at the best-possible track and intensity forecast, which will be broadcast to the public.

Figures 3-12 and 3-13 provide examples of the improvement in tropical cyclone track forecasts since the 1970s. Since the mid-1990s, dynamical models have had better track accuracy than the statistical models. In addition to improved NWP models, consensus tropical cyclone track forecast aids formed using tropical cyclone track forecasts from regional and global NWP models and ensemble techniques have recently become increasingly important as guidance to tropical cyclone forecasters at the TPC/NHC, CPHC, and JTWC (Goerss et al. 2004; Toth 2005). As seen from figures 3-12 and 3-13, average official track errors at 72-hours in 2005 are comparable to 48-hour model track errors in the late 1990s.

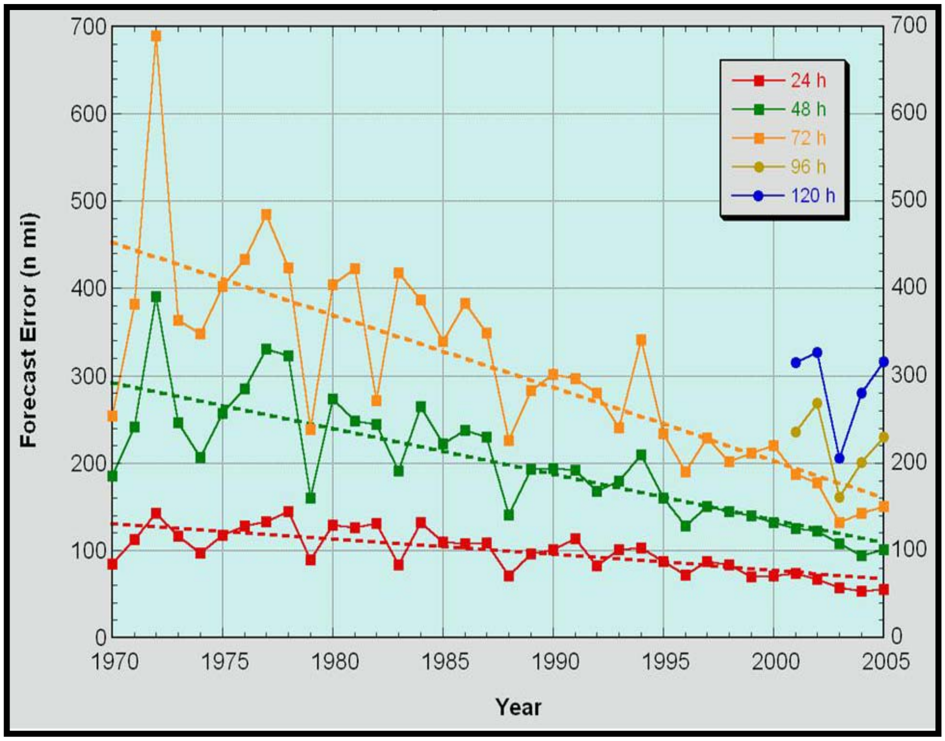


Figure 3-12. Annual average official track errors, with trend lines superimposed, for tropical storms and hurricanes in the Atlantic basin, 1970–2005.

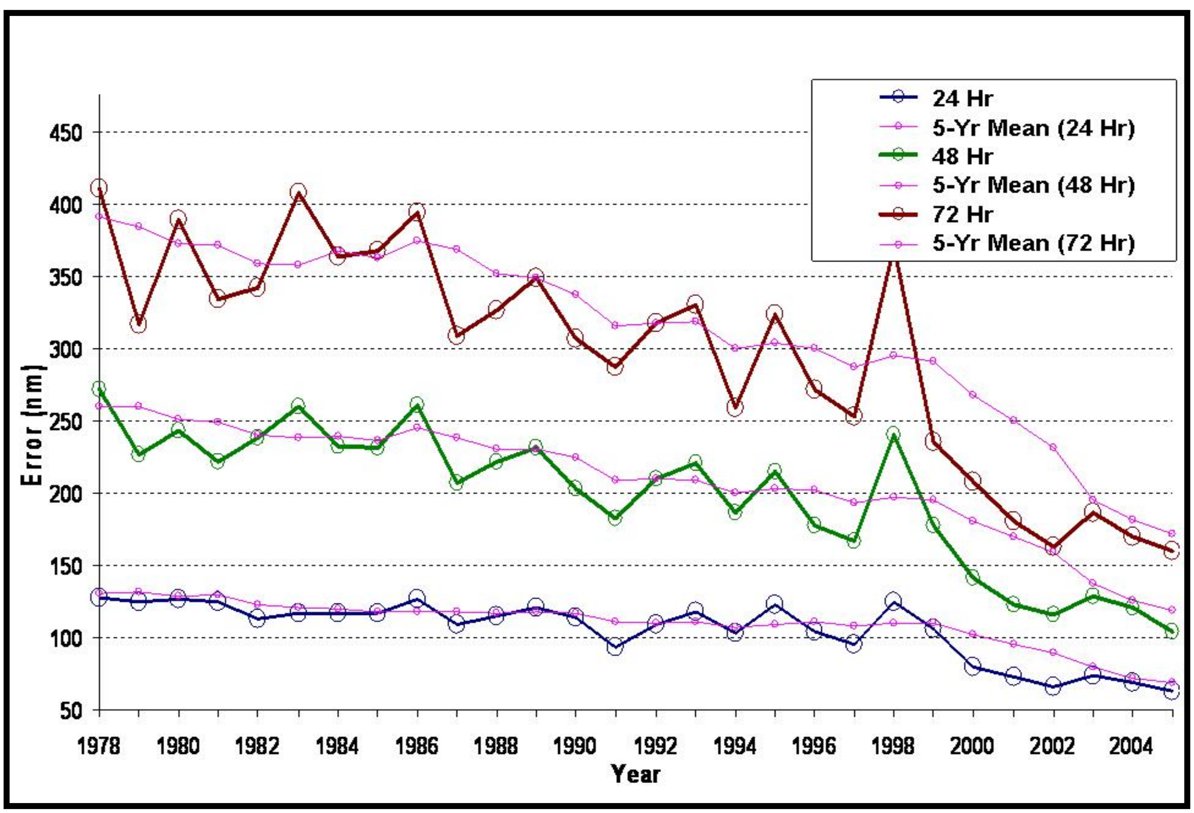


Figure 3-13. Mean track forecast error (nm) and 5-year running mean for 24, 48, and 72 hours for tropical cyclones in the western North Pacific Ocean, 1978–2005.

3.4.2 Consensus Forecasting

The benefits of consensus forecasting have long been recognized by the meteorological community (Sanders 1973; Thompson 1977). Leslie and Fraedrich (1990) and Mundell and Rupp (1995) applied this approach to tropical cyclone track prediction and illustrated the forecast improvement that resulted from using linear combinations of forecasts from various tropical cyclone track prediction models. Goerss (2000) first illustrated the superior tropical cyclone track forecast performance of multi-model ensembles (also called consensus forecasts) constructed from combinations of operational NWP models for the 1995–1996 Atlantic seasons and the western North Pacific for 1997 (Goerss 2004). Studies conducted by Goerss et al. (2004) and Sampson et al. (2005) found that increasing the number of models in the pool from which consensus members are drawn resulted in improved consensus forecasts. The consensus models in use by the tropical cyclone forecast and warning centers during 2005 are summarized in appendices D and E.

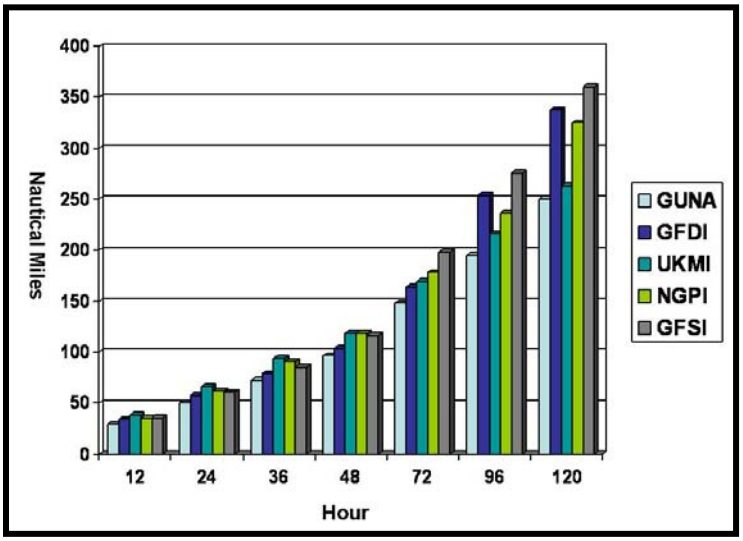


Figure 3-14. Atlantic basin track guidance model errors in nautical miles for 2005 of the GUNA model, a consensus model, and the individual models that are used to construct it.

Over the past 6 years, tropical cyclone forecasters at both TPC/NHC and JTWC have come to rely more and more heavily upon consensus models when making their track forecasts. Consensus models *routinely* outperform the individual models from which they are constructed and thus contribute to improved track forecasting capability. This trend was confirmed again in 2005, as illustrated in figure 3-14 and summarized in appendix F.

In summary, operational improvements in NWP modeling systems coupled with the routine availability of high-quality satellite observations, development of sophisticated data assimilation techniques, improved representation of model physics, major investments in supercomputing at operational NWP centers, and the use of consensus models have resulted in the continuing improvement in forecasting tropical cyclone track witnessed over the past several years.

3.4.3 Intensity and Structure

The intensity[3] of a landfalling hurricane is expressed in terms of categories that relate wind speeds and potential damage. In the widely used Saffir-Simpson Hurricane Scale (see table 1-1 in chapter 1), a category 4 hurricane would have winds between 131 and 155 mph and, on average, would be expected to cause 100 times the damage of a Category 1 storm (Pielke and

[3] Intensity is defined as the peak 1-minute sustained wind at 10-m altitude anywhere in the storm.

Landsea 1998). Depending on circumstances, less intense storms may still be strong enough to produce damage, particularly in areas that have not prepared in advance. Even winds of tropical storm force may be strong enough to be dangerous in certain situations. For this reason, emergency managers plan on having their evacuations complete and the public in shelters before the onset of tropical storm-force winds, since it would be dangerous to wait until hurricane-force winds are occurring.

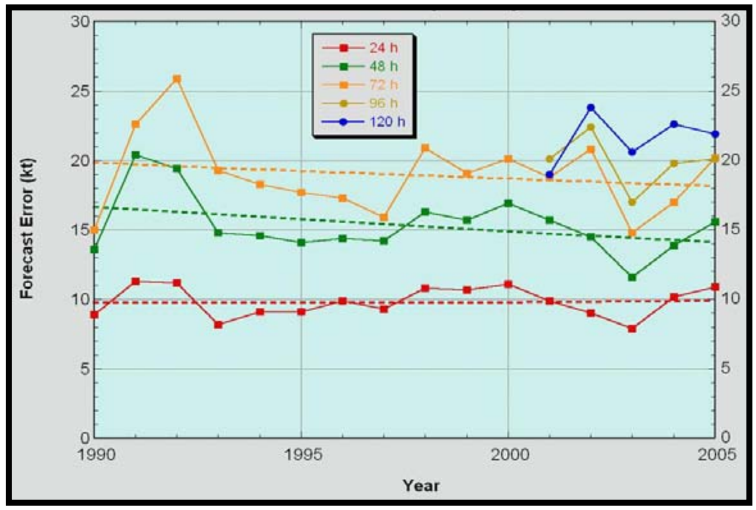


Figure 3-15. Annual average official intensity errors for the Atlantic Basin tropical cyclones for the period 1990-2005, with trend lines superimposed.

Figure 3-15 is an example of the modest intensity forecast improvement that has occurred from 1990 through the 2005 hurricane season. For intensity guidance, the official intensity forecasts were notably superior to the best objective guidance (appendix G). In contrast to track guidance, dynamical models have, until recently, lagged the statistical techniques for predicting intensity change. However, as described in section 3.3.2, recent advances in the GFDL operational coupled hurricane model have improved intensity forecasts. Forecasts with this improved coupled model are expected to be competitive with the operational statistical intensity guidance made available to the TPC/NHC and CPHC forecasters. This significant development is discussed further in chapter 4.

With respect to tropical cyclone structure, the horizontal extent of the storm-force wind field is of crucial importance to emergency managers and other decision makers. However, analysis of tropical cyclone structure and the surface wind field in particular has been hampered by insufficient data. Operational designation of structure is limited to the specification of the four-quadrant radii of surface winds at or above certain thresholds (e.g., 34, 50, and 64 kt); this is an oversimplification of the true two-dimensional wind field. Isolated ship reports—sometimes of dubious accuracy—are used whenever possible to estimate these radii.

For TPC/NHC operations, when a tropical cyclone threatens land, flight-level winds from aerial reconnaissance are used to make estimates of the surface wind distribution, based on standard adjustment factors that may or may not be appropriate for particular tropical cyclones. Dropsondes supplement the flight-level data by making direct surface or near-surface measurements. The dropsonde wind profiles also provide information on the flight-level to surface reduction factors. With the operational implementation of the SFMR instrument on more of the aircraft reconnaissance fleet, direct measurements of surface winds from the aircraft will eventually be routinely available, which should improve analyses of tropical cyclone structure. Data from the QuikSCAT sensor have provided extremely valuable information on the tropical cyclone surface wind field, particularly the horizontal extent of 34-kt winds. AMSU measurements are being used to infer the tropical cyclone wind field from estimates of the sea-level pressure distribution (Demuth et al. 2004), but these derived wind radii are rather noisy and have had very limited use in operations thus far.

For landfalling tropical cyclones, the Inland High Wind Decay Model (Kaplan and DeMaria 2001) can be used by emergency managers to estimate how far inland strong winds should be expected. In the decisionmaking process, this information is most useful for deciding which areas are most likely to experience high winds.

For JTWC operations, the limited amount of in situ data and the absence of aerial reconnaissance drive forecasters to rely on remotely sensed data—such as QuickSCAT and other microwave-derived products—numerical prediction models, and climatology to assess and forecast storm structure. These intensity guidance products have individual strengths and weaknesses, but in general they have shown limited skill. Military leaders continue to ask for increased fidelity in tropical cyclone forecasts, which can only be provided if there are significant improvements in the analysis and forecasts of storm structure.

In summary, prediction of tropical cyclone structure is problematic. Users of TPC/NHC tropical cyclone advisories continue to ask for more extended range structure information, such as wind radii at the 96 and 120 hour forecast times. The current view is that skillful forecasts of these radii cannot be made for these extended forecast times. Forecasters are attempting to use dynamical models as numerical guidance for making predictions of tropical cyclone wind radii. It appears that global models such as the GFS and UKMO models have some utility for predicting the outer wind field (i.e., extent of 34-kt winds). Recently, two CLIPER models for the prediction of tropical cyclone wind radii were developed by McAdie (2004) and Knaff et al. (2007). These are now being used as guidance for operational forecasting and eventually could serve as a baseline to measure the skill of official and NWP model wind radii forecasts. Unfortunately, due to the present lack of surface observations, it is very difficult to properly assess the accuracy of either the structure guidance or the official structure forecasts.

3.4.4 Sea State and Storm Surge

With the increase in the U.S. coastal population, hurricanes have become an increasingly greater threat to the lives and properties of residents living in vulnerable coastal regions. In these regions, storm surge and inundation are the greatest threat to life and property associated with a landfalling hurricane. Accurate forecasts of storm surge and inundation are therefore critical to hurricane preparedness and evacuation plans.

Previous sections have reviewed numerous in situ and remote observing capabilities used to analyze the current sea state associated with a tropical cyclone. The RTOFS (Atlantic), which was briefly described in section 3.3.4, is a forecast system that produces daily nowcasts and five-day forecasts of sea surface temperatures, sea surface height, mixed layer depth, salinity, and horizontal and vertical currents over the entire Atlantic Ocean from 25^{o} S to 70^{o} N, including the Gulf of Mexico, Caribbean Sea, Gulf of Maine, and Gulf of St. Lawrence. As previously mentioned, NCEP provides model-derived hurricane wave products for maritime operations from the WAVEWATCH-III model using blended winds from NCEP’s GFS and GFDL models (Chao et al. 2005).

Sea State

High sea state conditions can have disastrous consequences for maritime operations. To meet operational requirements, the JTWC reports maximum significant wave height on both its text and graphical warning products. The value for this indicator is determined by the Naval Maritime Forecast Center, Pearl Harbor, Hawaii, and is based on the current sustained wind speed and forward speed of movement of the tropical cyclone generating the high sea state condition.

The TPC/NHC includes in its analyses and forecasts the areal extent of the 12-foot seas around a tropical cyclone, along with the pattern of sea heights less than 12 feet farther away from the cyclone. The TPC/TAPF provides an estimate of the highest significant wave height. Ship, buoy, and satellite (altimeter) observations are the primary sources for estimating the pattern of sea heights around the cyclone. The highest seas are estimated using empirical programs that take into account wind speed, duration, and fetch. The WaveWatch III suite of models use GFS winds and, for some models in the suite, GFDL winds when available, to help provide forecast values for the range of 8–12 foot seas, as well as for the 12-foot sea radius. During 2004 and 2005 hurricanes, the TPC/NHC found that WaveWatch III provided significant skill in validations against measurements taken by buoys moored in the Gulf of Mexico.

Storm Surge

Storm surge is water that is pushed toward the shore by the force of the winds swirling around a storm. This advancing surge combines with the normal tides to create the hurricane storm tide, which can increase the mean water level by 15 feet or more (e.g., to an estimated 28 feet in Hurricane Katrina). In addition, wind waves are superimposed on the storm tide. This rise in water level can cause severe flooding in coastal areas, particularly when the storm tide coincides with a normal high tide. The following are some generalizations:

- The higher the hurricane category, the higher the storm surge is likely to be (i.e., tropical cyclone intensity forecasts are important for accurate storm surge forecasts).
- Maximum storm surge occurs to the right of the storm track, roughly at the radius of maximum winds (i.e., tropical cyclone track forecasts are important for accurate storm surge forecasts).
- Faster-moving hurricanes cause higher surges *at the coastline* than do slower-moving hurricanes.
- For areas with gentle slopes of the continental shelf, storm surge is large but waves are small.
- Areas with deep water just offshore experience large waves but little storm surge.
- Very small, compact hurricanes cause less storm surge than do large-sized hurricanes.

Because much of the densely populated Atlantic and Gulf Coast coastlines in the United States lie less than 10 feet above mean sea level, the danger from storm tides is tremendous.

The SLOSH model, which is a nondynamical model to estimate storm surge, calculates storm surge heights resulting from either historical, hypothetical, or forecast hurricanes. SLOSH incorporates ocean bathymetry and topography, including bay and river configurations, roads, levees, and other physical features that can modify the storm surge flow pattern.

SLOSH requires the following meteorological inputs:

- Track positions—latitude & longitude
- Intensity (minimum sea-level pressure)
- Size (radius of maximum winds

The accuracy of winds is one of the most important factors affecting accuracy of the forecasts of hurricane-caused storm surge, inundation, and waves. SLOSH accounts for astronomical tides (which can add significantly to the water height) by specifying an initial tide level, but does not include rainfall amounts, river flow, or wind-driven waves. This information must be combined with the SLOSH model results to provide a final analysis of at-risk-areas.

The current accuracy of the SLOSH model is about ±20 percent. For example, assuming a perfect tropical cyclone track, intensity, and size forecast, if the model calculates a peak storm surge for the event of 10 feet (3.0 m), the observed peak may range from 8 to 12 feet (2.4–3.6 m). Due to the importance of having accurate tropical cyclone track, intensity, and size forecasts, the TPC/NHC only makes the SLOSH data available through the anonymous FTP server 1 day prior to the predicted landfall of the tropical cyclone. Even so, the SLOSH storm surge output made available through the anonymous FTP server is for guidance purposes only. Customers receive official storm surge information from their local NWS or military forecast offices.

In the coastal engineering community, it has long been known that waves drive near-shore circulation systems, and that waves can result in "storm surges" on days without local winds. Recent studies suggest that the waves may be responsible for a significant part of hurricane-induced storm surges (e.g., Don Resio, USACE-ERDC, personal communication; Chen et al. 2007). Because the local water depth strongly influences wave breaking and hence the forcing of the local circulation and surge, wind waves and surges are strongly coupled. This, in turn, underscores the need for coupled wave-surge modeling for hurricane-induced storm surges. The plan for acquiring this capability is discussed in Chapter 4.

Unfortunately, there is a historical dichotomy between large-scale (operational) modeling and wave-driven storm surge modeling. The former models typically do not resolve the coastal areas sufficiently to consider detailed storm surges. However, they do consider the full unsteady equations, which are typically solved on regular structured grids. The surge models are either uncoupled to the atmosphere, or consider high-resolution models with only a small geographic coverage. The wave/surge applications furthermore use different wave modeling approaches with steady equations and/or irregular or unstructured grids. Well-established models for such applications are SWAN (Booij et al. 1999) and STWAVE (Smith et al. 2001).

3.4.5 Precipitation and Fresh Water Flooding

Among the principal dangers from landfalling tropical cyclones is the copious amount of rainfall they often produce. Drowning from inland flooding caused by landfalling tropical cyclones is the second leading cause of death from storms in the United States. The safety and economic risks from inland flooding highlight the importance of usefully accurate forecasts of rainfall from a tropical cyclone headed on a track to landfall. As noted above, forecasts of tropical cyclone track have recently improved substantially, and there is potential to substantially improve intensity forecasts. However, far less attention has been paid to improving rainfall forecasts for tropical cyclones through quantitative precipitation forecasting (QPF). An essential prerequisite for improving rainfall forecasts is the capability to validate forecasts against observations so that model biases and areas for potential improvement can be identified.

Due to the wide distribution in rainfall intensity from these storms and their unique spatial distribution of intense rainfall, standard QPF validation techniques such as bias and equitable threat scores do not adequately characterize the overall performance of tropical cyclone rainfall forecasts. To better identify forecast biases and potential improvements, a *scheme for validating QPF from landfalling tropical storms* needs to be developed. An approach for developing this capability is discussed later in this section.

Rainfall from a landfalling tropical cyclone depends on numerous factors, which in turn depend on both the storm and the larger environment in which it is embedded. Tropical cyclone track is a significant determinant of the distribution of rainfall from the storm: most of the heaviest rainfall occurs close to the track of the storm's center. The translational (forward) speed of the storm can also play an important role by creating azimuthal asymmetries in the rainfall field. Another important determinant of tropical cyclone rainfall is the topography the storm traverses. For example, the combination of strong winds, high moisture content, and sharp terrain gradients can create pronounced differences in rainfall on the windward and leeward sides of mountain slopes. The proximity of synoptic features such as frontal boundaries and upper-level troughs can create major bands of heavy rainfall at distances well-removed from the storm's center, while vertical shear of the environmental wind can create asymmetries in the inner-core rainfall field that depend on the magnitude and direction of the shear vector. Finally, the intensity of the storm, the environmental humidity, and the properties of the underlying surface can alter the amount and distribution of rainfall received from a storm after it makes landfall.

Various QPF techniques for tropical cyclones have been developed to account for some or all of these factors. The simplest technique, known as Kraft's rule of thumb, divides a constant value by the translational speed of the storm to estimate the maximum rainfall that will be produced for a given location traversed by the storm during a given time period. While this technique accounts for the translational speed of the storm, it does not consider variability in the rainfall field. The Tropical Rainfall Potential (TRaP) method, developed by NOAA's Satellite Services Division, uses a satellite-estimated precipitation field to generate a 24-hour rainfall accumulation.

An analytical model called the Rainfall Climatology and Persistence (R-CLIPER) Model, is an empirically derived, climatology-based scheme that was recently developed to provide a benchmark against which to compare rainfall forecasts, similar to the way in which CLIPER and SHIFOR predictions provide benchmarks for track and intensity forecasts, respectively (Tuleya et al. 2007; Rogers et al. 2006). The current operational version of R-CLIPER, which is based on tropical cyclone rainfall observations derived from the TRMM satellite, assumes a circularly symmetric distribution of rainfall and translates this distribution in time. It captures the dominant signals of translational speed and storm intensity, but it does not incorporate processes that create asymmetries within the rain field. A recently proposed improvement on R-CLIPER builds on that model by including corrective factors for the rain field asymmetries produced by wind shear and topography (Lonfat et al. 2006).

The most complex forecasting systems for tropical cyclone QPF are three-dimensional numerical models that produce spatially and temporally varying rainfall fields. Numerical models offer the advantage that they can depict changes in the structure of tropical cyclones over time and how these changes are reflected in the rain field, both in a storm-relative sense and with accumulated rainfall swaths over a geographical area. Numerical models do, however, suffer from constraints related to resolution limitations and deficiencies in the representation of the initial state of the atmosphere and to the degree of realism in the model's representation of physical processes. It is these deficiencies that need to be identified by applying validation schemes specific for tropical cyclone rainfall.

As an example of the varying abilities of numerical models to reproduce rainfall fields, figure 3-16, shows storm-total rainfall fields of Hurricane Isabel (2003) produced by four different models of varying resolution and complexity—GFDL, GFS, Eta, and R-CLIPER—as compared with observations. The observed rain maximum stretches along and just to the right of the storm track, and there is significant structure in the rain field, corresponding to rainbands and topographic effects (e.g., the maximum in Delaware and the minimum in southwestern Pennsylvania). R-CLIPER reproduced the general pattern of rainfall, but with lesser amounts than observed and with little structure in the rain field. GFDL produced rain amounts and structures comparable to the observations. Although the Eta and GFS results show some structure to the rain field, GFS produced a larger area of maximum rain than was observed., while Eta produced a smaller area of heavy rain. Further inland over Ohio and West Virginia, the three dynamical models (GFS, GFDL, Eta) show a shift in the axis of heaviest rainfall to the left of the storm track that is consistent with the observations. However, the R-CLIPER produced an axis of heaviest rainfall that is aligned with the storm track and about 300 km east of the axis of observed heavy rainfall.

QPF associated with landfalling tropical cyclones is even more problematic in the not-infrequent situations where the storm interacts with mid-latitude troughs and undergoes transition to an extratropical cyclone. In these cases, the precipitation shield typically broadens and becomes more asymmetric; the heaviest rainfall shifts to the left of the storm track.

A Scheme for Validating QPF from Landfalling Tropical Storms

A recent study developed a scheme for validating QPF from landfalling tropical cyclones. This scheme takes advantage of the unique attributes of tropical cyclone rainfall by evaluating the skill of rainfall forecasts in four characteristics: the ability to match QPF patterns, the ability to match the mean value and volume of observed rainfall, the ability to produce the extreme amounts often observed in tropical cyclones, and the sensitivity of a model's QPF errors to its tropical cyclone track forecast errors. These characteristics were evaluated for forecasts of all U.S. landfalling tropical cyclones from 1998 to 2004 by the NCEP operational models: GFS, GFDL, the Eta mesoscale model, and R-CLIPER.

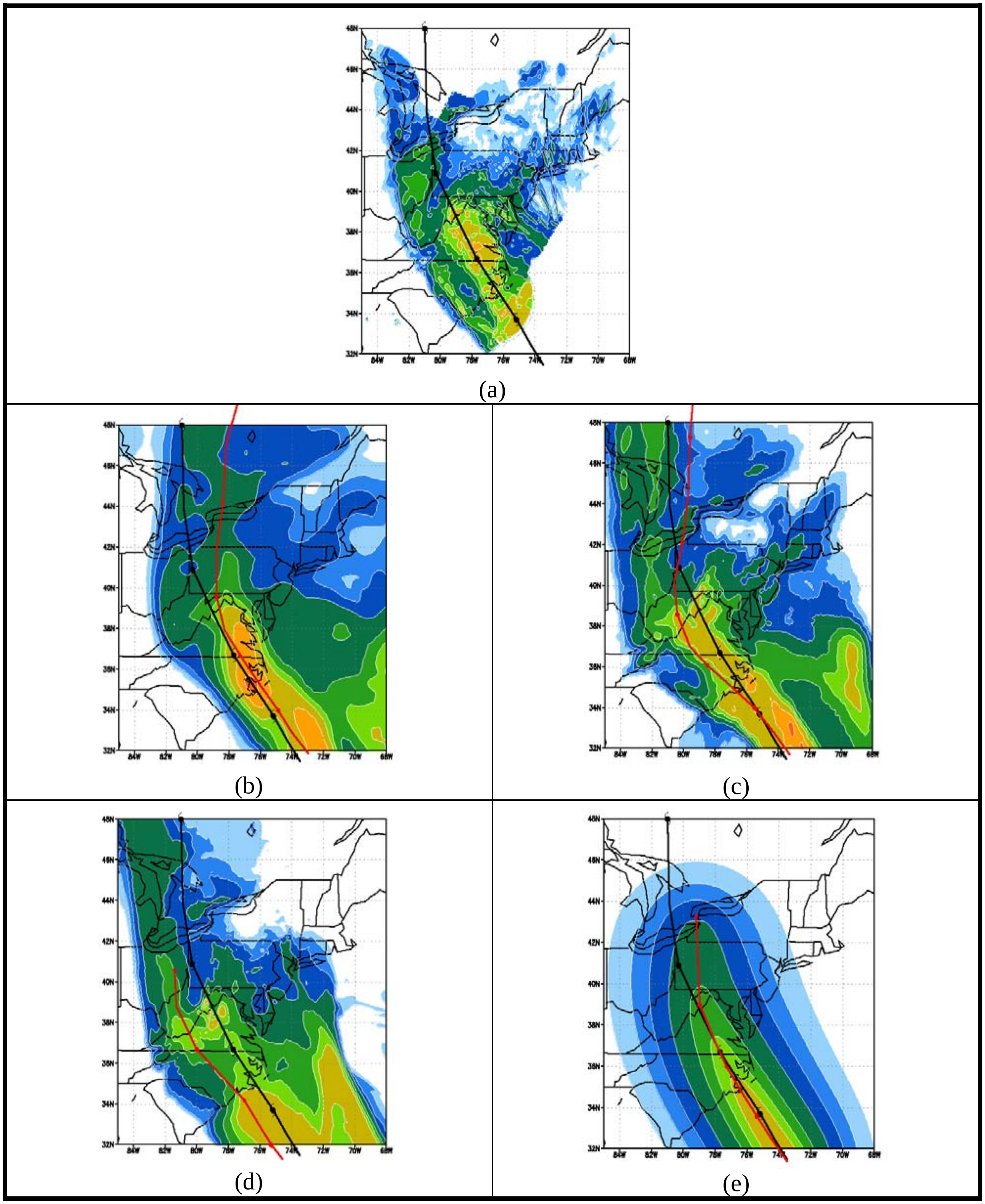


Figure 3-16. Plot of 72-h accumulated rain (shaded), 12 UTC 17 September to 12 UTC 20 September, 2003 for (a) Stage IV observations; (b) GFS; (c) GFDL; (d) Eta; (e) R-CLIPER.

Compared to R-CLIPER, all of the dynamical models showed comparable or greater skill for all of the attributes except sensitivity to track error (figure 3-17). The GFS performed the best of all four models for each of the skill attributes. The GFDL model showed a bias toward producing too much heavy rain, especially in the core of the tropical cyclones, while the Eta produced too little of the heavy rain. The R-CLIPER performed well near the track of the core, but it produced much too little rain at large distances from the track. Possible causes of these differences lie with the physical parameterizations and initialization schemes for each of the models. This validation scheme can be used to identify biases and guide future efforts toward model development and improvement.

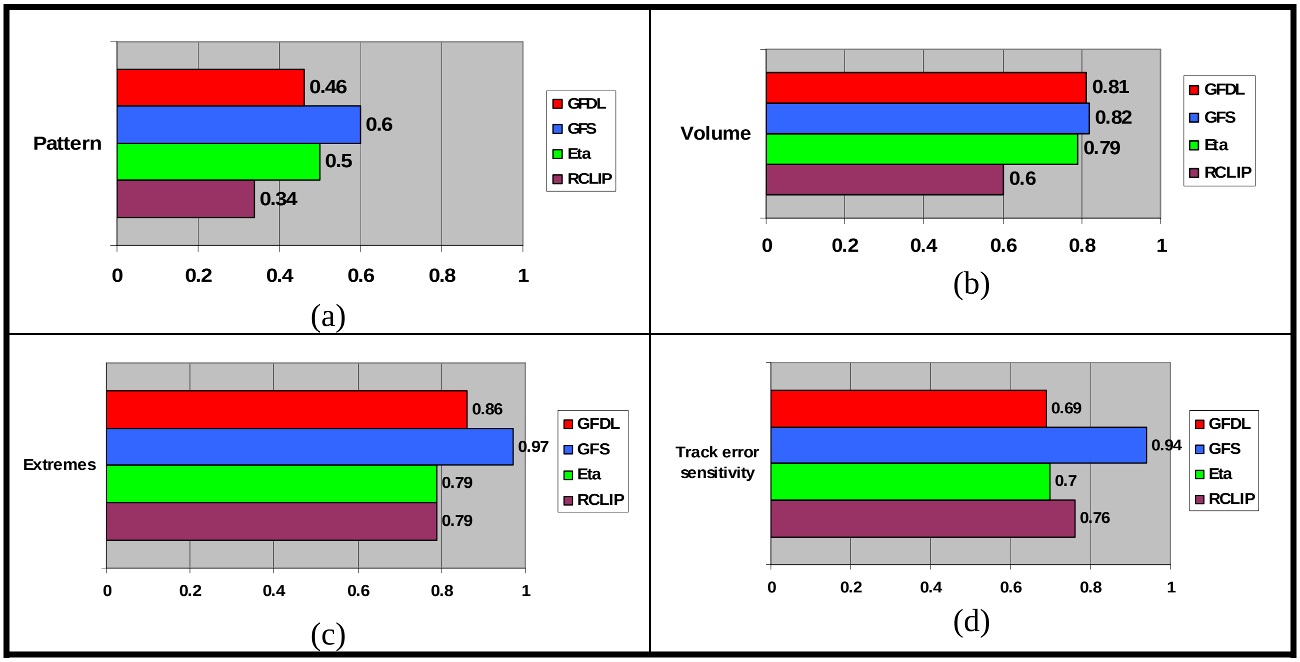


Figure 3-17. Comparisons of tropical cyclone QPF from different models showing how well they perform at (a) matching QPF patterns in the observed data; (b) matching extreme rainfall amounts, (c) matching the volume of observed rainfall, and (d) sensitivity of model QPF error to its storm track forecast error. The scores range from 0 (no skill) to 1 (most skill).

Precipitation Forecasting

All of these precipitation forecast techniques are used to develop predictions of maximum rainfall amount and extent of heavy rainfall. Both the HPC and TPC/NHC contribute to providing the general rainfall statement that appears in the Public Tropical Cyclone Advisory Products. The NCEP/HPC has the responsibility of providing more specific QPF estimates for landfalling tropical cyclones. The WFOs tailor these toward local forecasts of precipitation.

It should be noted that the JTWC does not have a requirement to produce precipitation forecasts. Precipitation forecasts are handled by the U.S. Air Force Operational Weather Squadron forecasters in support of Air Force and Army operations. The U.S. Navy regional forecast centers provide specific precipitation forecasts to meet their customers' needs.

3.4.6 Severe Weather Activity

Forecasting severe storms and other extreme weather conditions over the United States is the primary responsibility of NWS WFOs and the NWS Storm Prediction Center. Research to meet deficiencies in their capabilities is planned and provided through NOAA, other agencies, and academic institutions. Although some of this research is undertaken in coordination or cooperation with TPC/NHC-related research and operations, the JAG/TCR did not specifically include severe weather activity (e.g., tornadoes and severe thunderstorms) as a priority area for tropical cyclone R&D.

3.5 Tropical Cyclone Field Experiments

Field experiments play a vital role in improving scientific understanding of how and why hurricanes form, strengthen, and dissipate. This understanding is the foundation for improved tropical cyclone forecasts. Field programs are used to carry out scientific experiments designed to better understand and predict tropical cyclones and to address priority research areas. All of the experiments are coordinated with AOML/HRD’s annual hurricane field program, where the various partners—Federal agencies (e.g., NASA, NSF), universities and cooperative institutes, international partners, and scientists at NCAR— plan and conduct joint experiments. Some recent cooperative field experiments are described below.

3.5.1 NASA-Sponsored Experiments

The third Convection and Moisture Experiment (CAMEX-3) in 1998 studied inner core dynamics, synoptic flow environment, landfalling intensity change, and the genesis environment for several tropical storms. CAMEX-4, conducted during the 2001 hurricane season, studied rapid intensification, storm structure and dynamics, scale interactions, and intercomparison of remote sensing techniques.

The NASA-sponsored Tropical Cloud Systems and Processes (TCSP) experiment was conducted from San Jose, Costa Rica, during the 2005 hurricane season. Its purpose was to investigate the genesis and intensification of tropical cyclones The TCSP experiment included 12 NASA ER-2 science flights, including missions to Hurricanes Dennis and Emily, Tropical Storm Gert, and an eastern Pacific mesoscale complex that may have contributed to the development of Tropical Storm Eugene. NOAA WP-3D aircraft flew 18 coordinated missions with the NASA research aircraft to investigate developing tropical disturbances. In addition, the Aerosonde unmanned aircraft system flew eight surveillance missions and the Instituto Meteorologico Nacionale of Costa Rica launched RS-92 balloon sondes daily to gather humidity measurements and provide validation of the water vapor measurements. The research conducted during TCSP addressed the following overarching scientific themes: (1) tropical cyclogenesis, structure, intensity change, moisture fields, and rainfall distribution; (2) satellite and aircraft remote sensor data assimilation and validation studies pertaining to tropical cyclone development; and (3) the role of upper tropospheric/lower stratospheric processes governing tropical cyclone outflow, the response of wave disturbances to deep convection, and the evolution of the upper-level warm anomaly.

TCSP's successor program was the NASA African Monsoon Multidisciplinary Activities (NAMMA) experiment. NAMMA was based in the Cape Verde Islands, 350 miles off the coast of Senegal in West Africa. During NAMMA, NASA scientists and partners employed surface observation networks and aircraft to characterize the evolution and structure of the African Easterly Waves and Mesoscale Convective Systems near the West African coastline. The major NAMMA research topics included: (1) studying the formation and evolution of tropical hurricanes in the eastern and central Atlantic, and (2) studying the composition and structure of the Saharan Air Layer to determine if aerosols affect cloud precipitation and influence cyclone development.

3.5.2 NSF-Sponsored Rainband and Intensity Change Experiment

The Hurricane Rainband and Intensity Change Experiment (RAINEX) was a collaborative effort of NSF, NCAR, NRL, Remote Sensing Solutions, Inc., NOAA, the University of Washington, and the University of Miami (Houze et al. 2006). The Hurricane RAINEX was undertaken to address hurricane internal dynamics. Its primary elements were a high-resolution NWP model, Doppler radar measurements from three P-3 aircraft, and intensive airborne dropsonde coverage.

3.5.3 NOAA-Sponsored Experiments

In probing the whole life cycle of tropical storms—not just mature hurricanes—the Intensity Forecasting Experiment (IFEX) is taking a new approach to developing physical understanding and forecast abilities as well as testing and enhancing real-time observational capabilities (Rogers et al. 2006). The following set of goals were devised for IFEX:

- Goal 1—Collect observations that span the tropical cyclone life cycle in a variety of environments
- Goal 2—Develop and refine measurement technologies that provide improved real-time monitoring of tropical cyclone intensity, structure, and environment
- Goal 3—Improve understanding of the physical processes important in intensity change for a tropical cyclone at all stages of its life cycle

The experiments for Goal 3 included the Tropical Cyclone Genesis Experiment, Saharan Air Layer Experiment, Oceanic Interaction Experiment, Landfall Experiment, and Extratropical Transition Experiment.

A unique aspect of IFEX in 2005 was the large number of experiments that involved partnering. These experiments were NASA's TCSP experiment, which provided the high-altitude NASA ER-2 aircraft; the NSF's RAINEX project, which provided the NRL P-3 aircraft and additional dropsondes; and NOAA's Ocean Winds and Synoptic Surveillance experiments.

3.5.4 ONR-Sponsored Experiments

The hurricane component of the Coupled Boundary Layers Air-Sea Transfer Departmental Research Initiative (CBLAST-DRI) is an example of a hurricane field experiment to gain a better understanding of the physical processes involved in air-sea interactions (figure 3-18). The specific purpose of CBLAST-DRI was to measure, analyze, understand, and parameterize air-sea fluxes in the hurricane environment. During this experiment, comprehensive observational data sets in and around the tropical cyclone were obtained.

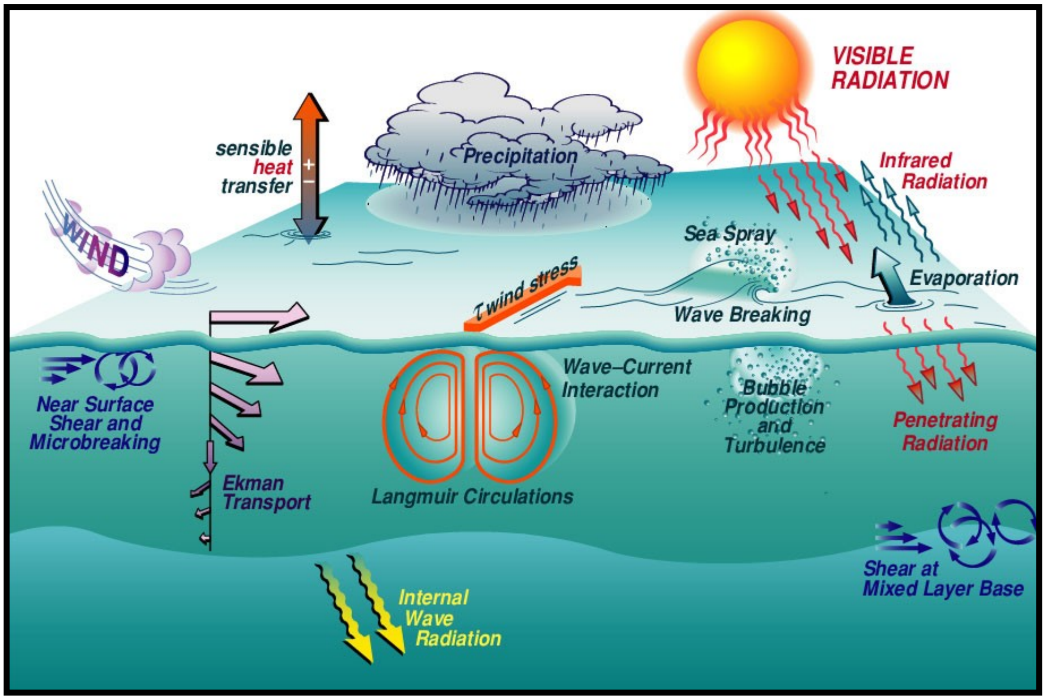


Figure 3-18. The hurricane component of CBLAST-DRI aimed to measure, analyze, understand, and parameterize air-sea fluxes in the hurricane environment. Credit: ONR.

3.5.5 Tropical Cyclone Field Experiments—Summary

Field experiments are essential elements to the overall tropical cyclone research program, helping to advance basic physical understanding and improve forecasts of tropical cyclones and other tropical meteorological systems. The experiments described above, along with others not highlighted here, have provided unique observational data sets to advance scientific understanding. ***Sufficient funding to sustain the analyses of the data sets from these experiments should be a priority.*** Equally important, research results from these experiments that are ready for transfer to operations require an efficient and clear process to achieve successful transition. Current approaches to the transition of research results to operations are described next.

3.6 Current Procedures for Transitioning Tropical Cyclone Research into Forecast and Warning Operations

3.6.1 The Challenge of Efficient and Productive Transition to Meet Operational Needs

A constant challenge facing the meteorological community is the efficient transfer of weather and climate research findings into improved operational forecast capabilities to meet the growing demand for accurate weather and climate predictions. An operational forecast system encompasses the collection and assembling of data and the use of such data in NWP models to produce forecast guidance in a timely fashion. Consequently, the system encompasses many elements, from the observational instruments to the computational resources required to create, display, and disseminate the forecast guidance. All elements of the system need to be enhanced, and both the private sector and the academic R&D communities contribute to that improvement. Nevertheless, moving a potentially valuable improvement from the R&D bench to the operations floor requires attention to, and planning for, the transition process.

Transferring research results and new technology into operations is not a trivial task (Knabb et al. 2005). The endeavor requires sufficient funding, facilities, and other resources, including systems and personnel to prepare, test, and evaluate new approaches. For projects targeted for operational implementation and long-term maintenance at a tropical cyclone forecast and warning center, complete tests must be performed in a quasi-operational environment of tools and techniques to evaluate the scientific performance, the ease-of-use, and production time, thereby simulating the time constraints experienced by operational forecasters. In some cases, new techniques require modification during the transition process to make them more forecaster-friendly and time-efficient.

A number of potential pitfalls may occur that hinder operational implementation of a new technique. Research results are often manifested as new software originally configured to run in an environment significantly different from that of an operational center. The techniques may also involve input data or supporting software that are not routinely available to the center. Forecasters and technical support staff may require extensive training, even after the R&D project formally ends, to use and maintain a new algorithm optimally. The testing and evaluation process must address all of these issues prior to the receiving center deciding to commit resources to operational implementation of a new technique.

Ideally, a sustained collaborative effort by operational, testbed, and research entities, beginning well before the arrival of the new product at its prospective operational home (e.g., a tropical cyclone forecast and warning center or an operational NWP modeling center), will ensure that all operational constraints and requirements can be met. In some cases, such as within NCEP/EMC, operational and research components are collocated; the essential coordinating and collaborative activities can thus occur "early and often" as a research project matures. In many cases, however, a key entity or principal investigator involved in the R&D project has a home base elsewhere than at the operational center. Or there may be multiple players with differing but essential roles to play in testing, evaluating, and adopting the research product. In such cases, formal procedures and supporting infrastructure, if well-designed to support the transition, can ease the process, avoid the pitfalls, and accelerate the operational implementation.

For tropical cyclone NWP modeling systems (similar to other functional areas of meteorology) there is a significant challenge to testing and implementing improvements because these systems support operations 24 hours a day, 7 days a week. With this operational mission, the system cannot be taken off line for testing and implementing improvements. ***Therefore, a parallel operational NWP research capability for testing and implementing changes to the operational NWP configuration is absolutely essential.***

Due to the large complexity of modern NWP forecast systems, diagnosing results requires extreme care and scientific discipline, and the ability to run adequate samples of cases (often several months of data assimilation). The control system is used not only to ensure that the changes improve the area targeted for improvement but also to verify that other aspects of the forecast system are not degraded due to the changes. ***To maximize improvements to the operational NWP model, it is also critically important to have a steady flow of relevant research focused on improvements to the operational NWP system (i.e., focused on the NWP research priorities outlined in chapter 5). The current infrastructure[4] at NRL/FNMOC and NCEP/EMC is inadequate to conduct extensive parallel testing.***

In the tropical cyclone R&D community, there are several processes currently used for transitioning promising research results into operations. The transition processes described here are the Joint Hurricane Testbed (JHT), the internal procedures used at the interface between the research and operational components of NWP modeling centers—specifically, the NRL–FNMOC interface and the interface between R&D and operations at NCEP/EMC—and the role of the JCSDA in transitioning new observing data into operational forecasting.

3.6.2 The Joint Hurricane Testbed

As noted in section 2.4.5, the mission of the JHT is the more rapid and smoother transfer of new technology, research results, and observational advances into improved tropical cyclone analysis and prediction at operational centers. The JHT Terms of Reference state that, "the JHT activities are divided into infrastructure actions and transition projects."[5] The infrastructure of the JHT includes the personnel and information technology (IT) resources that are necessary to select and conduct each JHT project (Knabb et al. 2005). Infrastructure actions include administration and system support. The JHT IT infrastructure, separate from but similar to an operational center's IT environment, is required for robust testing and evaluation of each technique without imposing unnecessary distractions, risk, and expense upon the operational center.

JHT Transfer Process

In a transition project, JHT facilitators serve as the interface between the researcher and the operational forecasters. A successful JHT transition can involve one or more of the following research products or techniques:

- A converted research code that, running with an operational data stream on forecast center computers and display systems, is effectively utilized by the operational forecasters to improve products and services
- A new observational system that has provided documented evidence of positive diagnostic or forecast impact
- A weather prediction product leading to better tropical cyclone forecasts

Final testing, validation, and acceptance of a transferred product is the responsibility of, and at the discretion of, the operational forecast center. Long-term maintenance of the new product after transfer is also the responsibility of the forecast center.

[4] Infrastructure is related to items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems.
[5] http://www.nhc.noaa.gov/jht/JHTTOR.13Sep2002.pdf.

The tropical cyclone forecast and warning centers, along with the supporting NWP modeling centers (NRL/FNMOC and NCEP/EMC), work closely with the JHT staff during the JHT process for selecting and conducting transfer projects. JHT projects proceed through a life cycle that includes identification via an announcement of opportunity, selection via a proposal review and grants award process, testing and evaluation at the operational center(s), and decisions for operational implementation by the operational center(s).

When a JHT project has concluded its test and evaluation phase, a final report is submitted to the director(s) of the tropical cyclone forecast and warning center(s) that participated (e.g., the TPC/NHC Director and/or the JTWC Commander). This report from the JHT staff is based on the staff's own evaluations and on input from the project's funded researcher(s) and operational center point(s) of contact. The operational center director/commander decides whether to implement the product/technique resulting from the project in center operations. These decisions are at the sole discretion of the operational center(s). The TPC/NHC Director's decisions, for example, are based on an analysis of the following four factors:

- Forecast or analysis benefit: expected improvement in operational forecast and/or analysis accuracy
- Efficiency: adherence to forecaster time constraints and ease of use needs
- Compatibility: IT compatibility with operational hardware, software, data, and communications
- Sustainability: availability of resources to operate, upgrade, and/or provide support

JHT Transfer Projects since Inception

Under the auspices of the JHT, experimental analysis and forecasting tools and techniques that were developed by the research community have been tested and evaluated at the TPC/NHC in real time. The 2005 hurricane season was the fifth consecutive season of these TPC/NHC test and evaluation activities (Knabb et al. 2005; Landsea et al. 2006). Ten initial JHT projects concluded in 2003, and six of them have been implemented operationally. A second round of 15 JHT projects began in late 2003. Of these 15, 10 were accepted and implemented into operations, while four more are undergoing continued testing. In this second round of projects, approximately 36 percent of the FY 2003 funds were awarded to organizations outside the Federal government—primarily state and private universities but also including a small amount to private-sector companies. A third round of projects began in the summer of 2005, with testing and evaluation taking place during the 2005–2006 hurricane seasons. The funding available for JHT-sponsored projects was approximately $1.5 million for the round that began in 2003 and $1.2 million for the projects that began in 2005. For FY 2006, 45 percent of the funds were awarded to groups outside the Federal government.

For additional information on the JHT, see its website at http://www.nhc.noaa.gov/jht/.

3.6.3 Transitioning ONR Research to Operations

The mission of ONR is to foster, plan, facilitate, and *transition scientific research* in recognition of its paramount importance to enable future naval power and the preservation of national security. The research supported by ONR falls into two categories:

- 6.1 Basic Research. This research involves innovation and discovery and provides fundamental building blocks to more applied research. It is mission oriented but not necessarily requirements-driven, and it may or may not lead to applications, foreseen or unforeseen, during a time horizon of ten or more years.
- 6.2 Applied Research. This research transitions 6.1 science into practical areas of high relevance to the Navy. It provide proof of concept and develops new applications. ONR supports applied research through external grants to the research community at large and through program alignment with NRL.

NRL conducts a broad program of scientific research, technology, and advanced development, primarily in 6.2 areas, in response to identified Navy needs that should be met in less time than can be anticipated for 6.1 basic research. Collectively, ONR and NRL balance long-term opportunities and short-term demands—both S&T "push" and requirements "pull." In general, 6.2 applied research projects require alignment with prospective sponsors and their customer base to carry the effort forward toward operational implementation. Therefore, the integration of 6.2 research with further development and transition occurs in a highly focused manner, illustrated by figure 3-19.[6] A key activity in weighing requirements and setting priorities is conducted under the Commander, Naval Oceanographic and Meteorological Command (CNMOC) by the Administrative Model Oversight Panel (AMOP). Overall, the process from 6.2 to operations can take as long as 10 years ("TRL" in figure 3-19). For shorter projects to meet high-priority needs, a Rapid Transition Project (RTP) designation may be applied. The RTP initiatives provide flexibility to meet new or changing requirements, They are an efficient means to exploit emergent, enabling S&T to support specific operational priorities.

The primary customers for ONR/NRL research that deals primarily with meteorological/ oceanographic data assimilation, NWP model systems and products, or Earth system–observing satellite products are FNMOC and other operational Navy centers that are tasked by CNMOC. Additional customers include the Defense Threat Reduction Agency, U.S. Strategic Command, Air Force Technical Applications Center, and Lawrence Livermore National Laboratory's National Atmospheric Release Advisory Center (NARAC). NARAC provides a national emergency response service for real-time assessment of hazardous incidents involving intentional or accidental release of nuclear, chemical, biological, or natural material. Most of these customers have the capability to receive global boundary conditions for their in-house modeling operations from the NOGAPS model runs performed at FNMOC.

3.6.4 The Transition Process at NCEP/EMC

The transition process at NCEP/EMC (figure 3-20) is guided by user requirements and includes processes that range from developing codes and algorithms to testing and implementation. As

[6] Note: 6.3 research, which is not shown in the figure, refers to Advance Technology Development (i.e., "gizmos and gadgets," generally not relevant in the current context).

Phase / Item	Applied Research /Technology Development	Demonstration/ Validation (DEM/VAL)	Operational Implementation	Operations
Resource Sponsor (Funding Category)	ONR (6.2 RDT&E)	CNO (N096) or Other Agent (6.4 RDT&E)	CNO (N096) or Other Agent (6.4 RDT&E and CNMOC O&M,N)	CNO (N096) or Other Agent (CNMOC O&M,N)
	Rapid Transition Process			
Objective	• Initial Development Through Proof-Of-Concept • Completion of Development	• Technical Validation • Demonstration (Incl "Simulated" Implementation)	• Full Integration • OPEVAL – OPCHECK – OPTEST	• Operation & Maintenance • Life-Cycle Support
			Technical Support & "Warranty" Service	
Deliverables	• Journal, Publication or Technical Report	• Source Code • Model Transition Plan • Validation Test Report • Preliminary DOD-STD Documentation	• Final DOD-STD Documentation • OPTEST Report	• Upgrades and Fixes
TRL	2-3	4-6	7-9	10
		Administrative Model Oversight Panel		
Participants	• ONR PIs • NRL Developer • Non-Navy S&T	• NRL Developer • Tech Validation Panel	• Implementation Panel (IP)	• NAVO/FNMOC/ Configuration Control Boards
	Transition I	Transition II	Transition III	

Figure 3-19. The U.S Navy/ONR process used to transition research to operations. CNMOC = Commander, Naval Oceanographic and Meteorological Command; CNO = Chief of Naval Operations; MOC = Fleet Numerical Meteorology and Oceanography Center; N096 = Oceanographer of the Navy; NAVO = Naval Oceanographic Office; O&M = operation and maintenance, RDT&E = research, development, testing, and evaluation.

figure 3-20 shows, once a project has been selected for implementation consideration, the level of effort shifts from research entities (e.g., NOAA/GFDL or other agency and academic partners in the research community) to personnel at EMC. During the transition process, if the project successfully passes Level I and II preliminary testing, the level of effort at NCEP Central Operations (NCO) begins a more marked increase. NCEP/EMC and NCO, along with the service center (e.g., TPC/NHC, JTWC) play integral roles in successfully transitioning a research project to operations.

3.6.5 JCSDA: Transitioning New Data Assimilation Systems into Operations

Section 2.4.6 introduced the role of the JCSDA in the tropical cyclone R&D community. Developing and transitioning data assimilation capability for new observing instruments into operational forecasting and warning is central to the JCSDA's mission:

> *The goal of the JCSDA is to accelerate the use of observations from Earth-orbiting satellites in operational numerical analysis and prediction models for the purpose of improving weather forecasts, improving seasonal to interannual climate forecasts, and increasing the accuracy of climate data sets….*
>
> *A key performance measure for the JCSDA will be a decrease in the time required to develop and transfer assimilation systems to NOAA, NASA, and the DOD for operational use, for each new instrument.*
>
> (Le Marshall et al. 2006)

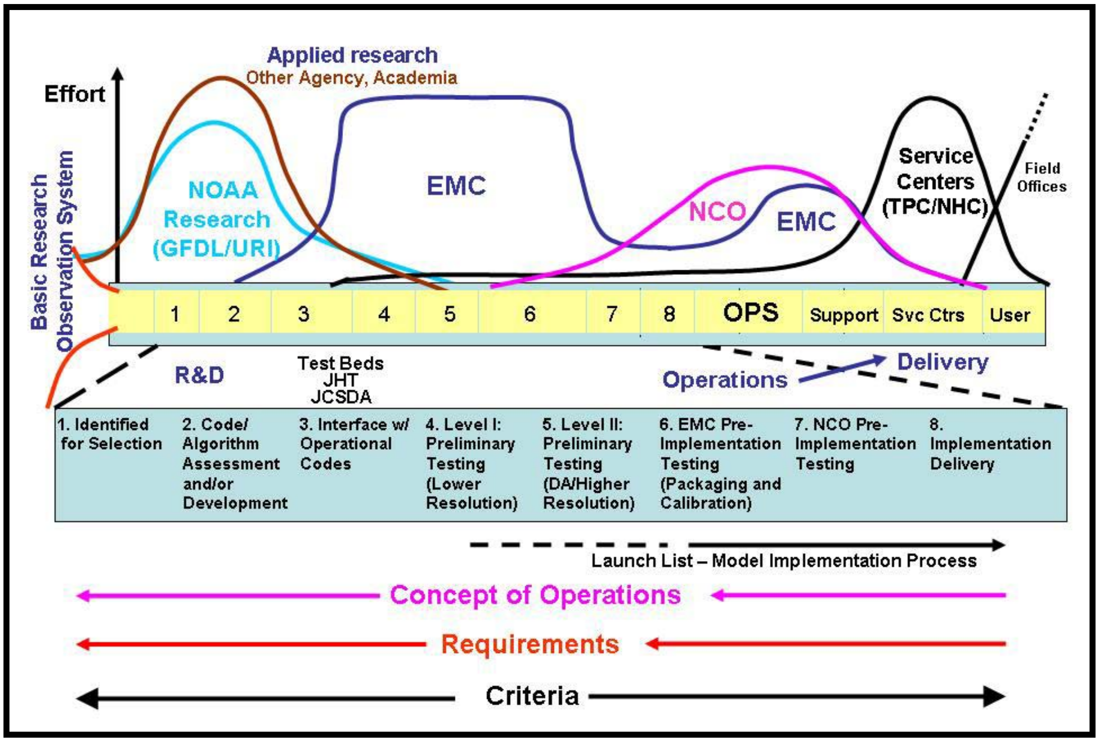


Figure 3-20. NCEP's role in transitioning research in models to operations through EMC processes.

The JCSDA is taking a life-cycle approach to data assimilation projects. This approach requires three critical elements for each data assimilation project undertaken by the center:

1. An end-to-end development, test, and evaluation process that begins with instrument definition and characterization of the instrument's in-flight performance, then moves to developing data assimilation algorithms, testing forward models, testing the impact of synthetic data, and—when the instrument is in flight and transmitting data—integrating the new data stream into operational systems and evaluating the data's impact on analyses and forecasts
2. Scientific review of each project by JCSDA personnel and by the JCSDA Science Steering Committee to evaluate whether a new system ins ready for implementation in operations
3. A transition-to-operations plan to ensure that the transition is completed smoothly

An early success from the JCSDA was a series of forecast tests for the radiance data, which profile atmospheric temperature and moisture, from the AIRS instrument on NASA's Aqua satellite.

Many more projects for transitioning new satellite data streams into operations are underway and planned at the JCSDA. Some of the larger programmatic plans are described in section 4.5.1

3.7 Education, Training, and Outreach

NOAA/NWS participates in numerous meetings and workshops with private sector participants, the university and research communities, the general user community, and the public. Examples include the twice yearly meetings of the NWS Family of Services and Partners; the annual meeting of the Cooperative Opportunity for NCEP Data Using IDD Technology (CONDUIT) User Group; and the American Meteorological Society's annual meeting. On the DOD side, ONR and NRL-Monterey participate in numerous formal and informal professional meetings and workshops, nationally and internationally, to keep abreast of the latest S&T developments and to identify niche areas where investments are necessary to fill gaps between DOD/Navy needs or requirements and the current/prospective external research efforts.

An important tropical cyclone outreach and education effort is National Hurricane Awareness Week. Every year in late May, the President of the United States issues a proclamation that designates National Hurricane Awareness Week. He calls upon government agencies, private organizations, schools, media, and residents in the coastal areas of our Nation to share information about hurricane preparedness and response to help save lives and protect communities. During National Hurricane Awareness Week, private organizations, public officials, and government agencies highlight the preparations necessary for the annual hurricane season, which begins on June 1.

3.7.1 Education, Training, and Outreach Efforts of NOAA/NWS, FEMA, and Other Civilian Agencies

In addition to the meetings and workshops listed above, NOAA/NWS also conducts meetings with emergency management organizations at the local, state, and national levels. These meetings may include participants from local media, support organizations, special user groups, and/or the general public. Exchanges at these events have led to improvements in NWS products and services, including improvements to the content of the NWS Internet website: http://www.nws.noaa.gov/. The sections that follow provide additional information on mechanisms for tropical cyclone education, training, and outreach, including examples of various methods for disseminating critical tropical cyclone information.

Hurricane Awareness Tours

Each year the TPC/NHC conducts tours pursuant to the National Hurricane Operations Plan (NHOP). The NHOP outlines an annual requirement to meet jointly with civic leaders, meteorological service representatives, disaster preparedness agencies, and air traffic control managers of countries in Regional Association IV of the WMO. Hurricane specialists work with local officials and the media to raise awareness of the threat posed by hurricanes in the region. Through these tours, NOAA increases awareness of the tropical cyclone threat for populations in these vulnerable communities. Injuries and loss of life both during and after a hurricane can be prevented through education and public awareness.

On March 13-18, 2006, the TPC/NHC conducted its annual Caribbean Hurricane Awareness Tour (CHAT) using U.S. Air Force Reserve Command WC-130J aircraft of the 53rd Weather Reconnaissance Squadron. Countries visited to enhance public education and outreach included

Mexico, Nicaragua, Curacao, Grenada, and Puerto Rico. The team also discusses lessons learned from the previous Atlantic hurricane season with Caribbean meteorological and emergency management officials and the public. The TPC/NHC also conducts a Hurricane Awareness Tour (HAT) each year, which alternates between the East Coast and the Gulf Coast regions of the United States. The most recent HAT concluded on May 5, 2006, in Tampa Bay, Florida.

Hurricane Liaison Team

The Hurricane Liaison Team (HLT), which is a joint activity of FEMA in DHS and NOAA, consists of Federal, state, and local emergency managers with extensive hurricane operational experience. The director of the TPC/NHC can request that the HLT be activated whenever tropical storms threaten. The HLT then deploys to the TPC/NHC. Once there, team members function as a coordination bridge among scientists, meteorologists, and the emergency managers who respond if the storm threatens the United States or its territories.

Team members provide immediate and critical storm information to government agency decisionmakers at all levels to help them prepare for their response operations, which may include evacuations, sheltering, and mobilizing equipment. State and/or local officials, not the HLT, make decisions concerning evacuations.

The HLT concept originated because of the volume of storms in the active 1995 hurricane season and the increase in requests by state and local governments for timely information from the TPC/NHC. The team's creation evolved from the need for the emergency management community to be kept updated on the growth and movements of storms and because of the increasing population of the nation's coastal areas.

Other TPC/NHC Activities

The TPC/NHC conducts a practical program of education and outreach on hazardous tropical weather for the public, emergency managers, WMO personnel, educators, students, scientists, businesses, and government agencies. Increased awareness of hazardous tropical weather and its potential impacts is vital to the public and to emergency managers charged with safeguarding lives and property. The TPC/NHC fulfills this responsibility through direct contact with these groups, formal and informal training, increased availability of products and data, dissemination of scientific and other publications, and gathering feedback to adapt more effectively to evolving needs. Three one-week courses for county/state emergency managers, titled "Introduction to Hurricane Preparedness," are sponsored by NOAA and FEMA and taught at the TPC/NHC by NHC forecasters. A two-week WMO class (WMO RA-IV) is taught for Caribbean forecasters. Workshops are offered at the National Hurricane Conference, the Florida Governor's Conference, and other events focused on emergency management and the media.

A media pool is activated at the TPC/NHC when a hurricane watch is issued for the United States, with round-the-clock television briefings. During 2004 and again in 2005, the TPC/NHC Director and Deputy Director together provided about 1,000 live television interviews each year. Other TPC/NHC staff handled hundreds more telephone interviews with media during landfalling hurricane threats.

The TPC/NHC produces Tropical Cyclone Reports (formerly known as Preliminary Reports) that contain comprehensive information on each tropical cyclone it has followed during a season, including synoptic history, meteorological statistics, casualties and damages, and the post-analysis best track (six-hourly positions and intensities). Tropical cyclones covered in this series include depressions, storms and hurricanes. The reports are available on the TPC/NHC website, http://www.nhc.noaa.gov. The TPC/NHC also provides articles describing and summarizing post-season information about hurricanes and other tropical systems of interest. These are usually available through newspapers, magazines and/or on various websites.

NWS WFO Warning Coordination Meteorologist

At NWS WFOs, a Warning Coordination Meteorologist interacts with NWS partners and customers. This coordination and collaboration includes input on requirements, especially service delivery requirements, and on innovative ways to use information technology. Similar staff fill this role at NWS River Forecast Centers and Center Weather Service Units.

World Wide Web

There are many Internet websites that are critical for education, training, and outreach, as well as for disseminating actual tropical cyclone products. Table 3-8 provides a snapshot of these websites.

Newspapers and Magazines

Newspapers and magazines, many of which are now available online, effectively disseminate routine weather forecasts and provide educational information. However, newspapers and magazines are less useful for short-lived, fast-breaking weather events such as tornadoes or severe thunderstorms.

Newspapers show a major interest in weather information, and some weather pages display considerable innovation in design, use of color, and other techniques to attract readers' attention and communicate useful detail to a nonspecialist audience. NOAA/NWS produces some ready-to-print weather pages, but many newspapers rely on private weather companies for custom-designed weather information packages.

A good example of valuable information on hurricane preparedness, shown in appendix H, is an article published in *NOAA Magazine* (Bedford 2006). *NOAA Magazine* provides an in-depth look at the stories behind NOAA news headlines. Since its debut in November 2001, *NOAA Magazine* has featured more than 200 articles and now averages nearly 230,000 hits per month. With the media and the general public as its primary target audience, it has earned a reputation as a valuable resource for anyone who wants to "get to know NOAA." *NOAA Magazine* articles are always available online and are distributed electronically to all the major national media (broadcast and print) outlets.

Table 3-8. Snapshot of Hurricane-Related Internet Sites

Agency/Organization	Topic/Focus	Web Site URL
TPC/NHC	Self Explanatory	http://www.nhc.noaa.gov
JTWC	Self Explanatory	http://www.npmoc.navy.mil/jtwc.html
CPHC	Self Explanatory	http://www.prh.noaa.gov/hnl/cphc
DHS/FEMA	Hurricane Disaster Information	http://www.fema.gov/hazard/hurricane/index.sht
DHS/FEMA	FEMA's National Hurricane Program	http://www.fema.gov/plan/prevent/nhp/index.shtm
DHS/FEMA, NOAA	Hurricane Preparedness And National Hurricane Preparedness Week	http://www.nhc.noaa.gov/HAW2/english/intro.shtml
NASA	NASA Hurricane Web Site	http://www.nasa.gov/mission_pages/hurricanes/main/index.html
NOAA	General Hurricane Information	http://hurricanes.noaa.gov
NOAA/NWS Office of Climate, Water, and Weather Services	Tropical Atlantic Weather Briefing	http://nwshqgis.nws.noaa.gov/tropical/atlantic
NOAA's NWS Office of Climate, Water, and Weather Services	Tropical Pacific Weather Briefing	http://nwshqgis.nws.noaa.gov/tropical/pacific
NOAA/OAR/AOML/HRD	HRD Home Page	http://www.aoml.noaa.gov/hrd/index.html
NOAA/OAR/AOML/HRD	HRD Frequently Asked Questions	http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html
Environmental Literacy Council—Hurricanes	General Hurricane Information, Including "Recommended Resources," "Data and Maps," and a section "For the Classroom"	http://www.enviroliteracy.org/article.php/258.html
NWS WFOs	Tailored Information Applicable for the Local Area and the Customers that Each Unit Supports	Numerous sites.
Military Weather Units	Tailored Information Applicable for the Local Area and the Customers that Each Unit Supports	Numerous sites.

An example of educating the general public on the challenges of tropical cyclone forecasting and the need for tropical cyclone research is an article that appeared in *The Washington Post* recently (Kaufman 2006). Summarizing the perplexing nature of tropical cyclone genesis, the article's author wrote, "Although many hurricanes that reach the United States are born as tropical depressions in the waters off Africa, little is known about why some dissipate and others become monster hurricanes on the other side of the ocean."

Bulletins and Newsletters

More targeted forms of print media, such as bulletins and newsletters, provide non–real-time information about tropical cyclones such as weather summaries, rainfall amounts and distribution, temperature values, and hydrological and agro-meteorological data. The design and printing of each issue may be done in-house for daily or weekly publications in this category. For publications with longer periods between issues, sponsorship may be required to cover overall costs.

Radio

Radio continues to be one of the most common and important means of disseminating weather information. In the aftermath of severe weather disasters, including landfalling hurricanes, radio is frequently the *only* effectively functioning mass medium. Many radio stations include weather forecasts in their news programs; some even schedule comprehensive, complete weather segments.

NOAA/NWS operates a weather warning and information system that provides a 24-hour continuous radio broadcast on special VHF frequencies. Known as NOAA Weather Radio (NWR), this system broadcasts NWS weather warnings, watches, and forecasts 24 hours a day. In addition, NWR broadcasts warnings and post-event information for other environmental hazards including those from natural events (e.g., earthquakes, forest fires, and volcanic activity), industrial incidents (e.g., chemical releases, oil spills, nuclear power plant emergencies), and national emergencies (e.g., terrorist attacks). Through its coordination with other Federal agencies and the Federal Communications Commission's Emergency Alert System (EAS), NWR provides an all-hazards radio network, making it the most comprehensive weather and emergency information available to the public.

During an emergency, NWS forecasters interrupt routine broadcasts and broadcast a special signal, which activates local weather radios. Weather radios equipped with a special feature to react to this signal will turn on with an alarm tone to alert listeners within range, then give information about an imminent life-threatening situation. Many of the weather-related emergency messages communicated via NWR are also broadcast via the EAS. The goal of the NWS and other emergency preparedness agencies is to expand the reach of these weather radio broadcasts to cover 95 percent of the U.S. population. Innovative partnerships between the NWS, private sector organizations, and state and local governments are key to accomplishing this expansion.

Television

Television is very popular as a dissemination medium for public weather products because of its extensive graphics capabilities, powerful visual impact, and ability to allow viewers to assess the severity of an impending event for themselves. Many television stations carry weather forecasts and related information as part of their news programs, and some have meteorologists doing regularly scheduled weathercasts. Several 24-hour weather channels are quite successful and attract large viewing audiences.

Television broadcasts provide a useful service to vacationers, travelers, and even local populations because they are widely available in hotels and on cable television channels. The use of television crawlers across the top or bottom of the screen is an effective way of capturing viewer attention regarding severe weather information, without interrupting the regular program. Through these "live updates," information about significant weather such as the hazards associated with tropical cyclones can be provided with increased frequency as a storm system approaches or threatens the broadcast area served by the station.

National Law Enforcement Telecommunications System

NOAA has worked with the National Law Enforcement Telecommunications System (NLETS), an interstate law enforcement network, to establish a new two-way communication link with the NOAA Weather Wire Service. A satellite collection and dissemination system that provides timely delivery of NWS weather information products can increase public safety through improved dissemination of weather forecasts and warnings. This link will provide NOAA's life-saving forecasts and warnings directly to first responders, public safety officials, and others who rely on this information to perform their critical task of protecting life and property. Efficient exchange of information between NWS forecasters and law enforcement agencies via NLETS provides another avenue to reach the public with important weather warnings when seconds could mean the difference between life and death.

NLETS consists of more than 400,000 workstations across the United States that will allow users to receive weather information from the NWS and enable them to relay real-time weather information directly to NWS meteorologists. For example, a state trooper could report roads flooded by a rain-swollen river directly to a NWS meteorologist, who would then issue flood alerts based on that information in conjunction with radar data and other observing tools. This dedicated circuit between the NLETS organization and the NWS, via the weather wire, facilitates a much easier exchange of information.

Arizona, Iowa, Maryland, and Oklahoma are participating in the initial evaluation of NLETS. National implementation was originally slated for mid-2005.

3.7.2 Education, Training, and Outreach Efforts of ONR, NRL, and the JTWC

JTWC Annual Tour and Center Visits

The JTWC conducts an annual tour of the military installations within the western North Pacific theater of operations. This tour includes training on the JTWC’s products and timelines and on tropical meteorology. Given the high annual personnel turnover at many of the installations on the tour, this annual training exercise is essential to the success of the JTWC mission. Operational commanders are briefed on the previous tropical cyclone season and on the plans and projections for the upcoming season. Military weather and oceanographic personnel are trained in tropical meteorology and the use of JTWC products.

In addition to the annual tour, the JTWC hosts visitors from all services at its Hawaii operations headquarters. It provides watch-floor tours and orientation for senior officials who transit Hawaii.

Internet-Accessed Education, Training, and Outreach

In addition to the Internet websites cited in table 3-8 above, several ONR or NRL-sponsored websites serve as primary mechanisms for outreach from ONR/NRL to the community. The content of these websites ranges from general information for the pubic at large, though lesson plans for primary and secondary school teachers, to S&T programs and professional-level interactions including research opportunities. The programs and opportunities encompass all

S&T disciplines of Navy interest and relevance, including tropical cyclone R&D. Some highlights are described below. The general websites for ONR and NRL are, respectively, http://www.onr.navy.mil and http://www.nrl.navy.mil/.

Multidisciplinary Research Program of the University Research Initiative
(http://www.onr.navy.mil/sci_tech/3t/corporate/muri.asp)

The Multidisciplinary Research Program of the University Research Initiative (MURI) is a multi-agency DOD program that supports research teams whose efforts intersect more than one traditional science and engineering discipline. Multidisciplinary team effort can accelerate research progress in areas particularly suited to this approach. Multidisciplinary research also can hasten the transition of research findings to practical application.

Programs for Small Business Research and Technology Transfer
(http://www.navysbir.com/overview.htm)

The purpose of the Small Business Innovation Research (SBIR) program is to strengthen the role of innovative small business concerns in Federally-funded research or R&D. Specific program objectives are to: (1) stimulate technological innovation; (2) use small business to meet Federal R/R&D needs; (3) foster and encourage participation by socially and economically disadvantaged small business concerns in working in technological innovation; and (4) increase private sector commercialization of innovations derived from Federal research and R&D, thereby increasing competition, productivity, and economic growth. Like other SBIR programs in Federal agencies, the Navy programs work through competitive award of grants to qualifying small businesses.

The Small Business Technology Transfer (STTR) program is a sister program to SBIR. A major difference in the two programs is that the STTR requires the small business to have a research partner consisting of a university, Federally funded research and development center, or qualified nonprofit research institution. To be eligible for an STTR grant, the small business must be the prime contractor and perform at least 40 percent of the work, with the research partner performing at least 30 percent of the work. The balance can be performed by either party or a third party.

Young Investigator Program
(http://www.onr.navy.mil/sci_tech/3t/corporate/yip.asp)

Under the Young Investigator Program (YIP), awards are made to outstanding new faculty members at institutions of higher education, to support their research and encourage their teaching and research careers. To be eligible, candidates must hold a tenure track or permanent faculty position at a U.S. institution of higher education and must have received a graduate degree (Ph.D. or equivalent) within the past five years. Award amounts are up to $100,000 per year for three years, with the possibility of additional support for capital equipment or collaborative research with a Navy laboratory, based on research proposals and supporting materials. Special attention is given to proposals in naval priority research areas.

Postdoctoral Fellowship Program
(http://www.onr.navy.mil/sci_tech/3t/corporate/postfe.asp)

The Navy, through the NRL, sponsors a Postdoctoral Fellowship Program at NRL and a number of Naval R&D centers and laboratories. The objective of this program is to encourage the involvement of creative, capable, and highly trained scientists and engineers who have received a Ph.D. or equivalent within the prior seven years in research areas of interest and relevance to the Navy.

Regional, District, and State Science and Engineering Fairs for High School Students
(http://www.onr.navy.mil/sci_tech/3t/corporate/hsawards.asp)

The Navy and Marine Corps participate each year in more than 425 regional, district, and state science and engineering fairs in which high school students exhibit their projects. Qualified experts drawn from local Navy and Marine Corps activities serve as judges and provide prizes to successful competitors

ONR Science and Technology Focus Site for Students and Teachers
(http://www.onr.navy.mil/focus/teachers)

Teachers can use this site for lesson planning, fact-checking, explaining difficult concepts, or linking to other resources. It provides links to educational resources such as lesson plans, activities, and teacher-training opportunities. The goal is to provide a reliable source of basic scientific information, as well as information on some current research.

NRL Collaborations
(http://www.nrlmry.navy.mil/collab.htm)

The NRL places a high value on external collaboration of differing sorts, which are identified and described at this website.

Media Center
(http://www.onr.navy.mil/media/)

The media center provides the latest news releases. It also has links to an image gallery and fact sheets.

3.7.3 Education, Training, and Outreach: Continued Efforts Needed

As described in sections 3.7.1 and 3.7.2, education, training, and outreach are integral parts of tropical cyclone information, alert, and warning services to the public and private sectors. Products and services need to be provided in formats that facilitate understanding and prompt responses that enhance safety of life and protect resources to the maximum degree possible. This process is a two-way street; it requires interaction with, and feedback from, everyone who is vulnerable to tropical cyclones or involved with informing/advising others about the dangers of these storms.

One of the continuing challenges is the education and training of the public to appreciate in a practical way the science (and especially the uncertainties) involved with tropical cyclone prediction and the impacts these storms can bring to communities. Hurricane Katrina is still a vivid reminder of the potential physical destruction that tropical cyclones can cause. "Similar to the images of grief and destruction on September 11, 2001, the images of suffering and despair from Hurricane Katrina are forever seared into the hearts and memories of all Americans."[7] But will people respond appropriately for the next major landfalling hurricane, a response needed to enhance safety of life and maximize the protection of resources? We can expect appropriate responses only when people justifiably trust tropical cyclone forecasts. That trust, in turn, largely depends on advances toward maximizing skill and minimizing the uncertainties in prediction of all tropical cyclone–related impacts on lives and property.

The importance of education, training, and outreach cannot be overemphasized. In all cases of potential disasters, including hurricane-related events, partnerships with industry and academia, participation in various science and education fora, and use of various forms of mass media (e.g. magazines, films, newspapers, radio, television, internet, books, CDs, DVDs, videocassettes) help scientists, stakeholders, and the public communicate and understand: (1) mutual challenges, (2) the evolving use of technology to address shortfalls and deficiencies in tropical cyclone prediction, and (3) the various delivery mechanisms of warnings to aid evacuation decisions. ***The agencies and organizations—public and private—involved with education, training, and outreach concerning the public's knowledge and appreciation of tropical cyclone impacts and the appropriate public responses to reduce those risks must never assume their task is done. These efforts must continue, and they must be accorded the priority they deserve.***

The above discussion may seem obvious, but the task is not trivial. The Board on Atmospheric Sciences and Climate (BASC) of the National Research Council considered the issue of severe weather warnings in a broader context (i.e., not just in the case of tropical cyclones) and concluded:

> There is an increasing gulf between the understanding of science within the scientific community and the comprehension of science in the outside world. Media organizations are more interested in hyping speculative advances in science than they are in getting it right. Current public education facilities for middle school students teach mostly rote science and almost never provide studies in critical thinking that are designed to engage the students in a way that will generate a real understanding of the scientific method—what science is and how it is accomplished.[8]

The BASC members suggested the following approach:

> Goals for education and training would follow from a new vision for atmospheric sciences and climate, for both research and operations. The vision will determine the priorities to follow (prioritization of the human resource needs to address the goals related to the vision). Education and training involves a long "pipeline" (formal education), shorter paths (retraining), and end training (e.g., meteorological system engineers). There is a need to identify who is responsible (one of the questions). This issue requires the consideration of political relevancy/will and finding the political venue to sponsor this. Education and training involves not only technical issues but

[7] The White House, 2006: *The Federal Response to Hurricane Katrina: Lessons Learned*, www.whitehouse.gov/reports/katrina-lessons-learned/, chapter 1, pg. 9.
[8] Draft output from the BASC Strategic Planning Retreat, Woods Hole, MA, 2006.

also should include methodologies of science, professional ethics, collaboration/partnerships (team skills), and data analysis/synthesis.

An area of extreme importance for improving tropical cyclone forecasts is advancing data assimilation and tropical cyclone NWP modeling systems. An important example of a deficiency in workforce development is that the United States is not producing enough new personnel with the education and training required for improving tropical cyclone forecasts via advanced data assimilation and numerical modeling systems.[9] Resolving this deficiency in human resources will require strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities.

Some Key Issues and Questions:

- Do we have the proper support, methods, and staff in place to educate and train an adequate number of new people in the field of data assimilation and NWP modeling?
- Do some practitioners enter the atmospheric sciences from other fields without adequate understanding of the application of the scientific method in the environmental sciences?
- How to communicate with the public in ways that recognize the limitations in the scientific literacy of the public?
- How can we advance the scientific literacy of the public and also motivate potential students to participate in fields of study critical to the atmospheric sciences?
- How can the atmospheric science community confirm that the general public understands what is communicated to them? Are oversight or verification functions needed to provide an objective basis for considering communications successful?

3.8 Summary

This chapter highlighted the current capabilities and limitations of the Nation's tropical cyclone forecast and warning system. Improvements in the system over the last several years, illustrated in this chapter, have resulted primarily from improved observations, development of sophisticated data assimilation techniques, major advances in global and regional operational NWP modeling systems, and investment in supercomputing at operational NWP centers.

The operational needs of the tropical cyclone forecast and warning centers are presented in section 4.1 of chapter 4. The remainder of chapter 4 summarizes future capabilities to meet those needs. The research priorities to further enhance the future capabilities are highlighted in chapter 5.

[9] An OFCM-led data assimilation (DA) survey, endorsed by the Federal Committee for Meteorological Services and Supporting Research (FCMSSR), validated that there is a deficiency within this Nation in producing enough personnel who are qualified with the requisite NWP modeling education and training.

4
FUTURE CAPABILITIES TO MEET OPERATIONAL NEEDS

Chapter 3 summarized the current capabilities of the Nation's tropical cyclone forecast and warning system. These capabilities reflect the vast improvements in track forecasting and modest improvements in intensity forecasting over the past two decades. These improvements resulted primarily through major advances in observations, global and regional operational NWP modeling systems, development of sophisticated data assimilation techniques and improved representation of model physics, and through major investments in supercomputing at operational NWP centers. While global and regional-scale NWP models have proven highly successful at forecasting tropical cyclone tracks, coupled models with much higher resolution will be necessary to make further strides in forecasting tropical cyclone intensity, structure (wind radii), sea state and storm surge, and precipitation. Increased skill in forecasting intensity and structure, sea state and storm surge, and precipitation is now on the horizon, much as improving track forecast skill was two decades or so ago.

To continue to advance operational tropical cyclone forecasting capability, the Nation must be committed to supporting—through research, development, and transition to operations—the following key areas vital to the tropical cyclone forecast and warning program:

- Advanced observations
- Advanced data assimilation technologies
- Advanced NWP models
- Investment in human and infrastructure[1] resources

Continued exploitation of observations via advanced data assimilation systems and improved NWP models will enhance the forecast guidance provided to forecasters on tropical cyclone track, intensity, structure (wind radii), sea state and storm surge, and precipitation. Viable processes and sufficient funding are integral to this effort to transfer new technology and research results into improved operational analysis and prediction at the tropical cyclone forecast and warning centers. Only a community-wide effort can meet the operational needs of the tropical cyclone forecast and warning centers, introduced previously in this plan and summarized in the next section.

Following a review of the operational needs of the tropical cyclone forecast and warning centers, this chapter summarizes current and planned activities regarding data collection (observations), advanced NWP modeling systems, and data assimilation technologies. It concludes with a discussion on transitioning research results to operational capabilities.

[1] Infrastructure resources are related to items such as computational power, network bandwidth, architectural/ engineering requirements, and maintenance of applicable systems.

4.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers

As explained in section 2.8.1, a list of operational needs of the three U.S. tropical forecast and warning centers was validated at the 59th Interdepartmental Hurricane Conference (IHC) in March 2005 and updated in a NOAA/OAR Announcement of Federal Funding Opportunity (AFFO) in June 2006. Table 4-1 lists these operational needs, in the priority order given in the 2006 AFFO, along with related needs statements stressed by the DOD participants at the 59th IHC. This listing thus represents the best available compilation and prioritization of operational needs across the three U.S. centers: the TPC/NHC, JTWC, and CPHC.

The operational needs in table 4-1 can be characterized by seven tropical cyclone–related, day-to-day operational forecast and warning categories identified with the bullets below. This plan addresses all of these categories.

- Intensity
- Structure
- Track
- Sea state
- Storm surge
- Precipitation
- Observations

The June 2006 AFFO also noted four high-priority areas identified by the NCEP/EMC for advancing NWP modeling and forecasting capabilities. These research priorities, summarized below, have been included in the research priorities outlined in chapter 5.

- General model improvements to advance track and intensity forecasts
- Improved boundary layer representation for coupled air/sea/land models by, for example, exploiting results from field projects such as C-BLAST (for improved parameterization of surface fluxes in high-wind regimes, and effects of sea spray on transfer coefficients)
- Model validation techniques suitable for three-dimensional, high-resolution verification for all phases of the tropical cyclone life cycle
- Diagnostic techniques to further increase the utility of global models (e.g., NCEP, UKMO, NOGAPS) in forecasting tropical cyclone genesis

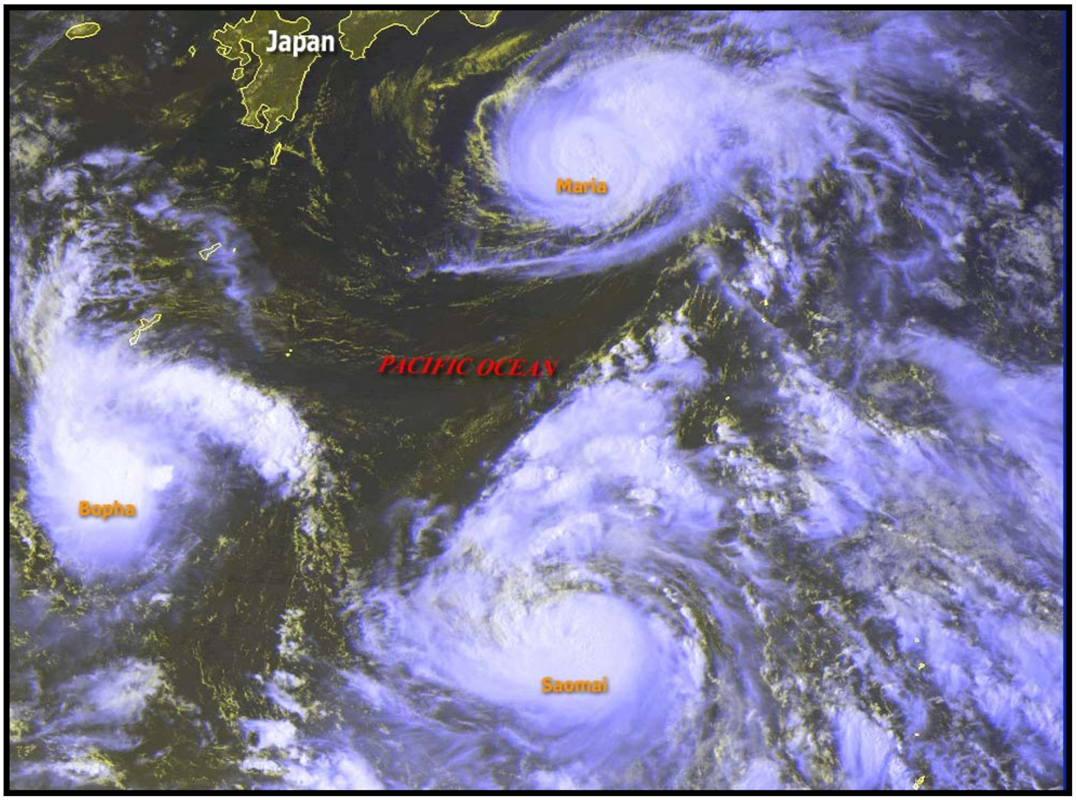
To meet the operational needs summarized in Table 4-1, focused efforts and sufficient investment in the four areas of advanced observations, advanced data assimilation technologies, advanced NWP models, and investment in human and infrastructure resources are critical to the future success of the Nation's tropical cyclone forecast and warning program.

Table 4-1. Operational Needs of the Tropical Cyclone Forecast and Warning Centers (TPC/NHC, JTWC, and CPHC)

Priority	Operational Need	Category[a]
1	Guidance for tropical cyclone intensity change, with highest priority on the onset, duration, and magnitude of rapid intensification events. Similar guidance is also needed on when rapid over-water weakening (such as had been observed in recent Gulf of Mexico hurricanes) will occur.	I
2	Improved observational systems in the storm and its environment that provide data for forecaster analysis and model initialization.	O
3	Statistically-based real-time guidance on guidance for track, intensity, and precipitation (e.g., multi-model consensus approaches), provided to forecasters in probabilistic and other formats.	I, T, P
4	Enhancements to the operational environment to increase forecaster efficiency, by expediting analysis, forecast, coordination, and/or communication activities.	A
5	Improved storm surge guidance models, including guidance on breaking waves and featuring high-resolution input and output (including probabilistic formats).	SG
6	Operational analysis of the surface wind field (including maximum sustained winds) in tropical cyclones. This also includes methods for forecasting the wind field over elevated terrain and high-rise buildings.	O, I, S, A
7	Guidance for changes in tropical cyclone size/wind structure and related parameters, including combined sea heights.	S, SS
8	Guidance for tropical cyclone precipitation amount and distribution.	P
9	Improved utility of microwave satellite and radar data in tropical cyclone analysis, particularly to determine structure and intensity.	O, I, S
10	Probabilistic forecast guidance for tropical cyclone surface wind speed.	I, S
11	Guidance for tropical cyclone genesis that exhibits a high probability of detection and a low false alarm rate, and/or provides probability of genesis.	I, S, T
12	Identification, and then reduction of, the occurrence of guidance and official track outliers, focusing on both large speed errors (e.g., accelerating recurvers and stalling storms) and large direction errors (e.g., loops), and on specific forecast problems, including interactions between upper-level troughs and tropical cyclones, track forecasts near mountainous areas, and extratropical transition.	T, I
13	Improved techniques for estimating the intensity of tropical cyclones passing over and north of sea-surface temperature gradients (e.g., in the eastern North Pacific Ocean and the Atlantic Gulf Stream).	I
14	Quantitative guidance tools for seasonal tropical cyclone forecasts for the Atlantic and North Pacific basins, using statistical and/or dynamical methodologies.	CL
DOD Priority[b]	**DOD Operational Need [b]**	
1	Improved track forecasts out to 5 days.	T
2	Improved structure forecasts: radius of 50-kt and 35-kt wind radii.	S
3	More accurate forecasts of wave heights and radius of 12-foot seas.	SS

[a] Category abbreviations: A = Automation; CL = Intraseasonal/Interannual Variability (Climate); I = Intensity; O = Observations; P = Precipitation; S = Structure; SG= Storm Surge; SS = Sea State; T = Track.

[b] As described in section 2.8.1, attendees at the 59th IHC validated the top 14 operational needs. The DOD emphasized its top three priorities, which are indicated at the bottom portion of the table. DOD's remaining needs were the same as the top portion of the table.



On August 7, 2006, there were three tropical systems in the Western Pacific Ocean: Typhoon Saomai, Tropical Storm Bopha, and Tropical Storm Maria. Typhoon Saomai later hit China as the strongest typhoon to make landfall there in 50 years (Fan 2006). Credit: NOAA

4.2 Data Collection: Plans for Observation Platforms and Instruments

Continuing to advance observational capabilities for tropical cyclone analysis and numerical weather prediction is a vital component of the Nation's tropical cyclone program. To help meet the operational needs identified in Table 4-1, there are many planned observation platforms and instruments to enhance observational capabilities critical to both tropical cyclone forecasters and tropical cyclone NWP systems. Some of the most promising platforms/instruments for both operational and research use are described in sections 4.2.1 through 4.2.12 below. With numerous new observational platforms and sensors potentially available in the next several years, a coordinated approach is needed to improving tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.).

There is a continuum from exploratory scientific research, conducted with new types and new generations of advanced instruments, to the proven operational systems relied upon for routine and severe-event analysis and forecasting. Over the past four decades and more, NASA research satellites and airborne observing systems flown by DOD and NOAA have made major contributions to the operational systems. This section emphasizes plans for future operational systems and instruments that could lead to operational systems—those which operational analysts, forecasters, and numerical modelers will use as part of the Nation's tropical cyclone forecast and warning system.

4.2.1 The GOES-N and GOES-R Series of Geostationary Satellites

On January 28, 1998, NOAA and NASA awarded a contract for the next generation of spacecraft for the Geostationary Operational Environmental Satellite (GOES) system (current GOES capability is discussed in section 3.1.2). GOES-N (figure 4-1), the first in this next generation of three GOES satellites, was launched in May 2006 and was renamed GOES-13 after reaching geostationary orbit and becoming an operational satellite. The GOES-N series of satellites will be followed by the GOES-R series, which is currently in the program definition and risk reduction phase. NASA's Goddard Space Flight Center is responsible for procuring, developing, and testing the spacecraft, instruments, and unique ground equipment for GOES spacecraft. NOAA is responsible for the overall program and its funding, for in-orbit system operation, and for determining GOES satellite replacement needs.

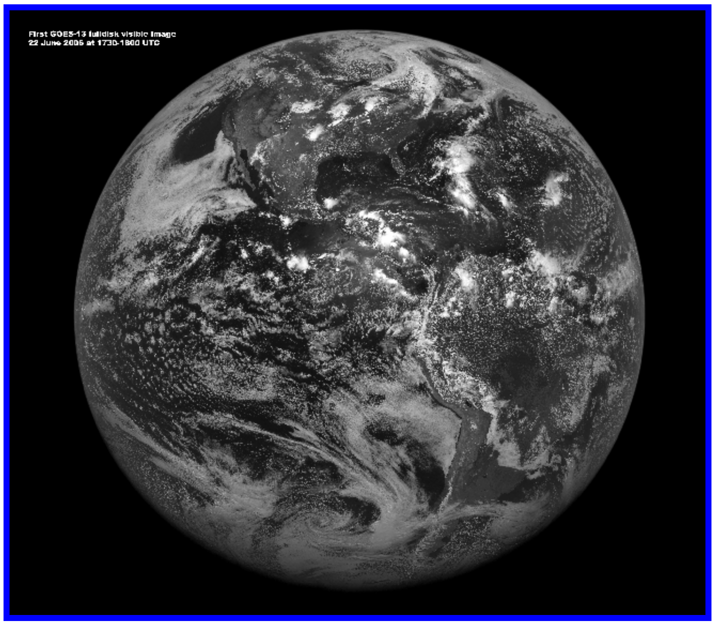


Figure 4-1. First GOES-13 full-disk visible image, June 22, 2006, 1730–1800 UTC. GOES-13 is the first of the GOES-N series of satellites. Credit: NOAA.

The instruments pertinent to tropical cyclone analysis and forecasting in the GOES-N series will continue to be an imager and a sounder. The imager is similar to the GOES-M imager, The GOES-N Sounder satisfies mission requirements for multispectral sensing in the visible and infrared regions. GOES-R will include an advanced imager with improved temporal, spatial, and spectral resolution, as well as a lightning mapper.

4.2.2 NPOESS and NPP

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) program converges the existing polar-orbiting systems of the DOC and the DOD. It is managed by a tri-agency integrated program office (the NPOESS IPO), which includes personnel from the DOC, the DOD, and NASA. Appendix I reviews the NPOESS sensors and data that are pertinent to tropical cyclone analysis and forecasting. In addition to the new sensors, a major advance with NPOESS is a reduction in the data latency, which will be about ½ hour compared with 2 to 3 hours for data from most of today’s polar orbiting satellites.

The NPOESS Preparatory Project (NPP) is an instrument risk-reduction project being conducted jointly by the NPOESS IPO and NASA. It is designed to bridge between the NASA Earth Observing System (EOS) program and NPOESS for developing the following sensors: Advanced Technology Microwave Sounder (ATMS), Cross-track Infrared Sounder (CrIS), Ozone Mapping and Profiler Suite (OMPS), and Visible/Infrared Imager Radiometer Suite (VIIRS). The NPP spacecraft is scheduled for launch in 2010. The launch of the first NPOESS satellite is tentatively scheduled for 2013.

Although profiling buoys provide information similar to that from satellite-based altimeters, the latter are essential for observing the ocean over large regions where in situ data are unavailable. As explained in section 3.1.3, measuring ocean heat content, not just sea surface temperature, is important for predicting the ocean's influence on tropical cyclone intensity, and sea surface altimetry data are essential for estimating ocean heat content. The NPOESS altimeter, which previously was part of the baseline instrument package, has been placed into a Deferred/Government Furnished Equipment category. The loss of this instrument without a suitable replacement will create a capability gap in determining the energy available in the oceans—a capability that is needed to help monitor and understand tropical cyclone intensity changes. **Since satellite altimetry is vital to addressing the needs of the tropical cyclone forecast and warning centers summarized in table 4-1, the JAG/TCR strongly endorses the acquisition of an altimeter instrument for NPOESS as an alternative to the cancelled NPOESS ALT instrument.**

The NPOESS Conical Microwave Imager/Sounder (CMIS) previously planned for NPOESS has been terminated. A new microwave imager/sounder will be competed and will be available on the NPOESS C2 spacecraft, which is tentatively scheduled for launch in 2016. The European MetOp-A spacecraft, which was successfully launched in October 2006, has an Advanced Scatterometer (ASCAT) instrument as one of its payloads (section 4.2.3). Therefore, until the new NPOESS microwave imager/sounder is available, the United States will need to increase its reliance on the MetOp ASCAT to obtain ocean wind vectors and will need to continue relying on DMSP sensors for ocean wind speed.

4.2.3 MetOp Satellites

MetOp-A, launched in October 2006 and renamed MetOp-2 when it became operational, is Europe's first operational polar-orbiting weather satellite. The MetOp program is a joint project of the European Space Agency (ESA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). ESA cofunds the MetOp satellites while EUMETSAT has overall system authority, develops the ground segment, cofunds the satellites, develops and procures the instruments, procures the launchers, and operates the end-to-end system. NOAA funds the U. S. instruments for MetOp. The present plan is to launch three MetOp satellites sequentially to maintain the service for at least 14 years.

MetOp-2 carries a set of seven "heritage" instruments provided by NOAA and the French Space Agency (Centre National d'Etudes Spatiales; CNES) and a new generation of five European instruments that provide improved sensing capabilities of value to both meteorologists and climatologists. The new instruments will augment the accuracy of temperature, humidity, wind speed, and wind direction measurements, especially over the ocean, and will provide a more accurate profile of ozone in the atmosphere. The MetOp sensors and data that are potentially pertinent to tropical cyclone analysis and forecasting are described in appendix J, which also links these instruments to the operational priorities and capability limitations in section 4.1.

4.2.4 Jason-2 and Oceansat 3 Satellites

Jason-2, a cooperative effort of CNES, EUMETSAT, NASA, and NOAA, will carry an instrument payload including the next generation of the Poseidon altimeter (Poseidon-3). One of its objectives is to provide a minimum of 3 years of measurement of global ocean surface topography. This mission, which will take over and continue the Topex/Poseidon and Jason-1 missions, is scheduled to launch in June 2008.

The CNES-built AltiKa altimeter, which will work in the Ka-band at 35 GHz on board the Indian Space Research Organization (ISRO) Oceansat 3 satellite, will complement the Jason-2 capability. Oceansat 3 is a cooperative effort of CNES and ISRO. It is planned to launch in the first half of 2009, with a design life of 3 years.

4.2.5 Global Precipitation Measurement Mission

The Global Precipitation Measurement (GPM) mission builds on the success of the Tropical Rainfall Measuring Mission (TRMM), a joint research project of NASA and the National Space Development Agency of Japan. TRMM, which was launched in November 1997, is the first satellite mission dedicated to measuring tropical and subtropical rainfall. TRMM’s contributions to understanding and prediction of tropical cyclone behavior have been substantial, as indicated by the following examples (Shepherd 2005):

- TRMM data support an association of energy-releasing deep convective clouds in the eyewall of tropical cyclones with storm intensifications. For example, TRMM data analyzed in near-real time identified the development of deep convective clouds, extending to 16 km) in the eyewall of Hurricane Katrina on August 28, when it intensified to category 5.
- TRMM is currently the only satellite that can provide three-dimensional rain structure information over open oceans, where most tropical cyclones breed and intensify. TRMM data provided a rain history of Katrina from her genesis over the Bahamas until her transition to an extratropical storm over the Ohio Valley.

Although TRMM has exceeded expectations and has provided a wealth of new knowledge about tropical cyclones and other phenomena (such as shifts in the El Nino Southern Oscillation), the mission has intrinsic limitations that the GPM mission is designed to overcome.

The GPM mission will be an international constellation of satellites consisting of one core spacecraft carrying multiple sensors, a smaller satellite with one sensor, and other Federal agency and international partnership platforms. The major sensors on the GPM core satellite are the Dual-frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), both of which represent advances in capability over the corresponding TRMM instruments. The smaller satellite will carry another GMI. The GPM constellation will provide coverage that is both global and more frequent than TRMM coverage. It will be capable of measuring rain rates from as little as a hundredth of an inch per hour to as much as 4 inches per hour. NASA and the Japanese Aerospace Exploration Agency (JAXA) are working together to build and launch GPM. The core spacecraft is scheduled to launch in 2013; the constellation satellites are scheduled for launch late in 2014.

4.2.6 CloudSat Mission

CloudSat, a cooperative satellite mission with Canada, carries a Cloud Profiling Radar designed to study the effects of clouds on climate and weather. CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission were launched together on April 28, 2006. With capabilities a thousand times more sensitive than typical weather radar, CloudSat uses its millimeter-wavelength radar to measure the altitude and properties of clouds. This advanced radar is able to penetrate clouds and gather data on their vertical structure, providing a new space-based observational capability. Earlier satellites could only image the uppermost layers of clouds. CloudSat is among the first satellites to study clouds on a global basis and will be used to investigate their structure, composition, and effects.

In addition to its wide-ranging applicability to air quality measurement, weather modeling, water management, aviation safety, and disaster management, CloudSat is directly relevant to tropical cyclone research for its advanced capability to report on the internal structure of cyclonic storms as they evolve. Especially relevant is the ability to measure the cloud structure in the upper levels of the storm and its environment, which will provide new information for validation of advanced hurricane prediction models.

4.2.7 Constellation Observing System for Meteorology, Ionosphere, and Climate

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) consists of a constellation of six satellites (figure 4-2) that were launched in April 2006 (figure 4-3). This satellite network will probe the atmosphere using radio occultation. Each satellite intercepts GPS signals that have passed through (have been occulted by) the atmosphere close to the horizon. This path brings the signal through a deep cross-section of the atmosphere.

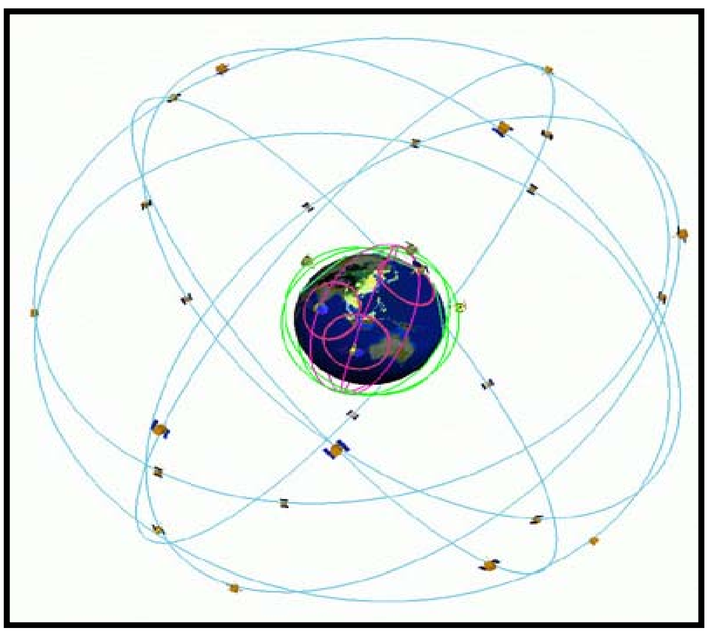


Figure 4-2. The constellation of six COSMIC satellites surrounded by satellites from the Global Positioning System, whose signals COSMIC will use. Credit: COSMIC Project Office.

Figure 4-3. Launch of the COSMIC constellation of six satellites. Credit: Orbital Sciences Corporation.

Variations in electron density, air density, temperature, and moisture bend the signal and change its speed. By measuring these signal shifts, scientists can determine the atmospheric conditions that produced them and derive temperature and water vapor profiles along thousands of angled, pencil-like segments of atmosphere. The horizontal scale of a single occultation sounding is between 200 and 600 km, with a typical value being 300 km. The vertical resolution of the receivers will vary from about 100 meters in the lower part of the troposphere to about 1 km in the upper troposphere and stratosphere. From COSMIC data, scientists will be able to infer the state of the atmosphere above some 2,500 locations every 24 hours, including vast stretches of ocean inadequately profiled by current satellites and other tools. The high vertical resolution of COSMIC data will complement the high horizontal resolution of present satellite sounding systems. Together, these observing system will provide accurate, high-resolution global observations with excellent and consistent representation of the important horizontal and vertical scales of motion in the atmosphere. Work is ongoing to assimilate GPS radio occultation data, such as that from COSMIC, into NWP models.

Radiosondes (weather sensors launched by balloon) have obtained vertical profiles since the 1930s. However, they are launched only twice a day in most spots, and few are deployed over the ocean. In contrast, the COSMIC data will be collected continuously across the globe (figure 4-4). The GPS radio signals can be picked up by the low-orbiting COSMIC receivers even through clouds, which are an obstacle for satellite-borne infrared-sensing instruments.

The COSMIC satellite network, which was developed through a U.S.-Taiwan partnership, was built to a system design provided by the University Corporation for Atmospheric Research

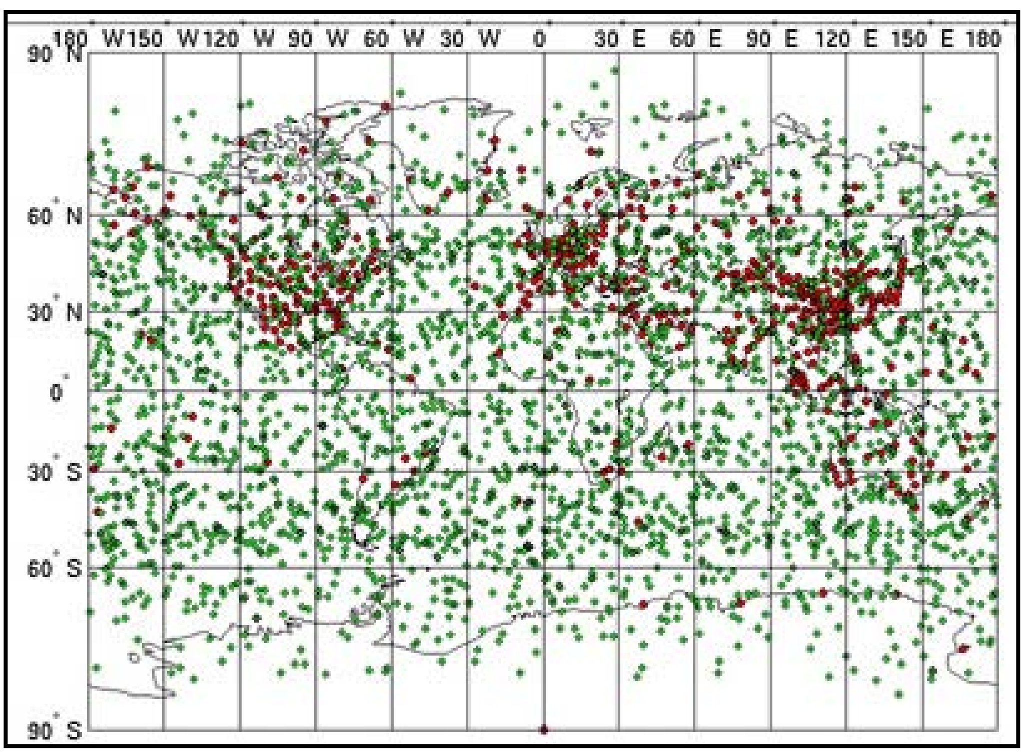


Figure 4-4. A comparison of the current global coverage of instruments launched via radiosondes each day (in red) with the expected coverage from the COSMIC satellite network in a 24-hour period (in green). Credit: COSMIC.

(UCAR), where the COSMIC Project Office is based. Orbital Sciences Corporation designed the COSMIC spacecraft. Taiwan's National Science Council and National Space Organization and the NSF in the United States are providing primary support for COSMIC. Other collaborators include NASA and NASA's Jet Propulsion Laboratory, NOAA, the Air Force, and NRL-Monterey.

4.2.8 Unmanned Aircraft Systems

Unmanned aircraft systems (UASs) represent a new type of observing platform that potentially can benefit tropical cyclone analysis and forecasting. UASs are being evaluated for their potential to obtain critical observations at low, medium, and high altitudes in and around tropical cyclones. As an example, in September 2005, a UAS flew into Tropical Storm Ophelia after it had weakened from hurricane intensity. The aircraft provided the first-ever detailed observations of the near-surface and high-wind tropical cyclone environment, an area often too dangerous for manned aircraft to observe directly. A recommendation from the interagency participants in a workshop on UASs, sponsored by NOAA, NASA, and the DOE and held in Las Vegas, Nevada, on February 28 to March 1, 2006, was that an initial demonstration should be conducted for low-level observations, by a UAS in a hurricane. The objective of the demonstration should be to obtain detailed observations of the near-surface tropical cyclone boundary layer environment. Some key questions this proposed demonstration project could address include the following:

- Will UAS platforms/instruments provide data that will improve tropical cyclone intensity forecasts?
- Will UAS platforms/instruments help improve our understanding of the rarely observed tropical cyclone boundary layer environment?
- Will the data improve the models and provide a better analysis for forecasters, particularly in the short-term?
- Will the data provide more information than already provided by satellites and manned aircraft?
- Where are the current data gaps and what combination of UAS and sensors would serve to fill those gaps?
- Could the UAS test platform(s) be used to develop and test new instruments?

At the same UAS workshop, the Air Force provided an update on the Weather Scout Unmanned Aerial Vehicle (WSUAV) initiative. The overall goal of the WSUAV is to improve situational and predictive battlespace awareness for commanders and mission planners in all the military services, in order to mitigate weather impacts on operations. A WSUAV would carry a flexible, directed weather sensor suite capable of operating in data-sparse and data-denied areas. The Pacific Air Forces (headquartered at Hickam Air Force Base, Hawaii) has been the lead agency working the WSUAV concept since Super-typhoon Pongsana emphasized the need to improve typhoon forecasting procedures. With manned aircraft missions for weather reconnaissance no longer operating in the western Pacific, the Pacific Air Forces began developing the WSUAV capability to augment satellite-based weather reconnaissance capability. Rather than buy or build a UAS focused on this mission, the initial decision was to lease a UAS as a commercial off-the-shelf data service, with the data to be available to the operational commander in near real time.

4.2.9 Multifunction Phased Array Radar

Multiple Federal agencies currently rely on radar networks to provide essential services to the Nation. The principal current uses are for weather surveillance, other atmospheric observations, and aircraft surveillance. A multifunction phased array radar (MPAR) network with the capabilities described in a recently published report (OFCM 2006) could perform all of the existing civilian radar functions. In addition, other existing and emerging needs not being adequately met by current systems could be met with this same MPAR network. Agencies whose current capabilities in essential mission areas could be improved by the enhanced weather surveillance capabilities of MPAR include the Department of Commerce (NOAA and NOAA/NWS), the Department of Transportation (Federal Aviation Administration and Federal Highway Administration), NASA, the Department of Agriculture (including the U.S. Forest Service), the Department of the Interior (National Park Service, Bureau of Land Management, and U.S. Geological Survey), the Department of Homeland Security (Federal Emergency Management Agency, U.S. Fire Administration, and U.S. Coast Guard), the DOD (Air Force, Navy, and Army for domestic and homeland defense operations), and the U.S. Environmental Protection Agency.

Two features of MPAR that would particularly benefit tropical cyclone forecast and warning services are its adaptive scanning and dwell capabilities. Because MPAR can produce multiple radar beams, each of which can be independently shaped and targeted, high-interest weather features can be targeted adaptively without interfering with full-volume scanning essential during a major cyclonic event. MPAR can target a beam to dwell on features such as convective cells spun off by a tropical cyclone over land or bands of heavy precipitation. Thus, two principal advantages of MPAR for tropical cyclone forecast and warning are longer lead times for tornado warnings and more accurate, higher-resolution precipitation rates to feed into QPF and hydrologic models.

At low scanning elevations, an MPAR beam can avoid beam blockage and ground clutter. At high scanning elevations, a larger angular volume can be covered, decreasing the full-volume scan time without decreasing resolution. These and other features of MPAR will contribute generally to improved weather surveillance, including tropical cyclone forecast and warning. In the future, weather radar system will continue to be essential to the tropical cyclone program as coastal radars provide a seamless transition from airborne to land-based observations, as a hurricane approaches the U.S. mainland.

When MPAR capabilities are compared with those of conventional radar technology, the technical advantages of MPAR are substantial. However, before a decision is made between continuing with single-function radars or an MPAR network, some specific technical issues need further testing and demonstration to ensure that the necessary MPAR technology is mature enough to proceed with this major shift in strategy. This work is ongoing.

4.2.10 Airborne Scanning Radar Altimeter

As stated in table 3-3, the NASA-developed airborne scanning radar altimeter (SRA), which has been tested during hurricane field experiments, was designed primarily to measure the energetic portion of the directional wave spectrum by generating a topographic map of the sea surface. The

SRA uses the radar return to measure the significant wave height and can resolve low-frequency surface waves. It sweeps a radar beam of 1^{o} half-power width (two-way) across the aircraft ground track within $\pm 22^{o}$ of nadir, simultaneously measuring the backscattered power at its 36 GHz (8.3 mm) operating frequency and the range to the sea surface at 64 points spaced across the swath at 0.7^{o} incidence angle intervals (Walsh et al. 2002). The range readings produce raster lines of sea surface topography at a 10 Hz rate. The SRA was designed primarily to produce sea surface directional wave spectra, but the backscattered power measurements can also be used to determine path-integrated rain rate below the aircraft.

This instrument has potential for transition into operations within the next several years. It will be particularly helpful to TPC/NHC for real-time wave forecasting and to NCEP/EMC for assimilation into HWRF/HYCOM in addition to providing critical verification of WAVEWATCH III results. Although the airborne SRA will contribute to operational priorities, it is not a substitute for a satellite radar altimeter.

4.2.11 Improvements to IWRAP

The Imaging Wind and Rain Airborne Profiler (IWRAP) is a dual-frequency, conically-scanning Doppler radar operating at C- and Ku-bands. The instrument measures rain reflectivity Z_e and Doppler velocity with a range resolution of 30 m. It also measures surface wind vectors via scatterometry (Contreras et al. 2006). As mentioned in table 3-3, IWRAP is the first high-resolution dual-band airborne Doppler radar designed to study the inner core of tropical cyclones. It has flown on research missions aboard a NOAA WP-3D aircraft during the 2002, 2003, 2004, and 2005 hurricane seasons as part of ONR’s CBLAST-DRI experiment, NASA’s Ocean Vector Winds research, and the NOAA/NESDIS Ocean Winds and Rain experiments.

One of the lessons learned during the above experiments was that IWRAP, as then configured, was constrained in retrieving the wind field at the lowest part of the ocean-atmosphere boundary layer. Because of the instrument’s off-nadir observing geometry, the radar return from the ocean surface interferes with the precipitation measurements from which the wind field is derived (Fernandez et al. 2006). To overcome this limitation, IWRAP was recently equipped with a new data acquisition system that allows acquisition of the raw radar return data, enabling post-capture spectral processing to separate both ocean and rain contributions. With this improvement, the wind field can be derived from the radar data virtually down to the ocean surface, creating a unique opportunity to estimate the drag coefficient in very high wind conditions. Moreover, the unique ability of the improved IWRAP to estimate the rain spectrum could lead to better understanding and characterization of the rain processes within the inner core of tropical cyclones. Further improvements that could aid in meeting these operational priorities include: (1) more efficient antenna design, (2) a unique single RF channel design, and (3) frequency diversity Doppler technique to decouple the range signal from Doppler ambiguities (Carswell and McMillan 2006).

4.2.12 Tropospheric Winds

According to the NRC report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, “tropospheric winds are the number one unmet measurement for improving weather forecasts” (NRC 2007, pg. 4-2). Two categories of tropospheric wind measurements from space that have particular relevance to tropical cyclone forecast and warning services are three-dimensional (3D) global winds measured with space-based lidar and ocean surface vector winds.

Three-Dimensional Global Winds

Tropical cyclones are generally steered by tropospheric winds, and the vertical shear of these winds is typically a major factor in tropical cyclone intensity changes. Data on 3D winds will improve the accuracy of NWP forecasts in general and of severe weather events in particular by decreasing the large analysis uncertainties in the 3D tropospheric wind field over the oceans, the tropics, and polar regions. The NRC study committee stated that 3D tropospheric wind observations from space would provide superior description of hurricane wind fields, even beyond recent advances in assimilation of radiances (NRC 2007, pg. 4-2).

A series of observing system simulation experiments (OSSEs) carried out at NASA Goddard Space Flight Center, NOAA/NCEP, and NOAA's Environmental Systems Research Laboratory show that accurately measuring the global wind field will have a major impact on numerical weather forecast skill at both regional and synoptic scales. Recent forecast impact experiments with actual measurements, obtained with an airborne Doppler wind lidar and assimilated into the ECMWF global model, confirm the OSSE predictions. **A new satellite mission to accurately measure the three-dimensional global wind field is needed to optimally specify global initial conditions for numerical weather forecasts and much improved tropical cyclone track forecasts.**

The Ocean Surface Vector Winds Data Requirement

Measurement of ocean surface vector winds (OSVW) for input to tropical cyclone analyses and NWP modeling requires higher spatial resolution (20 km versus 350 km[2]) and near-surface measurements, which 3D global wind measurements using lidar cannot provide. As noted in section 3.1.2, operational tropical cyclone forecasters at TPC/NHC, CPHC, and the JTWC rely heavily on OSVW data from research satellites in their forecast and warning activities. OSVW are also important to operations at tropical and coastal weather forecast offices and are a critical tool for marine forecasting at the NCEP Ocean Prediction Center and TPC/TAFB.

Remotely sensed OSVW help to fill the immense gaps inherent in the conventional ocean surface-based observation network. As summarized by Chang et al. (2006): "Remotely sensed OSVW often reveal small-scale characteristics of the wind field, which are used as a diagnostic tool in determining the development of potentially severe conditions, aid greatly in the determination of wind warning categories (severity), and help determine the radius of tropical storm force winds associated with tropical cyclones."

The first operational use of OSVW data began in 2000. The primary resource for this analysis has been data from the SeaWinds sensor on the NASA QuikSCAT satellite. The 1800 km–wide swath of the QuikSCAT scatterometer makes it possible for forecasters to view the entire

[2] These nominal spatial resolutions are from Table 10.2 in the NRC report *Earth Science and Applications from Space* (NRC 2007, page 10-9).

circulation of tropical and extratropical cyclones within a single pass. The NRC's community survey emphasized that the QuikSCAT data are critical for accurate hurricane forecasts and warnings (NRC 2007, pg. 4-48). Forecasters also use OSVW data from the WindSat instrument, when available, aboard the Coriolis satellite.

As noted in tables 3-4 and 3-5, QuikSCAT data have been assimilated routinely for NWP modeling at NCEP and NRL/FNMOC since 2002 and 2004, respectively. The assimilation of satellite data, including OSVW, has led directly to improvements in NWP tropical cyclone track guidance. This is clearly illustrated in figures 3-10 and 3-11. OSVW data also provide important verification data for NWP model forecasts.

The importance of OSVW to the Nation's tropical cyclone forecast and warning system is now well documented. QuikSCAT is already well beyond its planned lifetime and could fail at any time. Nevertheless, *7 years after the first operational use of OSVW data, the Nation still has no plans for an operational OSVW data stream that addresses the present and future requirements for satellite-based OSVW observations, including the platforms and instruments described above (sections 4.2.1–4.2.11).*

The OSVW requirements, defined at a NOAA-sponsored OSVW Workshop (Chang et al. 2006), are as follows:

- Provide accurate measurements in the presence of extreme wind conditions such as those found in intense storms and cyclones by extending the upper wind speed limit to 165 kt, (in the category 5 hurricane range); provide accurate measurements in the presence of rain
- Increase spatial resolution (decrease the characteristic dimensions) of individual measurements to allow definition of small-scale features in synoptic and mesoscale systems
- Provide accurate vector wind measurements closer to the coast
- Allow estimation of the required 1-minute sustained wind speed from the instantaneous spatially averaged wind measured by the space-based instruments
- Emphasize the overall operational requirement for an observing system (likely multiplatform) that satisfies revisit frequency requirements for measurements at every open-ocean location

As encapsulated in the workshop summary report, "Establishing an operational satellite OSVW data stream and closing the OSVW capability gaps will result in more accurate warnings, watches, and short-term forecasts; improved analyses, model initializations, and atmospheric forcing of ocean models; and a better understanding of coastal and oceanic phenomena." The bottom line: meeting this operational requirement will significantly improve the Nation's operational tropical cyclone forecast and warning capabilities. ***The development of new observational technologies is a research priority identified in chapter 5 of this report. Due to the importance of OSVW data—for use by tropical cyclone forecasters and in tropical cyclone NWP systems—the JAG/TCR strongly endorses the development and acquisition of a capability to meet the OSVW observation requirements. This capability is absolutely critical to***

meeting the operational needs of the tropical cyclone forecast and warning centers summarized in table 4-1.

4.2.13 Summary

These new and improved observation systems, which are under development or being planned, hold substantial promise to provide important information for tropical cyclone analysis; NWP modeling; and our fundamental understanding of the tropical cyclone atmosphere and ocean environment, the tropical cyclone inner and outer cores, and the interactions among these components. These systems include in situ measurements of winds over oceans in areas with tropical cyclones, as well as remote-sensing methods to measure temperatures, humidity, winds, sea surface heights, ocean wave heights and swell motion, and precipitation. The remote-sensing data will be provided from a combination of sensors located on aircraft, on polar-orbiting and geostationary satellites, and on land (e.g., weather surveillance radar). ***However, there are significant observation gaps that must be addressed, particularly satellite altimetry in the wake of the loss of the NPOESS ALT instrument (section 4.2.2), the ability to accurately measure the three-dimensional global wind field (section 4.2.12), and the requirement for operational OSVW data (section 4.2.12). Researchers and system developers must work together to seek viable solutions for these observation gaps.***

4.3 Statistical Analysis and Prediction Techniques

As mentioned in section 3.2, statistical modeling and analysis tools play substantial roles in tropical cyclone monitoring and prediction. While numerical modeling will take an increasingly larger role in tropical cyclone forecasting in the future, the need for statistical approaches will continue. Statistical models will continue to provide benchmarks for assessing the forecast skill of dynamic NWP models. They are also valuable for estimating uncertainties in forecasts of storm intensity and precipitation.

Track prediction is conducted most skillfully today with NWP models, although statistical models provide the benchmark against which that skill is measured. Even so, the use of optimal combinations of statistical and dynamic model predictions for track guidance, whether combined through simple consensus, corrected consensus, or super-ensemble techniques, will continue to be the state of practice for the foreseeable future. For intensity and structure forecasting, statistical methods likely will be competitive with numerical models for at least several more years. Continued improvement of sophisticated statistical intensity approaches—such as the Statistical Hurricane Intensity Prediction Scheme—is needed and should be encouraged.

4.4 Advanced NWP Modeling Systems

Progress is being made to meet the operational needs of the tropical cyclone forecast and warning centers identified in table 4-1. Recent improvements in the GFDL operational coupled hurricane model, for example, have led to improved intensity forecasts, which are now competitive with the operational statistical intensity guidance made available to tropical cyclone forecasters (see figures 3-8 and 3-9). As mentioned at the opening of this chapter, increased skill in forecasting intensity and structure, sea state and storm surge, and precipitation is now on the horizon, much as improving track forecast skill was two decades or so ago. These gains stem from the continuing improvements in observational capabilities described in section 3.1, as well as the advances in NWP model physics and data assimilation systems reviewed in section 3.3.

Nevertheless, substantial challenges to tropical cyclone forecasting remain. For example, current numerical guidance products show little skill in forecasting *rapid changes* in hurricane intensity or hurricane structure. None of the current numerical model guidance captured: (1) the rapid intensification, or the rapid decay before landfall, of Hurricane Lili (2002) in the Gulf of Mexico; (2) the rapid intensification of Hurricane Charley four and a half hours before landfall along the southwest coast of Florida in 2004; or (3) the unprecedented rapid intensification of Hurricane Wilma in the northwest Caribbean in 2005. For Lili and Charley, preparations probably occurred over a broader area than would have been necessary if the capability for more accurate forecasts of track, intensity, and structure had existed.

The difficulties in forecasting intensity and structure, along with other hurricane forecast challenges, are far more complex than simply running a higher resolution hurricane model on a more powerful computer. The extreme environment created by a tropical cyclone, coupled with the ability to describe features at resolutions not previously computationally feasible, necessitates the development of innovative coupled-model approaches with advanced subgrid-scale physical parameterizations. Improving NWP guidance for tropical cyclone forecasting requires (1) sufficient computing resources, (2) a coupled air-sea-land prediction system with advanced physics, (3) a state-of-the-art data assimilation capability that can take advantage of current and next generation observations for initializing the hurricane core circulation and the tropical environment in NWP models, and (4) sufficient investment in human and infrastructure[3] resources.

Improving tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state and storm surge, and precipitation is the overall goal guiding the ongoing development of next generation hurricane forecast systems. The work led by NOAA/EMC to develop the HWRF Air-Sea-Land Hurricane Prediction System is described in section 4.4.2. The parallel and complementary effort led by NRL-Monterey and FNMOC to continue improving the COAMPS Tropical Cyclone System is described in section 4.4.3. These complementary development efforts should be a national priority. They should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies.

Additional human and infrastructure resources (e.g., items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems) will be necessary to support development, operations, and maintenance of advanced data assimilation and NWP modeling systems. In any development of advanced techniques, it is critical to have a balance of human and computing resources not only for the development and deployment of the initial implementation but also for subsequent maintenance and future code enhancement activities. The additional computational expense and code complexity of any advanced technique permeates the entire development and operational activities at an operational center. On the development side, all experiments must use a parallel

[3] Infrastructure resources are related to items such as computational power, network bandwidth, architectural/ engineering requirements, and maintenance of applicable systems.

version of an operational system. Experimental changes are therefore carefully controlled, and interpretation of results is facilitated. Due to the great complexity of modern NWP forecast systems, diagnosing results requires extreme care and scientific discipline, as well as the resources (infrastructure, computational, personnel, and budgetary) to run adequate samples of cases (often requiring several months of data assimilation).

4.4.1 The Earth System Modeling Framework

The Earth System Modeling Framework (ESMF) collaboration is building standards-based, open-source software that aims to increase software reuse, component interoperability, performance portability, and ease of use in Earth science applications (Balaji et al. 2004). The project is a multi-institutional, cross-disciplinary collaboration that includes many of the largest Earth science modeling centers in the United States. The ESMF defines an architecture for composing complex, coupled systems and includes data structures and utilities for developing individual models. The aim is to create a framework usable by individual researchers as well as major operational and research centers. ESMF is funded by the NASA Science Mission Directorate, the DOD High Performance Computing Modernization Program (HPCMP), and NSF.

The basic idea behind ESMF, as explained on the ESMF website (http://www.esmf.ucar.edu), is that complicated applications should be broken up into smaller pieces, or components. A component is a unit of software composition that has a coherent function, well-delineated behavior, and a standard calling interface. Components can be assembled to create multiple applications, and different implementations of a component may be available. In ESMF, a component may be a physical domain or a function such as a coupler or input-output system.

Figure 4-5 is an ESMF example, showing the structure of the NASA GEOS-5 Atmospheric General Circulation Model (AGCM) (Collins 2005). (For more information on the GEOS-5 AGCM, see appendix C.) Each box in the diagram, including the couplers, is an ESMF component. Every component has a standard interface so that it is swappable with other versions of that component. In addition, new components can easily be added to the hierarchical system. Coupling tools include regridding and redistribution methods.

NASA conducted demonstrations of the GEOS-5 application to hurricane modeling in 2005 and 2006 as part of the NASA Modeling, Analysis, and Prediction (MAP) program. These demonstrations, respectively called MAP05 and MAP06, emphasized assimilation of NASA satellite remote sensing data and other earth system modeling capabilities. MAP06 was used to support the NASA NAMMA field experiment studying tropical cyclone development.

One ESMF-based initiative to create an interoperable modeling environment within a particular domain is DOD's Battlespace Environments Institute (BEI). The BEI is a DOD-wide effort to develop integrated forecasts by achieving a full coupling of environmental models to analyze and predict the total battlespace environment. The connection with the ESMF community enables broad civilian-DOD, cross-service, and cross-agency collaboration. The BEI is a High Performance Computing (HPC) Software Applications Institute (HSAI) sponsored by the DOD

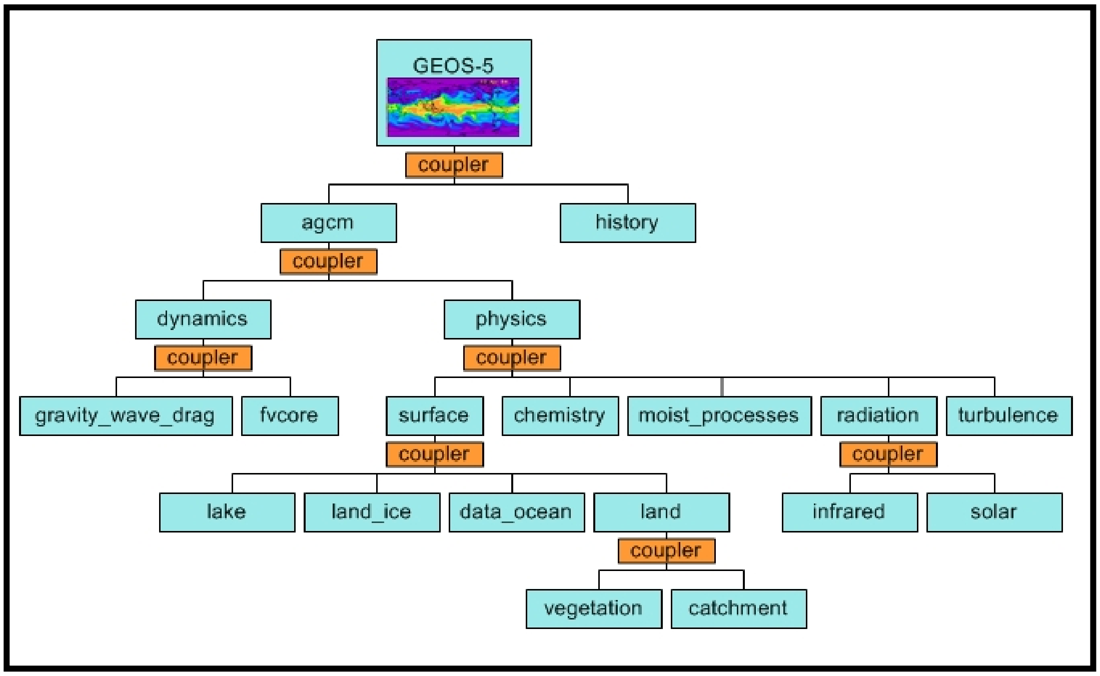


Figure 4-5. ESMF application example using NASA's GEOS-5 AGCM.

HPCMP. The BEI lead is at NRL Stennis Space Center, Mississippi. Other participants include NRL-Monterey, the U.S. Army ERDC, NCAR, and AFWA.[4]

It is possible to "wrap" an entire existing model with ESMF-compliant interfaces without changing the model's internal data structures. In effect, the model with interfaces becomes one component box in the framework, enabling that model's software to be coupled more easily with other ESMF components. Some current models that can run as ESMF components include the Navy's COAMPS and NOGAPS models, NCEP's GFS and WRF-NMM modeling systems, and NCAR's WRF-ARW, as well as the GEOS-5 system and other models at NASA/GMAO. As explained below, NOAA and DOD both plan to pursue development of ESMF-compatible systems for their global and regional models used in preparing guidance for tropical cyclone forecasting.

In summary, participation in the ESMF collaboration of all these modeling system development activities—including the NOAA and DOD tropical cyclone modeling systems discussed below—will enhance the connections between the operational centers and the modeling research communities. With time, ESMF will increasingly become an infrastructure for more efficient transition of results from modeling research activities to operational forecasting, as discussed in section 4.5. Plans are currently underway to advance the timeline for transition to ESMF.

4.4.2 NOAA's Plans for Hurricane Prediction Systems

The NCEP/EMC plan for addressing the operational priorities listed in table 4-1 focuses on development of the HWRF Air-Sea-Land Hurricane Prediction System. Model development for

[4] NRL Press Release, May 31, 2005. http://www.nrl.navy.mil/pressRelease.php?Y=2005&R=32-05r

this system will be based on the EMC HWRF model and will draw on the community modeling infrastructure paradigm. This approach facilitates comparison of results, while promoting research and technology that can, after testing, be transitioned efficiently to EMC's operational systems. Subsections below describe NCEP's development plans for, respectively, the next generation of GFS as the global model and the HWRF Air-Sea-Land Hurricane Prediction System as the high-resolution tropical cyclone forecasting system nested under GFS. These component systems will provide the modeling system backbone for EMC's forecast guidance for tropical cyclones. The first subsection provides an overview of NCEP's plans for an improved data assimilation capability to support both components of this planned forecasting system while enhancing the utility of existing and newly emerging observational data.

Data Assimilation Development for GFS and HWRF

The development of new techniques for assimilating high-resolution data sets is a fundamental activity required for advancing numerical prediction of hurricane intensity and structure, both of which are important to improved forecasts of intensity, structure, sea state, storm surge, and precipitation. New data sources are critical to initializing the forecast system in two key domains: (1) the large-scale environment, and (2) the vortex core. By 2010, the GFS will run as a global atmosphere/ocean coupled system with an advanced four-dimensional data assimilation system, called A4DDA. One of the most significant challenges to be met by NCEP and other operational NWP modeling centers over the next two decades is the assimilation of satellite data (Surgi 2006 and 2004). As described in sections 2.4.6 and 3.6.5, this challenge is being addressed through the JCSDA. Additionally, initializing the hurricane core in the HWRF with real-time airborne radar data, as discussed in section 3.1.6, poses a new challenge in mesoscale data assimilation.

NCEP proposes to develop a next generation data assimilation capability for both global and regional applications. The approach is multifaceted, is directed toward the most fundamental problems in data assimilation, and requires major new investments in development personnel, development computing resources, and operational computing resources.

Advanced Data Assimilation Techniques

The new techniques developed recently to improve data assimilation can be classified broadly into three categories: four-dimensional variational data assimilation (4D-VAR), ensemble data assimilation (EDA), and situation-dependent background errors (SDBE). The overall thrust of these advanced techniques is to improve the use of observations with high time resolution (e.g., hourly) and to improve the projection of observed information onto the proper spatial scales and patterns in the analysis. General descriptions for each category, including advantages and disadvantages of the techniques in each, are included in appendix K.

It is widely recognized that the major outstanding analysis problem is improved formulation of the background error part of the analysis equation. For a robust enhancement to operational analyses, items such as improved background errors must be developed very carefully; otherwise, erratic results (namely, major busts) will occur. The SDBE approach attacks the fundamental analysis problem directly and is particularly relevant to the tropical cyclone prediction problem. However, there has been little explicit development of the SDBE technique. Some early work on SDBE was done at the Met Office of ECMWF, but that approach was abandoned in favor of a simplified 4D-VAR.

One of the most significant challenges to improving the prediction of hurricane structure and intensity using high-resolution models is the initialization of the hurricane vortex. To advance this effort, NCEP/EMC is developing a local 3D-VAR technique for HWRF in which SDBE covariances are used to initialize the hurricane core circulation with real-time airborne Doppler radar data. These data come from NOAA's WP-3D aircraft or the newly funded instrument upgrade package on the NOAA Gulfstream IV (see sections 3.1.1 and 3.1.6)**.** For storms approaching landfall, the data assimilation system will also use the high-resolution data from coastal WSR-88D radars. The NCEP Gridpoint Statistical Interpolation (GSI) analysis system now contains coding structures intended for inclusion of SDBE in the analysis. Through the development of flow-dependent algorithms, GSI will be exploited in the HWRF Air-Sea-Land Hurricane Prediction System to initialize the hurricane core. Appendix K further details the advantages of incorporating SDBE corrections using extensions to the GSI.

GRADAS: NCEP's Global and Regional Advanced Data Assimilation System

For increased efficiency of code development and sustained maintenance, a data assimilation system should be adaptable to both the global model and regional applications that are most advantageous to the hurricane problem. Although different scientific and computational considerations are involved for each application, having one basic code system will increase focus, lower code maintenance costs, and afford users much increased flexibility. To prepare for a more unified global and regional numerical forecast system at NCEP, ongoing consolidation efforts are occurring in many areas, including handling of the observations, verification, ensemble products, and model physics. An ESMF-compatible code superstructure and infrastructure are also being developed.

The preferred development strategy for the planned NCEP Global and Regional Advanced Data Assimilation System (GRADAS) is, first and foremost, to develop SDBE within the GSI. To improve use of observations with a high time resolution, such as surface and airborne radar data and satellite imagery, 4D-VAR extensions to the GSI will be developed, using a simple model for observation increments. These improvements will occur as systematic and incremental augmentations to the current NCEP global and regional analysis code. The simplified 4D-VAR approach will also enable use of ensemble-based information. Appendix K contains a listing of the NCEP data assimilation priorities associated with this development strategy, a brief review of the data assimilation challenges for NWP modeling of weather in the tropics and tropical cyclones in particular, and the data assimilation efforts focused on dealing with a coupled ocean-atmosphere modeling system.

Essential Observational data to be Assimilated into the HWRF Prediction System

Table 4-2 summarizes essential observations to be assimilated into the HWRF Air-Sea-Land Hurricane Prediction System to aid in meeting the operational needs listed in table 4-1. As previously discussed in section 3.1.3, a coordinated effort to improve ocean observations and develop a coherent ocean data assimilation system will increase the accuracy and resolution of the thermal structure of the upper ocean layer. The observations of interest include data from both in situ instruments (e.g., AXBT, XBT, and drifting buoys) and data from altimeters—for example, from satellites such as JASON-1, ERS-2, and GFO.

Table 4-2. Essential Observations to be Assimilated into HWRF

Environmental Flow	• **"Routine:"** operational atmospheric observations, including satellite data (see Appendix A) • **Additional:** ▪ Data obtained from NOAA G-IV surveillance missions ▪ Data obtained from next generation (e.g., NPOESS, MetOp) satellite instruments (see Appendices I and J)
Ocean	• **"Routine:"** operational oceanic observations, including satellite altimeter data • **Additional:** XBTs and AXBTs (other air-deployable expendable instruments—reference Table 3-3), drifting profiler floats
Hurricane Core	• **Additional:** ▪ SFMR (surface winds) from NOAA WP-3D (when tasked) or AFRC WC-130J (when installed), or NOAA G-IV (new initiative) ▪ Airborne tail Doppler radar (3D structure) from WP-3D (when tasked) or NOAA G-IV (new initiative)

NCEP Global Model Development

The GFS model has many critical applications and functions in the NCEP operational job suite and is the cornerstone of NCEP's suite. Some of these forecast applications are noted below, with explicit relevance to hurricanes highlighted in boldface:

- Global weather (1 to16 days) with applications such as aviation, medium-range (3 to 8 days) precipitation and severe weather, and **hurricane tracks**
- **Initial and boundary conditions for hurricane regional model (i.e., GFDL currently, HWRF in the future)**
- Boundary conditions for NCEP's North American run (WRF-based regional model)
- Boundary and initial conditions and background field for the Regional Spectral Model
- Driver for ocean wave models and, in the future, other ocean models
- Ozone distribution and transport and, in the future, other atmospheric constituents
- **Background field for global data assimilation system**
- **Ensemble system model (to include hurricane tracks)**
- Coupled Climate Forecast System (CFS) model

In developing its next generation global model, NCEP considered the following specific items:

- Ensembles and forecast system diversity

- ESMF and the common modeling infrastructure/framework.
- Model dynamics
- Model physics
- Computational efficiency

During 2006, NCEP developed and analyzed five strategic options for the development of the next generation model's dynamics. After weighing the advantages and disadvantages, and in light of the above considerations, NCEP adopted a strategy of consolidating EMC model development efforts into three projects:

- Develop an ESMF-compatible Prototype Framework, which will run the latest version of GFS
- Scale up the Nonhydrostatic Mesoscale Model (NMM) to a global domain and incorporate semi-implicit and fully implicit semi-Lagrangian techniques
- Generalize the Prototype Framework to incorporate the NMM as both a global and regional model

The outcome of this strategy will determine EMC's longer-term development work (for the period 2007–2011). Appendix L contains a more detailed discussion of these plans for global model development.

The HWRF Air-Sea-Land Hurricane Prediction System

The HWRF Air-Sea-Land Hurricane Prediction System, which will be available for use by TPC/NHC and CPHC forecasters, is NOAA's next generation, high-resolution hurricane prediction system. Figure 4-6 and the following bullets describe this system, which is designed to address the tropical cyclone forecasting challenges of intensity, structure, track, sea state/storm surge, and precipitation.

- NOAA's next generation hurricane prediction system
- A coupled air-sea-land prediction system
- Advanced data assimilation capability to initialize the hurricane core circulation with real-time airborne Doppler radar and other data assimilation advancements for the coupled air-sea hurricane environment
- Advanced physics suitable for high-resolution and coupled air-sea-wave-land modeling processes
- Land surface component coupled to hydrology/inundation models
- Moving nests with two-way feedback in the atmospheric, ocean, and wave models
- Coupling to dynamic storm-surge model

HWRF is scheduled for operational implementation at NCEP in 2007. In this initial operational implementation, HWRF will have an updated movable, two-way nested grid. The inner grid horizontal resolution will be 9 km. The outer grid will have a horizontal resolution of 27 km, extending over a 75x75 degree domain, and a vertical resolution of 42 levels. Over the next

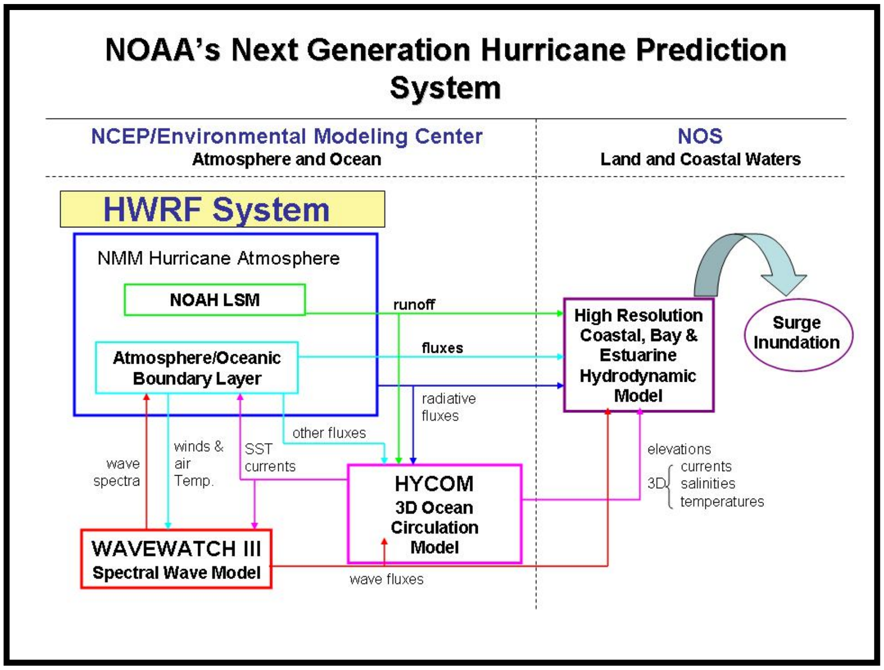


Figure 4-6. HWRF Air-Sea-Land Hurricane Prediction System.

several years after this initial implementation, HWRF will be enhanced with incremental increases in horizontal and vertical resolution. However, as noted in chapter 5, the relative merits of very high resolution deterministic model guidance compared with advanced probabilistic guidance will be a research priority.

The next five subsections describe planned NCEP work on other model systems that will serve as components, shown schematically in figure 4-6, of the HWRF Air-Sea-Land Hurricane Prediction System. Several of these (e.g., NMM, HYCOM, WAVEWATCH III, and the Noah LSM) have wider applications in the NCEP operational suite beyond tropical cyclone forecasting; their roles in the HWRF Prediction System are emphasized here.

NMM in the HWRF Air-Sea-Land Prediction System

The regional NMM will be used as the core model of the HWRF system. The NMM has been developed at NCEP within the larger WRF community modeling effort (Janjic et al. 2001; Janjic 2003). In NMM, the favorable features of hydrostatic model formulation are preserved within the valid range of the hydrostatic approximation.

- The basic idea for NMM was to split the system of nonhydrostatic equations into two parts: (a) the part that corresponds to the hydrostatic system, but including corrections due to the vertical acceleration; and (b) the part that is used to compute the corrections appearing in the first system. Thus, the nonhydrostatic effects are introduced as an add–on module that can be turned on or off. In this way, the hydrostatic and nonhydrostatic solutions can be compared, or the model can be run in the hydrostatic mode at lower resolutions to reduce the computational cost.
- The numerical schemes were designed following the principles set out by Janjic (1977, 1979, 1984). The approach employs "isotropic" horizontal finite differencing that

conserves a variety of basic and derived dynamical and quadratic quantities. Among these are conservation of energy and entropy, which improves the accuracy of the nonlinear dynamics (Arakawa 1966).

- In the vertical dimension, the hybrid pressure-sigma coordinate (Arakawa and Lamb 1977) was chosen as the primary option. Since the hydrostatic pressure is used as the vertical coordinate above 400 hPa, the possible inaccuracies due to the sloping coordinate surfaces are restricted only to about the lower half of the atmosphere. Note that the largest errors in the sigma coordinate generally occur in the stratosphere. Thus, the most serious problems associated with the sloping sigma surfaces are eliminated.

Hybrid Coordinate Ocean Model and WAVEWATCH III

As figure 4-6 indicates, the HWRF component will be coupled to the Hybrid Coordinate Model (HYCOM), a three-dimensional ocean circulation model. Thus, HWRF-HYCOM will replace the GFDL-POM modeling system currently used in NCEP operational forecasting (see section 3.3.3). HYCOM will have an ocean data assimilation system to take advantage of remote and in situ hurricane-related ocean observations. A hybrid coordinate model is isopycnal in the open, stratified ocean but smoothly reverts to a terrain-following coordinate system in shallow coastal regions and to *z*-level coordinates in the mixed layer or in unstratified seas. The theoretical foundation for implementing a hybrid coordinate system in an ocean circulation model was set forth by Bleck and Boudra (1981) and Bleck and Benjamin (1993).

HYCOM has been developed by the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling, which continues to improve the model and promotes its use by the community.[5] The consortium is funded by the National Ocean Partnership Program (NOPP), which was established by Congress in 1997 and now includes partners from academia (U.S. and French), U.S. government entities, industry, and a French government institute. Principal collaborators in HYCOM's development have been the University of Miami, the Naval Research Laboratory (NRL Stennis Space Center and NRL-Monterey), and the Los Alamos National Laboratory. NOAA participants in NOPP include the National Ocean Service (NOS), the Marine Modeling and Analysis Branch of NCEP, NOAA/AOML, TPC/NHC, and the Ocean Prediction Service.

As discussed in section 3.3, including the dynamic feedback of surface waves on the air-sea processes and the ocean thermal structure has produced significant improvements in forecasting hurricane structure. To incorporate this feedback in the larger prediction system, HWRF will also be coupled to an advanced wave model from the NCEP operational WAVEWATCH III suite of models. This advanced multi-grid (multiscale) wave model will include a movable, nested telescoping grid around the hurricane that is physically and computationally consistent with the coupled HWRF-HYCOM system. This Multi-grid WAVEWATCH III (MWW3) will simulate several grid configurations with different resolutions into a single wave model, with full two-way information flow between all grids for higher resolution near coastlines and lower resolutions in the deep ocean. In the deep ocean and in shelf areas, the initial benefit from the MWW3 in the HWRF context is parameterization of fluxes from the ocean to the atmosphere. In shelf and

[5] The consortium's website, which provides download access to the HYCOM code, documentation, and other support for new users, is http://hycom.rsmas.miami.edu/index.shtml.

coastal waters, the initial benefit will be for coupling with a storm surge model, as discussed below.

In addition to a movable, nested telescoping grid around the hurricane, the new MWW3 will allow for a more directed application of high-resolution wave modeling at the coast. This application will render the present large regional wave models obsolete. As the MWW3 system is incrementally implemented through 2009, its multi-grid approach is expected to make a 5 km coastal resolution feasible for operational modeling of the entire U.S. coastline. With this dramatic increase in coastal resolution, the need for surf-zone physics in the wave model will become even more urgent. Appendix M contains further information on other roles for WAVEWATCH III and MWW3 beyond their role as components in the HWRF Hurricane Prediction System.

Coupling of a Dynamic Storm-Surge Model to the HWRF System

As noted in section 3.4.4, ocean waves drive near-shore circulation patterns and can produce storm surges even when local winds are negligible. The waves produced by a tropical cyclone couple with the local water depth and near-shore topography to force the local circulation and other characteristics of a storm surge. This physical coupling underlies the requirement to incorporate coupled wave-surge modeling to improve prediction of hurricane-induced storm surges.

Hurricane storm surge height and coastal inundation are strongly influenced by both meteorological conditions and the geometry of the shelf and coast (especially features that act as hydrodynamic controls). Therefore, NCEP is partnering with the Coast Survey Development Laboratory in NOAA/NOS to provide predictions of storm surge height by combining the coupled HWRF system with a high-resolution coastal hydrodynamic model. One candidate model is the ADvanced CIRCulation (ADCIRC) model (Luettich et al. 1992; Luettich and Westerink 2004). Appendix M, paragraph 2, has details on this planned collaborative work.

ADCIRC has several features beneficial for storm surge application and has been demonstrated to be effective at predicting water levels in complex coastal systems (Blain et al. 1994, Blain et al. 1998). The ADCIRC code solves the fully nonlinear governing equations for shallow water using the generalized wave continuity equation formulation. This formulation minimizes spurious oscillations without excessive nonphysical dissipation by propagating the shortest so-called $2\Delta x$ waves. For efficient computation of water levels developing over a short time scale, the two-dimensional depth-integrated form of the model is applied. To exploit the advantages of an unstructured grid technique, ADCIRC uses a second-order Galerkin finite element method to solve the governing equations.

To model the propagation of a hurricane-generated storm surge from offshore across the shelf and inland, increasingly higher resolution is required as the surge approaches shore. The unstructured grid methodology not only provides this but can readily and accurately represent irregular shoreline and coastal features including barrier islands, rivers and waterways, and topography. ADCIRC domains with resolution exceeding 100 m are routinely used to determine storm surge propagation in riverine and estuarine systems while providing orders-of-magnitude larger elements at locations with deep water boundary conditions. Furthermore, ADCIRC has a wetting and drying scheme that predicts flood wave propagation over initially dry topography and incorporates weir formulae to model overtopping of vertical barriers to flow, such as levees.

To summarize, the HYCOM basin-scale ocean circulation model will provide the boundary conditions to a dynamic storm surge model. The meteorological conditions, including description of the hurricane wind and pressure fields will be specified by the HWRF model. Coupling of MWW3 with HWRF and HYCOM will allow more realistic modeling of wind-wave interactions and storm-driven wave propagation in the deep ocean and as a storm approaches the coast. This coupled HWRF-HYCOM-MWW3 system will provide an operational product with which coastal inundation can be predicted by including a high-resolution dynamic storm-surge model.

Advanced, high resolution, regional model-based probabilistic guidance (e.g., HWRF ensembles) are necessary to adequately address forecast uncertainties in critical storm attributes and related impacts such as intensity, structure, track, precipitation, and *storm surge*. Therefore, the use of a dynamic storm-surge model (i.e., coupling of a dynamic storm surge model to the HWRF system) is critically dependent on having sufficient computing power to run HWRF ensembles. This is discussed further below.

The Atmosphere-Ocean Boundary Layer in the HWRF Prediction System

As discussed in section 2.8.6, an important workshop on air-sea interactions was held at NCEP/EMC in May 2005. The workshop's objective was to bring the research and operational communities together to discuss and identify fundamental issues related to the physics of air-sea interactions under high-wind regimes in hurricanes and the representation of those interactions in NCEP's next generation coupled hurricane models (Shay et al. 2005). A series of focused questions from this workshop, listed in appendix N, has fostered collaboration across the entire community in hurricane air-sea R&D, with the goal of resolving fundamental issues in order to advance the HWRF and other air-sea coupled hurricane models. Many of the problem areas covered by these questions are represented in the JAG/TCR research priorities listed in chapter 5.

Some progress is being made with results from CBLAST-DRI and other important data sets in advancing flux parameterizations in the GFDL model, as noted in section 3.3.2. However, aggressive efforts need to continue in refining the momentum fluxes and formulating the enthalpy fluxes. Preliminary experiments in the GFDL model have shown extreme sensitivity of hurricane track (and presumably hurricane structure) to the formulation of heat fluxes. Investigation of the impact on hurricane structure of the wave-coupling of momentum fluxes is also underway at the University of Rhode Island and will continue in collaboration with EMC for HWRF.

The Noah Land-Surface Model as an HWRF Prediction System Component

A comprehensive land surface model (LSM) known as Noah was developed collaboratively by **N**CEP, the University of **O**regon, the U.S. **A**ir Force, and the NOAA/NWS Office of **H**ydrology (figure 4-7). More information on the origins, development, and physical references for the Noah LSM is provided by Ek et al. (2003). The far-reaching physical improvements added to the Noah LSM by NCEP/EMC over the past 15 years reflect numerous collaborations between EMC's

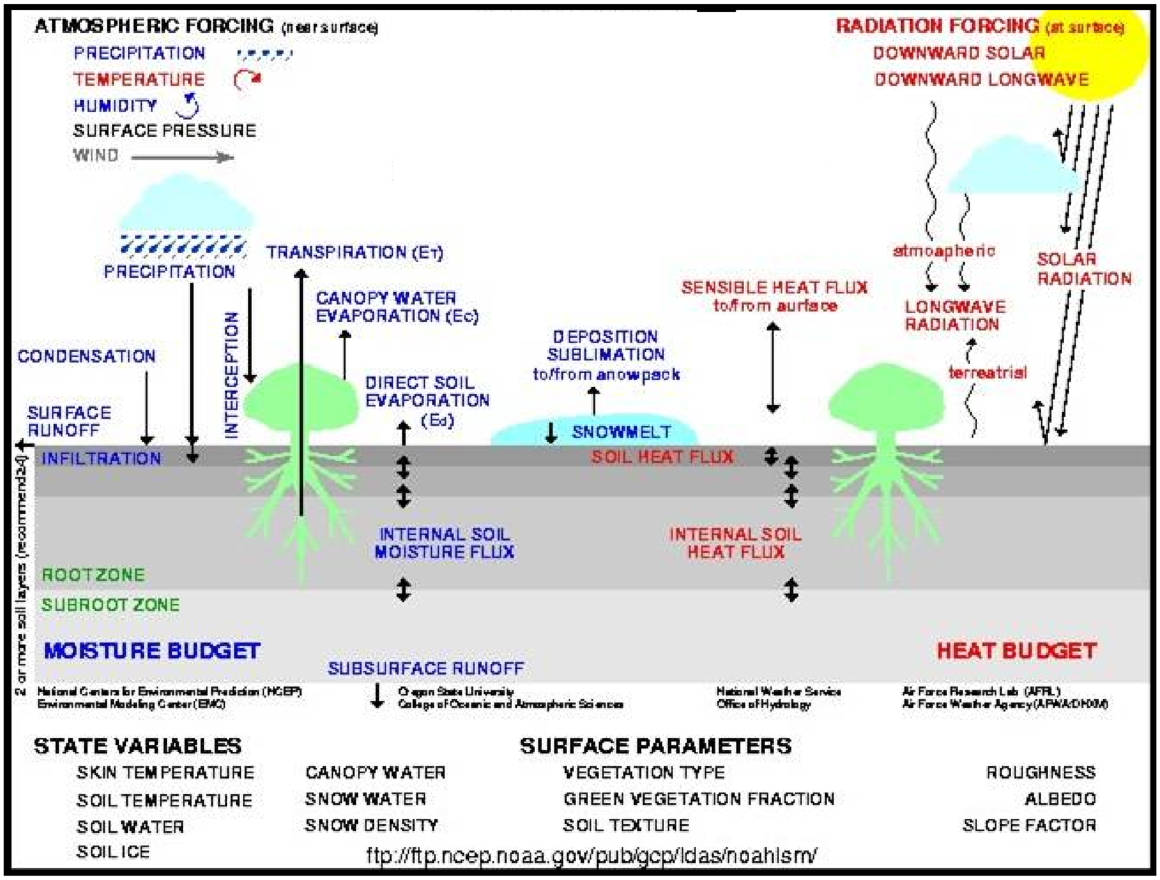


Figure 4-7. The Noah Land-Surface Model.

Land/Hydrology Team and many external partners in Federal laboratories and the university research community.

The plans for coupling HWRF to the Noah LSM are key to addressing the challenge of forecasting inland flooding by improving QPF for landfalling tropical cyclones. HWRF implementation plans call for the Noah LSM to be coupled with the HWRF atmospheric model to provide rainfall input to hydrology and inundation models and improve predictions of inland flooding. Early experiments directed toward this objective involved replacing the GFDL's current "slab" LSM with the Noah LSM to determine the latter's impact on improving hurricane intensity, structure, and precipitation forecasts for landfalling hurricanes (Shen et al. 2004). In these preliminary experiments, relatively small impact was demonstrated for hurricane intensity and structure, but *very promising results were found for improved precipitation forecasts.* This testing is now being extended to the fully coupled high-resolution HWRF system, an effort that will be aided by a proposed collaboration with the University of South Alabama. In particular, land-wind interaction effects need to be modeled better, to forecast more accurately the decay of wind intensity over land and the effects on wind and precipitation distributions.

The Noah LSM simulates land surface temperature, the components of the surface energy balance (eight surface-energy flux components such as latent, sensible, and ground heat flux), the components of the surface water balance (infiltration of precipitation, runoff, surface evaporation, snow pack evolution, and changes in soil water storage), and the evolution of soil temperature and soil moisture (both liquid and frozen) in four soil layers (with layer thicknesses of 10, 30, 60, and 100 cm). The surface infiltration scheme in the Noah LSM accounts for subgrid spatial variability in soil moisture and precipitation. The surface evaporation treatment includes direct evaporation from soil, transpiration from vegetation, evaporation of precipitation intercepted by the foliage of the vegetation, and snow sublimation.

For mid-latitude applications, advancement and assessment of the Noah LSM includes testing with NCEP's coupled land-atmosphere models (e.g., GFS and the mid-latitude WRF) and with the uncoupled North American Land Data Assimilation System (NLDAS). A Noah version that is essentially a stand-alone, uncoupled, one-dimensional column model is frequently configured to execute at locations where validating ground-based surface-flux stations are available. The NLDAS is a comprehensive continental-scale LSM testbed developed by EMC and its LSM partners for the purpose of testing and evaluating Noah and several other LSMs (Mitchell et al. 2004). It includes a stream-flow submodel for predicting river stage. This stream-flow model can execute as a standalone post-processing step that is driven by the runoff fields forecast by the Noah LSM component of NCEP NWP models (e.g., Eta, GFS, or the mid-latitude WRF).

Appendix M, paragraph 3, describes the plans for HWRF coupling with the Noah LSM and for testing the coupled system’s forecast skill with respect to the distribution of low-level surface winds and rainfall amounts, stream and river flows, and flood levels.

Development of HWRF Ensembles

Another future task at NCEP, beyond developing and testing the above components of the HWRF Air-Sea-Land Prediction System, is the development of HWRF ensembles. Ensemble forecasting techniques are important to the overall plan to improve tropical cyclone forecast guidance. In the integrated HWRF Prediction System depicted in figure 4-6, improvements in one component directly influence other system components. For instance, ensemble simulations to reduce and estimate the uncertainty in the strength and path of a hurricane will be useful for all system components, including the storm surge and inundation component. Probabilistic guidance based on advanced high-resolution regional models (e.g., HWRF and COAMPS ensembles) is necessary to estimate adequately the forecast uncertainties in critical storm attributes and in related impacts such as damaging winds, precipitation, and storm surges that arise from the combined uncertainties in track, structure, and intensity. However, the capability to run HWRF and COAMPS ensembles and multi-model ensembles within operational forecasting time constraints depends directly on the available computing power As stated above, the utility of coupling the HWRF system with a dynamic storm-surge model (see figure 4-5) is also critically dependent on having sufficient computing power.

In the development of advanced, high-resolution probabilistic guidance (e.g., HWRF ensembles), construction and configuration of optimal ensembles is a research priority identified in chapter 5. Another research priority noted there is to investigate the relative value, within the operational forecasting context, of *very* high-resolution deterministic forecasts versus ensembles.

4.4.3 DOD Plans for Hurricane Prediction Systems

The U. S. Navy and U. S. Air Force contribute substantially to the Nation's tropical cyclone forecast and warning capability. Their plans for NWP and ocean modeling are reviewed below.

Planned Data Assimilation Development

NRL has developed a prototype 4D-VAR data assimilation system, the NAVDAS Accelerated Representer (NAVDAS-AR), which is planned for operational implementation at FNMOC in 2008. NRL will be collaborating with NASA/GMAO and NCEP/EMC on further development of NAVDAS-AR.

The benefits of 4D-VAR have been demonstrated at other global forecast centers, most notably at the ECMWF. One such benefit is the ability of 4D-VAR assimilation to make better use of same-level observations at multiple times, such as ship and buoy observations, QuikScat ocean wind vectors, and SSM/I ocean surface wind speeds. These types of observations are especially abundant in the tropics, and current 3D-VAR data assimilation systems do not take full advantage of them. Furthermore, the unique design of NAVDAS-AR makes it much more computationally efficient than current 3D-VAR data assimilation systems for the order-of-magnitude or more increase in observational data expected with future satellite systems.

The following observation systems targeted for assimilation by NAVDAS-AR in the future (beyond those it already assimilates) are expected to have the greatest impact on tropical forecasting:

- AMSU-B water vapor retrievals (1D-VAR approach)
- High-resolution Infrared Radiation Sounder–3 (HIRS/3) radiances
- COSMIC GPS refractivities
- Military aircraft soundings (ACARS) of winds and temperatures
- SSMI/S radiances
- AIRS and AMSU radiances from Aqua
- HIRS/4 radiances
- Microwave Humidity Sounder (MHS) retrievals (1D-VAR approach)
- MetOp instruments: Infrared Atmospheric Sounding Interferometer (IASI), HIRS, AMSU, MHS, and ASCAT
- NPOESS CrIS/ATMS radiances (with NPP)
- Geostationary radiances
- WindSat radiances
- SSMI radiances

By providing more effective incorporation of this information from satellite systems and permitting the assimilation of more satellite observations, NAVDAS-AR will further enhance the forecast skill of NOGAPS for tropical cyclone tracks.

Planned Enhancement of the NOGAPS Global Model

A new land surface parameterization was transitioned into NOGAPS in August 2006. This transition provided NOGAPS with improved lower atmospheric forecasts of temperature and moisture and resulted in improved track forecasts for tropical cyclones. While a number of upgrades are planned for the NOGAPS global spectral model in the future, the following upgrades are expected to have the most impact on tropical forecasting:

- Upgrade to the physics of the land surface parameterization in NOGAPS (FY 2007). This transition is planned to improve the lower-atmospheric forecasts over tropical regions.
- Transition the semi-Lagrangian advection of moisture (FY 2007). This transition will improve NOGAPS forecasts of moisture and clouds and will especially affect forecasts for the tropics.
- Transition new flux algorithms for the planetary boundary layer parameterization of NOGAPS (FY 2008). The improved surface fluxes are expected to have a large impact on forecasts for the tropics, especially in the vicinity of tropical cyclones.
- Transition the semi-Lagrangian/semi-implicit advection of temperature, vorticity, and divergence; increase horizontal resolution and the number of vertical levels to 48 (FY 2008). The semi-Lagrangian scheme will permit use of a substantially longer model time-step, which will allow a higher-resolution model to be run within the same operational constraints on run time and computer resources.

Plans for High-Resolution Regional Models

For the U. S. Navy, regional high-resolution model development is based on enhancements to COAMPS. The future COAMPS Tropical Cyclone System will make use of ESMF compliance to couple the NRL Coastal Ocean Model (NCOM) and WAVEWATCH III to the COAMPS nonhydrostatic atmospheric dynamical core. The resulting coupled system will use moving nests with two-way feedback in the atmospheric model and will eventually include nested grids in the ocean models. The target horizontal resolution for the atmospheric and ocean models is 5 km or less on the finest grid mesh. The finest grid mesh will be capable of explicitly resolving deep convection. In order to model the fluxes more accurately, the atmospheric and ocean wave models will interact with a sea spray submodel to represent the air-sea exchanges in the wave boundary layer. An analysis system that is capable of initializing a tropical cyclone with the proper intensity will be used.

Development of this COAMPS Tropical Cyclone System will occur in parallel with NCEP's development of the HWRF Air-Sea-Land Prediction System. Statistics on tropical cyclone track guidance clearly demonstrate that superior guidance is produced using a multi-model consensus. In the future, a multi-model capability for consensus forecasting of tropical cyclone intensity will be equally valuable.

As discussed in section 3.3.2, AFWA currently runs the MM5 model to produce bulletins for use by tropical cyclone forecasters at the JTWC. AFWA's ability to transition new tropical cyclone prediction capabilities based on a high-resolution regional model arises from its community modeling partnerships. The transition from MM5 to NCAR's Advanced Research WRF (WRF-

ARW) as the NWP engine is one example. WRF-ARW also will have an improved tropical cyclone-following capability that will maintain the tropical cyclone in the center of the nest. Specific capabilities and schedule are currently under review.

4.5 Transitioning Research Results to Operational Capability

Section 3.6 reviewed current processes in place for transitioning hurricane research results into operational capability at an operational center. This section describes current plans for improving the efficiency of the transition process, often through enhanced collaboration involving entities in the tropical cyclone R&D community (see chapter 2) in partnership with one or more of the operational centers for tropical cyclone forecasts and warnings (described in section 1.4).

4.5.1 Plans for Major Transition Programs at the JCSDA

The JCSDA has plans for major transition programs in two areas of particular relevance to tropical cyclone forecast and warning:

- A major near-term goal for the JCSDA is to lay the groundwork and establish a common data assimilation infrastructure for assessing new satellite data and optimizing the utilization of these data in operational models. A step toward this goal will be to establish on JCSDA computer systems parallel versions of the global and regional data assimilation systems used at NCEP/EMC, NASA/GMAO, and the DOD partners in the Center (Le Marshall et al. 2005).
- As part of NOAA's involvement in THORPEX, JCSDA will be working with NOAA's THORPEX Science and Implementation Team to prepare in advance for new satellite-based observations before the spacecraft are launched. Thus, data assimilation systems will be ready for use when data are first acquired. In addition, JCSDA will work with the THORPEX team on evaluating new data assimilation strategies during the THORPEX Observing System Tests

By 2007, JCSDA deliverables will include developing a community forecast and data assimilation system for both global- and regional-scale applications. This system will be accessible to the research community through the U.S. Weather Research Program and will serve as the primary mechanism for infusing data from both research and operational satellites into NCEP, GMAO, and DOD operations.

4.5.2 Developmental Testbed Center

The Developmental Testbed Center (DTC) is a facility where the NWP research and operational communities interact to accelerate testing and evaluation of new models and techniques for research applications and operational implementation, without interfering with current operations. Having the DTC support the HWRF Air-Sea-Land Hurricane Prediction System could increase opportunities in the NWP hurricane research community to collaborate with NCEP and have a direct influence on improving operational hurricane forecasts. More information on the DTC is at the following Web site: http://www.dtcenter.org/index.php.

4.5.3 Essential Elements of an Efficient Transition Process in a Community Context

The programs/processes described above and in section 3.6 play an integral part in implementing valuable research results in operations. Essential elements of an effective transition of research to operations program include the following:

- Research and model development priorities, such as those presented in chapter 5 of this plan, must be clearly articulated to the tropical cyclone community.
- There needs to be a steady flow of *relevant* research.
- The tropical cyclone R&D community must be aware of the transition of research to operations processes.
- The transition process needs to be supported by sufficient human and infrastructure resources for transition of research to operations activities, including the resources to support collaborative ventures.
- The program needs a long-term commitment of adequate resources to improve and maintain the sufficient infrastructure.

Funding for the transition of research to operations remains deficient. Within an era of constant or diminishing dollars, R&D and transition needs will likely be competing with each other. ***A mechanism is needed to enhance development and transition of research to operations activities throughout the tropical cyclone operations and research community to further improve operational, high-resolution tropical cyclone NWP models, thereby maximizing benefits for the Nation.*** This need is discussed in more detail in chapter 6.

In summary, having a viable program for highly capable transition of research to operations is essential to achieving marked improvements in the Nation's tropical cyclone forecast and warning capability in a timely and efficient manner. Increasing human and infrastructure resources at NRL/FNMOC and NCEP/EMC and increasing the flow of relevant research focused on improvements to the operational NWP systems (i.e., focused on the NWP research priorities outlined in chapter 5) will greatly aid in improving these systems, thus increasing the protection of human lives, enhancing personnel safety, and improving economic benefits.

4.6 Summary

This chapter introduced the operational needs of the tropical cyclone forecast and warning centers. Meeting these needs will require continuing advances in observations, data assimilation technologies, and tropical cyclone NWP models. Key to these advances is the Nation's commitment to provide sufficient human and infrastructure resources for tropical cyclone research, development, and transition of research to operations activities, along with sufficient resources for the operational NWP model environment. Through these mechanisms and commitments, operational tropical cyclone forecasting skill will increase, which will lead to reduced loss of life, injuries, and vulnerability to tropical cyclones. The next chapter discusses the tropical cyclone research priorities.

5
RESEARCH PRIORITIES

The operational needs of the tropical cyclone forecast and warning centers, as summarized in section 4.1, can be characterized by the following seven tropical cyclone–related, day-to-day operational forecast and warning categories (or a combination of these categories):

- Intensity
- Structure
- Track
- Sea state
- Storm surge
- Precipitation
- Observations

As shown in chapter 4, meeting the operational needs will require continued advances in observations, data assimilation technologies, and numerical weather prediction (NWP) models for tropical cyclones. Absolutely essential to these advances is sufficient human and infrastructure resources for tropical cyclone R&D and the transition of R&D results to operations, along with sufficient human and infrastructure resources for the operational NWP environment. This chapter focuses on the tropical cyclone research priorities to aid in enhancing the future capabilities of the tropical cyclone forecast and warning centers.

5.1 Research Priorities in Atmospheric and Ocean Science

Table 5-1 lists the JAG/TCR's recommended priorities for tropical cyclone research in atmospheric and ocean science. The numbering is for reference only and does not indicate relative priority. When the terms "basic" or "applied" research are used in this chapter, refer to figure 5-1 and the definitions in section 3.5.3 as a guide in distinguishing between the two types of research. The JAG/TCR has formulated these priority topics to respond to the operational needs and capability limitations discussed in chapters 3 and 4. The priorities and their formulation reflect the many discussions and iterations by the JAG/TCR regarding agency views on priorities for tropical cyclone R&D in atmospheric and ocean science. It provides a consensus view from the Federal agencies represented on the JAG/TCR and is intended to become part of a "living document" to be updated annually. Additionally, the OFCM intends to structure portions of the annual IHC around these research priorities.

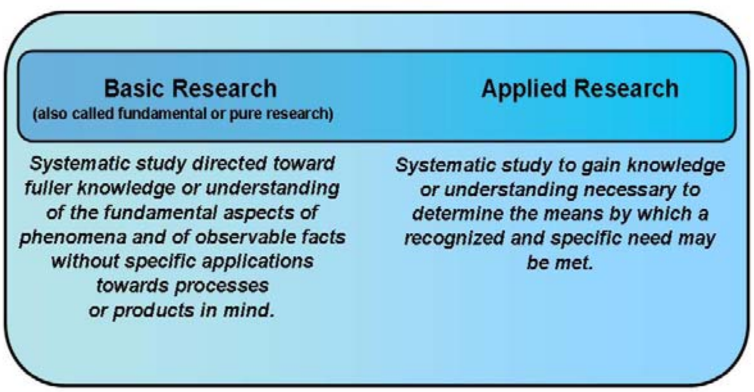


Figure 5-1. Distinction between basic and applied research.

The research priorities are arranged under three main areas: (1) General Research and NWP Modeling Topics, (2) NWP Model Development Topics, and (3) Observations and

Table 5-1. Research Priorities in Atmospheric and Ocean Science

Research Topics	Type of Research B = Basic; A =Applied
General Research and NWP Modeling Topics	
1. Role of inner core processes on intensity and structure changes (e.g., eyewall replacement cycles, mixing).	B
2. Relative role of vortex versus environment in influencing intensity and structure (e.g., role of vortex mixing and resiliency [vortex Rossby waves and stability]).	B,A
3. Role of rainbands on intensity and structure changes.	B
4. Role of dry air, midlevel easterly jet, and suspended mineral dust from Saharan Air Layer on intensity and structure changes.	B,A
5. Role of vertical shear of horizontal wind on intensity and structure changes.	B,A
6. Tropical cyclone genesis.	B,A
7. Determinants of structure and relationship with preexisting wave disturbance; relationship between structure and intensity.	B
8. Role of ocean; role of oceanic heat content.	B,A
9. Physics a. Relative importance of physics (e.g., air-sea fluxes, microphysics, convection) on intensity and structure changes in various environments (e.g., sheared vs. non-shear) b. Processes within atmosphere-ocean boundary layer on intensity/structure changes (i.e., momentum and enthalpy fluxes); role of boundary layer wind structure on the transfer of energy and mass. c. Role of radiation and interaction of radiation with microphysics. d. Role of vortex-scale moisture convergence and cloud microphysics in precipitation processes. e. Role of landfall effects (e.g., surface flux changes) on intensity, structure, and precipitation processes. f. Resolution studies (considering a-e above) to determine what scales can be explicitly resolved.	B,A
10. Theoretical limits to tropical cyclone forecast errors for track, intensity, and structure.	B
NWP Model Development Topics	
1. Tropical cyclone vortex initialization; ocean initialization	A
2. Atmosphere-ocean boundary layer for coupled air-sea-wave problem; momentum (wave-induced drag) and enthalpy fluxes (sea spray complexity).	B,A
3. Land surface coupling: Complexity of coupling with HWRF; sensitivity of LSM on track, intensity and structure, precipitation	A
4. Coupling of HWRF with hydrology/inundation models.	A
5. Verification for three dimensional, high-resolution NWP model for all phases of the tropical cyclone life cycle; varying atmosphere/ocean environment.	A

Table 5-1. Research Priorities in Atmospheric and Ocean Science

Research Topics	**Type of Research** B = Basic; A =Applied
6. Diagnostic techniques to further increase the utility of global models (e.g., NCEP, UKMO, NOGAPS) in forecasting tropical cyclone genesis.	A
7. Development of advanced, high-resolution probabilistic guidance (e.g., ensembles); optimal ensemble construction and configuration; value of very high-resolution deterministic forecasts vs. ensembles	A
Observations and Observing Strategies	
1. Where to take observations for initialization of hurricane vortex; what is the hurricane “core” circulation and how do we define?	A
2. Alternatives and tradeoffs for observing storms and their environment with in situ (e.g., buoys, aircraft) and remote sensors (e.g., satellite).	A
3. Required observations to support model diagnostics and verification (e.g., IFEX effort led by HRD).	A
4. Techniques to evaluate the uncertainty and representativeness of observations and use of observations for initializing NWP models.	A
5. New observational technologies.	B,A

Observing Strategies. The first area, General Research and NWP Modeling Topics, contains scientific and modeling issues that need to be addressed. The second area, NWP Model Development Topics, strictly focuses on NWP model development challenges that require focused research. The third area, Observations and Observing Strategies, highlights the use of observations to aid in providing improved analysis and forecast guidance. Many of the research priorities listed in table 5-1 are explicitly discussed in the body of this report. The subsections below provide additional information, summarized from the JAG/TCR deliberations, on the rationale for these research priorities. In some instances, the subsections include specific questions of importance for a particular research topic/area, as an aid in clarifying the research required.

5.1.1 General Research and NWP Modeling Topics

The gains made over the past several decades in our understanding and forecasting of tropical cyclones have paralleled the improvements in observational capabilities (e.g., instrumented aircraft, land-based and airborne Doppler radars, usage and quality of satellite data), improved resolution and improved representation of model physics in NWP models, and the use of these observations through more sophisticated data assimilation capabilities. The fact that a tropical cyclone spends the majority of its life over the tropical ocean, where few data are available, has forced the community to pioneer mobile observing strategies in order to provide critical observations for the operational forecast and modeling communities. In addition, these techniques have evolved to include measurements of the upper ocean and the atmosphere in the vicinity of the storm. However, continued exploitation of existing observations via advanced data assimilation systems and improved NWP models would enhance tropical cyclone track and intensity forecast guidance provided to forecasters. In the case of intensity, wind structure, and precipitation associated with tropical cyclone landfall, an aggressive research program is needed that will provide the understanding, technology, and applications necessary to further enhance NWP models and forecast guidance products.

The modest improvement in the intensity forecasts may be attributed to deficiencies in the current prediction models, including items such as inadequate initialization of the hurricane vortex and inadequate representation of the atmosphere-ocean boundary layer (Ginis et al. 2006a; 2006b). Research is required to better understand the physical processes that contribute to tropical cyclone intensity, wind field changes (i.e., structure), and how those processes are represented in operational forecast models. A synergism between observations and NWP models is required to isolate the important physical processes. High-quality, high-resolution observations are critical to model parameterizations for atmospheric, oceanic, or coupled processes. This research is essential for improving track, intensity and wind structure, and quantitative precipitation forecasts.

To most effectively support improvements in operational forecasts, modeling research must be closely integrated with operational models and priorities. The recommended research will improve understanding of key physical processes that influence tropical cyclones, such as the processes involved in the following research topics.

Internal Vortex Dynamics

Numerical models must be able to simulate the development and breaking of unstable vortex-Rossby waves in the eyewall (e.g., Montgomery and Kallenbach 1997; Schubert et al. 1999). This will require a fully three-dimensional turbulence scheme because the horizontal shears in the eyewall region and around convective cells are very strong and capable of producing resolvable turbulence.

The role of vortex-scale moisture convergence and cloud microphysics is a priority topic because microphysical parameterizations are sensitive to whether or not the convective updrafts and downdrafts are correctly represented in the model (Rogers et al. 2007). The effects on ice nucleation processes by mineral dust (e.g., Saharan Air Layer) are also not understood. The following topics also need to be addressed:

- Role of vortex mixing and resiliency (e.g., vortex-Rossby waves and vortex stability)
- Role of rainbands and eyewall replacement cycles
- Role of asymmetries in the evolution of the vortex core

Interaction of the Vortex with its Environment

Fine-scale structure must be considered in the context of the interactions of the tropical cyclone with its environment. In particular, the effects of vertical shear of horizontal wind play a critical role in storm intensity and rain forecasts. Interactions with vertical wind shear are an important part of current statistically-based intensity forecast models and have been the subject of considerable research (e.g., DeMaria 1996; DeMaria and Kaplan 1994, 1999). Frank and Ritchie

(2001) and Rogers et al. (2002) show that the impacts of vertical shear on both inner-core structure and rainfall patterns of tropical cyclones are significant. Other topics that need to be addressed include the following:

- Distinction between a trough that leads to a storm's intensification upon interaction and one that leads to a storm's decay
- Role of dry air, mid-level easterly jet, and suspended mineral dust from Saharan Air Layer
- Interactions that lead to vortex asymmetries and changes in vortex dynamics

Tropical Cyclogenesis

A critical unresolved aspect of tropical cyclone intensity change is how a vortex reaches sufficient organization or vorticity to enable the storm to continue to intensify (cyclogenesis). Simulations suggest that the building blocks of the tropical cyclone intensification process are cores of deep cumulus convection that produce large values of cyclonic vorticity on cloud scales via the stretching of already vorticity-rich air in the pre-storm environment (e.g., Montgomery et al. 2006). Subsequent intensification is hypothesized to be a two-stage process. In the first stage, multiple convectively-concentrated low-level potential vorticity anomalies are produced, while in the second stage, the multiple potential vorticity anomalies undergo merger and axisymmetrization as part of the intensification of the warm-core vortex. Reasor et al. (2005) explored the first stage of the intensification through an examination of the genesis of Hurricane Dolly (1996) using an analysis of airborne Doppler radar observations. They found that the early development of Dolly supports a stochastic view of tropical cyclone genesis in which multiple lower-to-middle-tropospheric mesoscale cyclonic circulations are involved in building the surface cyclonic circulation. These findings suggest that the development of the initial low-level cyclonic circulation is a bottom-up process that fundamentally occurs as convective scale vortices amalgamate and intensify. A number of fundamental questions arise with respect to genesis, including the following:

- What processes lead to a disturbance becoming a tropical depression and subsequently a tropical storm?
- What is the mesoscale/synoptic-scale vorticity structure in the upper troposphere during cyclogenesis and how does it modulate the convection environment?
- How does convection respond to the presence of preexisting vorticity anomalies at different levels?
- How does deep moist convection modify the vorticity associated with the triggering disturbance?

Determinants of Structure

This topic includes determinants of wind radii, the relationships between wind structure and preexisting wave disturbance; and the relationship between structure and intensity. Many basic controlling parameters that define the structure of hurricanes are not yet understood and remain difficult to predict. For example, not much is known about what determines the radius of maximum wind, one of the most important dynamical properties necessary to describe any given hurricane.

Interaction of the Vortex with the Underlying Surface

Tropical cyclones draw energy from the ocean and cool the ocean by wind-induced surface fluxes and vertical mixing in the ocean. The extreme high winds, intense rainfall, large ocean waves, and copious sea spray push the surface-exchange parameters for temperature, water vapor, and momentum into untested new regimes. Air-sea interactions in the eyewall region are largely unknown, due primarily to a lack of observations at the air-sea interface. The heat, moisture, and momentum exchange coefficients under the high-wind conditions are difficult to determine. Partially resolvable boundary layer secondary circulations, such as those described by Foster (2005) and Nolan (2005), further modulate surface fluxes and must be included in new parameterizations. Other topics that need to be addressed include the following:

- Boundary layer wind structure and the transfer of energy and mass
- Role of air-sea flux of energy and water
- Impact of wave field on surface transfer of energy and mass
- Impact of spatial variability in the air-sea fluxes within and surrounding the eye, and their relationship to upper-ocean processes
- Landfall effects on the boundary layer wind structure and transfer of energy and mass

5.1.2 NWP Model Development Topics

NWP Model Initialization

Research is needed on how best to initialize the tropical cyclone vortex in the next generation, operational, high-resolution tropical cyclone models (HWRF Air-Sea-Land Hurricane Prediction System and COAMPS Tropical Cyclone System). This research needs to include instances when there is an absence of airborne Doppler radar, as these observations will not always be available. Also, since the HWRF Air-Sea-Land Hurricane Prediction System and COAMPS Tropical Cyclone System are fully coupled systems, initialization of the ocean from a basin-scale ocean model with a cycled ocean data assimilation system (ODAS) must provide initial conditions for the models.

Atmosphere-Ocean Boundary Layer

Research is needed to develop improved air-sea parameterizations for tropical cyclone high-wind regimes and improved wave drag relationships. One challenge is improving the incorporation of sea spray in the next generation, operational, high-resolution tropical cyclone models, through research that investigates the impact of feedback processes for evaporative and heat transfer in the planetary boundary layer on tropical cyclone intensity and structure. A second research challenge with respect to air-sea interactions is to improve the representation of wave-induced drag. Preliminary studies have shown that, under hurricane wind conditions, the younger waves produce smaller drag such that hurricane intensity and structure can be significantly affected by the explicit simulation of surface waves (see section 3.3.2).

Land Surface Coupling

During tropical cyclone landfall, flood forecasting depends critically on the precipitation distribution, hydrological and topographic factors, and the tropical cyclone size and motion. To address this critical service requirement, the HWRF Air-Sea-Land Hurricane Prediction System will be coupled with a land surface and hydrology system for prediction of inland flooding (see section 4.4.2). The impact of the modeled hydrological cycle on tropical cyclone precipitation has yet to be explored. Some work has been done on coupling an LSM to the GFDL hurricane model, and the HWRF system will use the operational Noah LSM. However, the full sensitivity of the HWRF for track, intensity and structure, and precipitation needs to be explored.

Development of Advanced, High-Resolution Probabilistic Guidance (e.g., Ensembles)

For the improvement of tropical cyclone intensity and structure guidance, studies need to be conducted to determine the feasibility, optimal construction, and configuration of HWRF and/or COAMPS ensembles (e.g., ensemble resolution and ensemble members within the constraints of the operational environment). In addition to providing explicit HWRF/COAMPS guidance for intensity and structure, these studies will have a large impact on next generation tropical cyclone challenges that involve the forcing for wave and storm-surge models.

Relative Value of Very-High-Resolution Deterministic Forecasts and Ensembles

The improvement of intensity and structure guidance needs to be investigated using very high-resolution deterministic guidance from the HWRF Air-Sea-Land Hurricane Prediction System or COAMPS Tropical Cyclone System (< 4 km) versus using ensembles from a lower resolution version of these NWP systems. From an operational perspective, is it better to have one solution [deterministic] from a very high-resolution model or a range of uncertainty, as determined by running ensembles with a lower-resolution version of the model?

Research Studies

Research studies must take full advantage of the operational capabilities (HWRF Air-Sea-Land Hurricane Prediction System and/or COAMPS Tropical Cyclone System). These systems must be used for both testing of potential operational improvements as well as for exploratory research beyond immediate operational capabilities. Impacts of improved intensity forecasts on tropical cyclone track must also be evaluated to ensure no degradation of present track forecasting capability. A focused and directed research program, culminating in transition-to-operations—which uses the HWRF Air-Sea-Land Hurricane Prediction System and/or COAMPS Tropical Cyclone System—must be promoted and supported. Direction for each element of the program must come from operational NOAA or NRL/FNMOC components. Studies can include observing system impact studies (which can feed back on future deployment of observations), studies of numerical forecast system sensitivity to resolution, and preliminary tests of upgrades to fundamental components of the forecast system.

5.1.3 Observations and Observing Strategies

Continuing to advance observational capabilities for tropical cyclone analysis and numerical weather prediction is vital to the Nation’s tropical cyclone program. To maximize the benefit from limited resources, research is needed to systematically evaluate observing systems, develop observing system requirements, and document the benefits that can be expected from new observing systems to forecasts of tropical cyclones and related hazards.

To evaluate current and potential new observing systems and/or sampling strategies, techniques (likely statistical) need to be developed that address the uncertainty and representativeness of observations. In particular there are two places these uncertainties are applicable: (1) in real-time estimates of the storm structure and intensity; and (2) in the use of observations for initializing NWP models. A good example of the first type of uncertainty is the best-track estimate of tropical cyclones (see figure 1-3 for an example). The best-track estimate of Hurricane Frances intensity is shown in figure 5-2. There are large differences (scatter) in the winds, with some of the differences due to the storm structure (particularly for the aircraft and dropwindsonde observations), whereas other differences are due to uncertainty in the type of estimate used (e.g., Dvorak techniques [regular and automated], aircraft, SFMR, etc.). Each of these observational tools has an uncertainty. The uncertainty needs to be characterized to better quantify the goodness of the best-track estimates. Additionally, the uncertainty will be applicable to NWP model initialization, as the uncertainty/error of each data type used in the model is an important element. Another important aspect associated with NWP models is how the observational data is best utilized. For example, for surface observations, how do we extend the influence of the observation in the vertical? For dropwindsondes and Doppler (airborne and land-based) observations, how should the influence of these observations be extended horizontally or temporally to make best use of them?

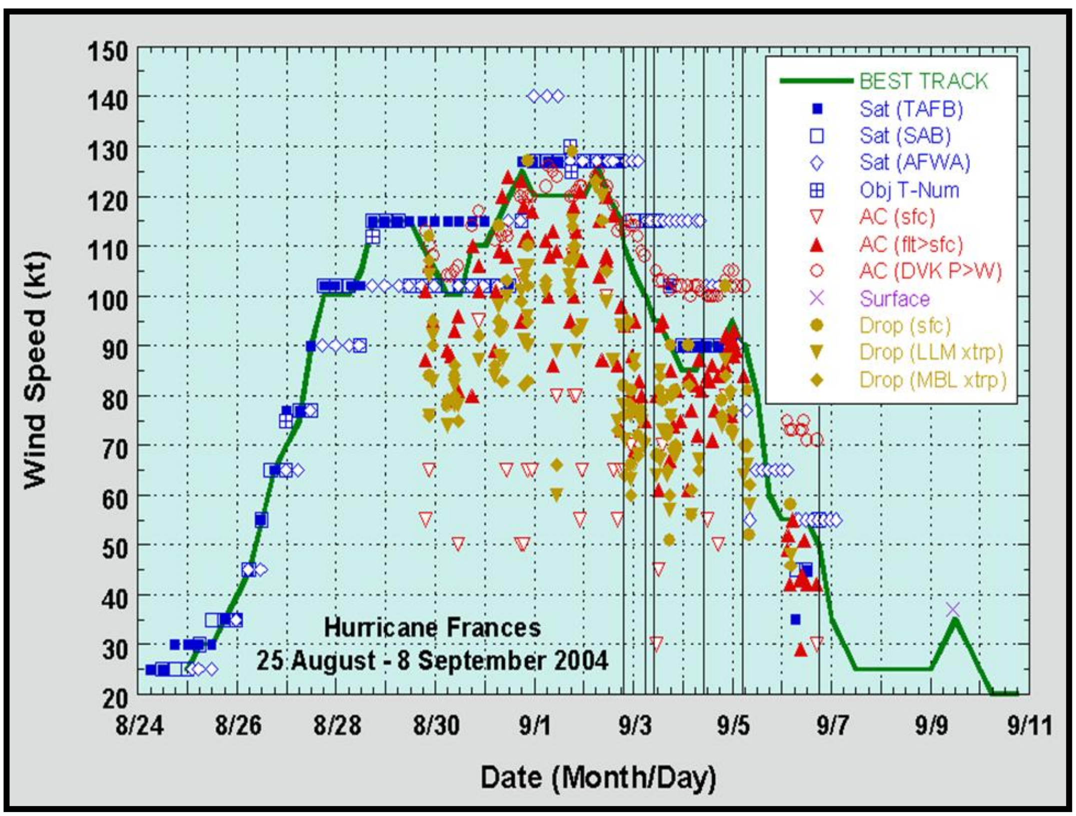


Figure 5-2. Best-track estimate of Hurricane Frances intensity as determined in the post-analysis of all available data (e.g., satellite, aircraft, GPS dropwindsondes). Credit: TPC/NHC

Another example of required research concerns the observing strategy to best utilize the WC-130s and WP-3Ds in sampling the maximum wind at flight level and/or sea-surface level. The current strategy, as described in section 3.1.1, uses Alpha Patterns flown through the storm. While the TPC/NHC attempts to make the best use of the aircraft, better quantification with modeling simulations and sampling theory is needed.

5.2 Climate Research Priorities—Intraseasonal, Interannual, and Longer-Term Variability of Tropical Cyclones

This section details the climate research priorities regarding intraseasonal, interannual, and longer-term variability of tropical cyclones. Tropical cyclone activity varies on multiple temporal scales: intraseasonal, interannual, decadal, and multidecadal. Paleoclimate work even suggests distinct variations on the centennial and millennium scales. Increasingly, there are requests for predictions on all of these time scales, which NOAA and other agencies—both public and private—are striving to provide.

On the intraseasonal—or monthly—time scale, research efforts have demonstrated the impact of features such as the Madden-Julian Oscillation (MJO) to produce clustering in time of tropical cyclone occurrences. These tend to last for 20–30 days of active and quiet cycles each, primarily for tropical cyclones forming in the low latitudes. NOAA is currently responsible for predictions up to two weeks in advance for global tropical cyclone activity outlooks based upon anticipated MJO phases. These are produced through a combination of statistical techniques, numerical model guidance (such as the GFS), and forecaster input. Continued research into the physical mechanisms for intraseasonal variability is needed, as well as improved statistical and numerical model tools.

Seasonal forecasts have been issued for the Atlantic basin over the past two decades, and NOAA has been providing official predictions since 1998. NOAA's predictions are released in late May (at the beginning of the Atlantic and eastern North Pacific hurricane seasons) and in early August (for the Atlantic, at the onset of the traditionally most active portion of the season). These are based upon pre-season assessments of current oceanic and atmospheric factors known to influence tropical cyclone activity (such as SSTs, sea-level pressures, tropospheric vertical wind shear, etc.) and how these may vary by the peak (August to October) of the hurricane season. The assessments use statistical tools (such as canonical correlation analyses and multiple regression techniques), numerical models (such as NOAA's Climate Forecast System), and forecaster interpretations of current climate trends. In deciding how the environment may behave during the peak of the season, it is often difficult to assess what components of the current oceanic and atmospheric conditions are transient (intraseasonal oscillations) versus longer-term (interannual and decadal) variations. One of the key factors for interannual predictions is the El Nino-Southern Oscillation (ENSO) phenomenon. Skillful long-lead forecasts of ENSO have been problematic, which is one of the reasons why NOAA issues its first forecast in late May. Additionally, little predictability is available for knowing the genesis locations and preferred tracks of hurricanes on a seasonal basis. Continued efforts are needed into the physics of what determines overall tropical cyclone activity on interannual time scales, including genesis and track preferences, as well as more skillful statistical and numerical model guidance.

Strong variability of tropical cyclones on long (25–40 years) time scales occurs in the Atlantic Basin, as has been documented by many studies over the past several years. During the past century, Atlantic tropical cyclone activity—especially the major hurricanes—tends to be in active and quiet phases for about 25–40 years each. Active periods were observed during the 1870s to early 1900s, the late 1920s to the late 1960s, and most recently from 1995 onward. Conversely, quiet episodes have been noted from the mid-1900s until the mid-1920s and again from about 1970 until the mid-1990s. These active and quiet periods are driven by combined ocean-atmosphere changes, with warm SSTs/reduced vertical shear and cool SSTs/increased vertical shear occurring in active and quiet periods, respectively.

Recently, there have been studies that suggest that the Atlantic activity in the past decade has been unprecedented compared with previous active eras and that such changes are linked to increased SSTs that may be caused by anthropogenic global warming. Moreover, even the longer-term swings in activity have also been suggested to have man-made origins. Such conclusions are currently quite controversial and depend in part upon the reliability of earlier historic hurricane databases. Much research is needed to ascertain both how much impact global warming is having today and in the future and how much longer the current active era will last. Efforts in coupled climate modeling, theoretical climate change studies, observational work on multidecadal time scales, and reanalyses of existing tropical cyclone databases are urgently needed to address the inconsistencies and controversies in this field.

5.3 Research Needs in the Social Sciences

As outlined in section 2.8.7, NOAA and other agencies are experiencing cultural shifts as they recognize the importance of social science to their mission. There is a growing understanding that hurricane disasters are social phenomena—intersections of atmosphere, human populations, social institutions, and the built environment—and that the tools and methods of the social sciences are essential to mitigating the impacts. Coastal population growth and land development have resulted in a dramatic rise in both the assets at stake and the value of an effective response system. Based on estimates that annual U.S. hurricane losses average about $10 billion (Pielke et al. 2007), cost savings of $100 million would result from every 1 percent of prevented losses. Knowledge gains in the social, economic, and decision sciences will lead to the implementation of better response strategies and can help set priorities as to where increased research would be most beneficial.

The next four subsections discuss four areas of social science research of particular importance to the hurricane forecast and warning system. Appendix P lists representative research questions in each of the four areas. These questions were developed at a workshop arranged by NCAR in February 2005 with funding from NSF.[1] They reflect a growing recognition of the contributions of social science in addressing the needs of the tropical cyclone program.

[1] For further information on the workshop see: http://swiki.ucar.edu/sip/uploads/31/Hurricane_Forecasting_and_Warning_System_Report.pdf.

5.3.1 Warning Process

Accurate forecasts are effective only if they result in appropriate actions at every level of response. It is important to understand how various end-user groups interpret forecasts and warnings and weigh their level of risk. The utility of products such as the Saffir-Simpson hurricane scale should be evaluated for effectiveness in predicting risk and impact. Warning terminology and graphics need to be tested for effectiveness with different segments of the population. What was once perceived as a simple linear warning communications process has become more complex with the development of new technologies and new intermediaries. NWS warnings are interpreted and even tailored for the individual needs of end users by broadcast media, private entrepreneurs, and public officials. They can be received via personal digital assistants (PDAs), cell phones, and the Internet. Social science research can answer questions regarding how these new communication processes and media affect hurricane response.

Effective risk communication requires an understanding of how people interpret and react to various levels and types of danger. Hurricane forecasts carry a level of uncertainty, and more research is needed to better understand effective ways of communicating probabilities.

Hurricane resiliency, whether at the household or community level, is largely a product of social and economic resources. Understanding how issues of race, gender, and class tend to increase the vulnerability of certain segments of the population is an important step toward tailoring the content and delivery of warning messages to target high-risk groups.

5.3.2 Decisionmaking

Understanding how different stakeholder groups utilize forecast and warning messages to make decisions is a social science challenge. It requires understanding how various terminologies and graphics are interpreted, as well as the process by which they are turned into recommendations and actions at various levels and spheres of response. Official response to warnings is inherently a political process that the forecast community can best navigate if it understands how issues of power and authority play out in its jurisdiction. It is important to understand the role of formal and informal social networks at all levels of hurricane response.

Severe weather warnings have to be clear not only in terms of the type of weather that the public and the authorities should prepare for but also how likely it is to occur. How to convey forecast uncertainty is an important topic for social science research. A major problem when issuing severe weather warnings is that the probability of the most extreme events occurring is very low. Social science research can lead to a better understanding of how people react to warnings about low probability, high-impact events. Most people respond to hurricane warnings as members of families and households. Research efforts to model household decisionmaking, especially related to evacuation, are promising and should be expanded.

5.3.3 Behavioral Response

The social sciences are making important contributions toward understanding and modeling hurricane response, including evacuation. Many factors, including the following, influence household response:

- Whether the message was received and understood
- The level of confidence or trust in the source
- Their assessment of risk
- The feasibility of various responses given their circumstances
- The extent to which the message is confirmed by other sources and social networks
- The resources available to facilitate their response

The first step toward promoting effective response is to better understand this process. Post-event behavioral studies provide important data in this regard; however, there is a paucity of comparative studies across events. Protocols need to be developed to promote data sharing and multi-event, long-term research.

5.3.4 Social Impacts and Valuations

The NWS is increasingly asked to quantify the value of improved forecasts. An example of important social science research that needs to be undertaken is to better estimate the cost per mile of tropical cyclone watches, warnings, and evacuations. However, conventional cost-benefit analysis fails to account for the social or human costs incurred when hurricanes affect communities and families. Qualitative social science research methods can make important contributions toward documenting impacts not readily measured by standard economic techniques.

Recovery from major hurricanes usually takes many years and support for multiyear research projects is important in order to understand long-term impacts. Spatial analysis, using a geographical information system (GIS), is crucial to understanding and assessing impacts on various segments of the community, including where the homes of high-risk segments tend to cluster.

5.3.5 Social Sciences Summary

The theories, tools, and methodologies of social sciences are crucial to the enterprise of improving hurricane response. Surveys, focus groups, in-depth interviews, field observations, and demographic analysis are some of the methods that can lead to a better understanding of how forecasts and warnings are received, interpreted, and used. **While there is a growing recognition of the potential contributions of social sciences research, to date it remains underfunded and underutilized.**

5.4 Oversight of the R&D Program for Tropical Cyclones

The preceding sections of this chapter, along with appendix P, have detailed the R&D priorities to further improve the effectiveness of tropical cyclone forecast and warning services, with the goal of preventing loss of life and injuries associated with tropical cyclones and of reducing the Nation's vulnerability to these potentially devastating storms.

The research priorities, coupled with the processes for transition of research to operations outlined in section 4.5, are important to a successful overarching R&D program for tropical cyclones. Another element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to conduct the following activities:

- Monitor and update a listing of the operational needs of the tropical cyclone forecast and warning centers
- Monitor and update a listing of the research priorities to meet the needs of the operational tropical cyclone forecast and warning centers
- Develop a succinct 10-year, multiagency research implementation plan that outlines specific strategies to address all of the research priorities
- Update the implementation plan (above bullet) as required (e.g., at least annually)

The JAG/TCR recommends that this coordination requirement and development of a research implementation plan be satisfied ***through the OFCM infrastructure*****.** One possible solution is to form a Working Group for Tropical Cyclone Research, cochaired by NOAA, NASA, NSF, and the U.S. Navy—with the working group tasked to maintain/publish the items identified above and, at a minimum, provide updates at the annual OFCM-sponsored Interdepartmental Hurricane Conference.

5.5 Summary

This chapter introduced the operational needs of the tropical cyclone forecast and warning centers and drove home the point that meeting the operational needs will require continued advances in observations, data assimilation technologies, and tropical cyclone NWP models. Key to these advances is the Nation's commitment to provide sufficient human and infrastructure resources for tropical cyclone research, development, and transition of research to operations, along with sufficient resources for the operational NWP model environment. Through these mechanisms and commitments, operational tropical cyclone forecasting skill will increase, which will help to reduce loss of life, injuries, and economic and societal vulnerability to tropical cyclones. At the same time, research in the social sciences is essential to identifying and implementing more effective end-user communication and response strategies, along with documenting long-term social and economic impacts. The next chapter discusses the key findings and recommendations for a roadmap of activities to improve tropical cyclone forecasting and warnings during the next decade and beyond.

6
KEY FINDINGS AND RECOMMENDATIONS: THE WAY AHEAD

6.1 Introduction

To improve the predictability of tropical cyclones will require a concentrated, collaborative, all-inclusive community effort. Accurate forecasts of tropical cyclone behavior are a critical need for many segments of society. Obtaining a better understanding of the complex interactions of tropical cyclone intensity, structure, track, and environmental forcing is too large a problem for any single research entity or Federal agency to address alone.

As shown in chapters 1 and 2, numerous organizations and entities in the public and private sector, including the academic community, contribute to tropical cyclone research. It is imperative that this community of practice (see section 1.5) work together to further improve the forecast skill of all tropical cyclone–related components (e.g., intensity and structure [wind radii], track, sea state and storm surge, and precipitation). Table 6-1 illustrates the community of practice. Additionally, social sciences research needs to be enhanced and integrated with the research of other disciplines, and those results must be incorporated into operational procedures. The key findings and recommendations that are summarized later in this chapter involve all of these organizations/entities. This all-inclusive plan provides a collaborative "way ahead" for the Nation's tropical cyclone program.

To review, chapter 1 illustrated the fundamental rationale for continuing efforts to further advance the Nation's tropical cyclone forecasts and warnings. It introduced the operational centers for the Nation's tropical cyclone warning service, serving both civilian and military needs, and the community of practice that supports these operational centers. Chapter 2 described in more detail the community of practice and also reviewed recent and concurrent planning activities that were taken into account in formulating the research priorities. The results of the planned R&D will need to be transitioned to operational NWP models to reap real benefits for the Nation.

Chapter 3 assessed the current capabilities and limitations of the Nation's tropical cyclone warning service. These capabilities constitute a classic end-to-end meteorological warning and forecasting system, from data collection through data assimilation and NWP modeling to dissemination of warnings and forecasts, including end-user education, training, and outreach. Chapter 4 used the same end-to-end system structure to present the JAG/TCR's perspective on future capabilities planned to meet the operational needs identified by the operational centers.

Chapter 5 presented the tropical cyclone research priorities to aid in meeting the future operational needs of the tropical cyclone forecast and warning centers and enhancing all aspects of the end-to-end forecast system. The priorities were divided into three categories: atmospheric/oceanic, seasonal forecasts (climatological), and social sciences.

Table 6-1. Illustration of the Tropical Cyclone Community of Practice

Entity/Organization	Contribution
NASA	Remote sensing/satellites – New instrument development Field experiments/tropical cyclone research JHT JCSDA (GMAO)
NSF	Field experiments/tropical cyclone research – Includes social sciences Sponsor – University/academia research grants – NCAR
U. S. Navy	Field experiments (ONR)/tropical cyclone research NWP modeling (NRL/FNMOC) JHT JCSDA
U.S. Air Force	53rd Weather Reconnaissance Squadron SFMR Air Force Weather Agency JCSDA
USACE - ERDC	Field research facility—continuous coastal field data collection Typhoon field data collection—Pacific Islands Numerical model development (WaveWatch III, ADCIRC, STWAVE, ESMF)
NOAA	Field experiments/tropical cyclone research – OAR laboratories (e.g., AOML HRD) – NESDIS – NOS – Aircraft Operations Center – JHT NWP ,modeling (NCEP/EMC) – Operations and research JCSDA
Academia	Field experiments/tropical cyclone research (numerous universities) – Includes social sciences – Focused education programs
International Organizations	Tropical cyclone research NWP modeling
JTWC (U.S. Navy, U.S. Air Force)	Operational tropical cyclone forecasting Tropical cyclone research, development, and testing
TPC/NHC and CPHC (NOAA)	Operational tropical cyclone forecasting Tropical cyclone techniques development and testing

This chapter presents the JAG/TCR summary of key observations/findings and recommendations for a roadmap of activities to improve tropical cyclone forecasting and warnings. The ultimate goal of these activities is to enable precise, high-confidence decisions that save lives and reduce property damage in storm-threatened areas.

6.2 Summary of Key Findings

This plan highlights several key findings, which are summarized below. For a detailed discussion of a finding, refer to the referenced section within this plan.

6.2.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers

1. Table 4-1 lists the operational needs, in the priority order given in the 2006 AFFO, along with related needs statements emphasized by the DOD participants at the 59th IHC. This listing thus represents the best available compilation and prioritization of operational needs across the three U.S. centers: TPC/NHC, CPHC, and JTWC **(section 4.1)**.
2. To continue to advance operational tropical cyclone forecasting capability and to meet the operational needs summarized in table 4-1, the Nation must be committed to supporting—through research, development, and transition to operations—the following key areas vital to the tropical cyclone forecast and warning program **(chapter 4, introduction)**.
    - Advanced observations
    - Advanced data assimilation technologies
    - Advanced NWP models
    - Investment in human and infrastructure resources

6.2.2 Data Collection/Observations

1. Continuing to advance observational capabilities for tropical cyclone analysis and numerical weather prediction is a vital component of the Nation's tropical cyclone program. With numerous new observational platforms and sensors potentially available in the next several years, a coordinated approach is needed to improving tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.) **(section 4.2)**.
2. Observations of the tropical cyclone inner core are essential for tropical cyclone analysis and the initialization of the tropical cyclone vortex in operational, high-resolution, next generation NWP models. The initialization is critical to improving tropical cyclone intensity and structure forecasts. Given the current limitations in satellite observations, the only inner-core wind data routinely available are collected by aircraft reconnaissance (**section 3.1.6**).
3. The new and improved observation systems that are under development or being planned (sections 4.2.2 through 4.2.12) hold substantial promise for improving tropical cyclone analysis; NWP modeling; and our fundamental understanding of the tropical cyclone atmosphere and ocean environment, the tropical cyclone inner and outer cores, and the interactions among these components. These systems include in situ measurements of

winds over oceans in areas with tropical cyclones, as well as remote-sensing methods to measure temperatures, humidity, winds, sea surface heights, ocean wave heights and swell motion, and precipitation. The remote-sensing data will be provided from a combination of sensors located on aircraft, on polar-orbiting and geostationary satellites, and on land (e.g., weather surveillance radar). However, as discussed in s**ections 4.2.2 and 4.2.12**, there are significant gaps in meeting the observation requirements for altimetry and ocean surface vector winds that must be addressed. Researchers and system developers must work together to seek viable solutions to meet these requirements (**section 4.2.13**). The development and evaluation of new observational technologies and observing strategies are research priorities identified in chapter 5 of this report.

a. Tropospheric Winds

   i. Due to the importance of ocean surface vector winds (OSVW) data—for use by tropical cyclone forecasters and in tropical cyclone NWP systems—the JAG/TCR strongly endorses the development and acquisition of a capability to meet the OSVW observation requirements. This capability is absolutely critical to meeting the operational needs of the tropical cyclone forecast and warning centers summarized in table 4-1 **(section 4.2.12).**

   ii. The JAG/TCR also strongly endorses the development of a capability to accurately measure the three-dimensional global wind field to optimally specify global initial conditions for numerical weather forecasts and much improved tropical cyclone track forecasts **(section 4.2.12)**.

b. Since satellite altimetry is vital to addressing the needs of the tropical cyclone forecast and warning centers summarized in table 4-1, the JAG/TCR strongly endorses the acquisition of an altimeter instrument for NPOESS as an alternative to the cancelled NPOESS ALT instrument (**section 4.2.2**).

6.2.3 NWP Modeling and Data Assimilation

1. While global and regional-scale NWP models have proven highly successful at forecasting tropical cyclone tracks, coupled models with much higher resolution will be necessary to make further strides in forecasting tropical cyclone intensity, structure (wind radii), sea state and storm surge, and precipitation***. Increased skill in forecasting intensity and structure, sea state and storm surge, and precipitation is now on the horizon, much as improving track forecast skill was two decades or so ago*** **(sections 3.3, 4.4.2, and 4.4.3).**

2. The development of new techniques for assimilating high-resolution data sets is a fundamental activity required for advancing numerical prediction of hurricane intensity and structure, both of which are important to improved forecasts of intensity, structure, sea state, storm surge, and precipitation. New data sources are critical to initializing the forecast system in two key domains: (1) the large-scale environment, and (2) the vortex core. One of the most significant challenges to be met by NCEP and other operational NWP modeling centers over the next two decades is the assimilation of data from new satellite instruments that are scheduled to be launched. As described in **sections 2.4.6** and **3.6.5**, this challenge is being addressed through the JCSDA **(section 4.4.2)**.

Improving tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state and storm surge, and precipitation is the overall goal guiding the ongoing development of next generation hurricane forecast systems. The work led by NOAA/EMC to develop the HWRF Air-Sea-Land Hurricane Prediction System is described in **section 4.4.2**. The parallel and complementary effort led by NRL-Monterey and FNMOC to continue improving the COAMPS Tropical Cyclone System is described in **section 4.4.3**. These complementary development efforts should be a national priority. They should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies. **(section 4.4)**.

a. Additional human and infrastructure resources (e.g., items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems) will be necessary to support development, operations, and maintenance of advanced data assimilation and NWP modeling systems **(section 4.4)**.

b. The HWRF Air-Sea-Land Hurricane Prediction System is NOAA's next generation, high-resolution hurricane prediction system scheduled for operational implementation at NCEP in 2007. The HWRF system will use advanced data assimilation capabilities and incorporate sophisticated physics suitable for high-resolution and coupled air-sea-wave-land modeling processes. The Nonhydrostatic Mesoscale Model (NMM) will be the core model of the HWRF system. The system will make use of moving nests with two-way feedback in the atmospheric, ocean, and wave models. By coupling the HWRF system with advanced wave and storm-surge models, the HWRF system will provide improved predictions of coastal inundation. To address the inland flooding problem, the land-surface component of the HWRF system will be coupled to a hydrology model for improved precipitation guidance for landfalling tropical cyclones **(section 4.4.2)**.

c. For the U. S. Navy, regional, high-resolution model development is based on COAMPS. NRL has developed a prototype advanced data assimilation system which is targeted for operational implementation at FNMOC in 2008. NRL will collaborate with NASA/GMAO and NCEP/EMC during the future development of this data assimilation system. The future COAMPS Tropical Cyclone System will couple an ocean and wave model to the COAMPS nonhydrostatic atmospheric dynamical core. The system will make use of moving nests with two-way feedback in the atmospheric model and will eventually include nested grids in the ocean models. In order to model the fluxes more accurately, the atmospheric and ocean wave models will interact with a sea spray submodel to represent the air-sea exchanges in the wave boundary layer **(section 4.4.3)**.

d. Development of the COAMPS Tropical Cyclone System will occur in parallel with development of the HWRF Air-Sea-Land Hurricane Prediction System. Statistics on tropical cyclone track guidance clearly demonstrate that superior track guidance is produced using a multi-model consensus. For the future, it is vital to have such a multi-model capability for intensity forecasting as well **(section 4.4.3)**.

3. A parallel operational NWP research capability for testing and implementing changes to the operational NWP configuration is absolutely essential. To maximize improvements to the operational NWP model, it is also critically important to have a steady flow of relevant research focused on improvements to the operational NWP system (i.e., focused on the NWP research priorities outlined in chapter 5). The current infrastructure at NRL/FNMOC and NCEP/EMC is inadequate to conduct extensive parallel testing **(sections 3.6.1 and 4.5)**.
4. Funding for the transition of research to operations remains deficient. Within an era of constant or diminishing dollars, R&D and transition needs will likely be competing with each other. A mechanism is needed to enhance development and transition of research to operations activities throughout the tropical cyclone operations and research community to further improve operational, high-resolution tropical cyclone NWP models, thereby maximizing benefits for the Nation **(section 4.5.3)**.

6.2.4 Forecasting and Warning

1. Probabilistic guidance based on advanced high-resolution regional models (e.g., HWRF and COAMPS ensembles) is necessary to estimate adequately the forecast uncertainties in critical storm attributes and in related impacts such as damaging winds, precipitation, and storm surges that arise from the combined uncertainties in track, structure, and intensity. However, the capability to run HWRF and COAMPS ensembles and multi-model ensembles within operational forecasting time constraints depends directly on the available computing power **(section 4.4.2)**.
2. An action that stemmed from the 60th IHC was that the Nation's hurricane warning program warranted a review, which should include NOAA working with user groups to develop and test warning message format modifications to optimize desired outcomes. Both technical and actionable messages should be reviewed and optimized, and product timing cycles should be coordinated with end users, especially for media news cycles. Additionally, the OFCM will organize meetings to bring together the appropriate Federal agencies to begin the process of reviewing and improving the National hurricane warning system **(section 2.8.9)**.

6.2.5 Tropical Cyclone Research and Research Coordination

1. **Research**
    a. **Section 5.1** provides the consensus views of the Federal agencies on specific atmospheric- and oceanic-related tropical cyclone research priorities. **Section 5.2** details the climate research priorities regarding intraseasonal, interannual, and longer-term variability of tropical cyclones. **Section 5.3** and **appendix P** discuss social science research areas important for the hurricane forecast and warning system.
        (1) In addition to physical sciences research that must continue to meet forecast challenges, greater emphasis is needed on social sciences research **(section 1.3).**

(2) While there is a growing recognition of the potential contributions of social sciences research, to date it remains underfunded and underutilized **(section 5.3.5)**.

b. Sufficient funding to sustain the analyses of the data sets from field experiments should be a priority. **(section 3.5.5)**.

2. **Coordination**

   Another element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to conduct the following activities **(section 5.4)**:

   - Monitor and update a listing of the operational needs of the tropical cyclone forecast and warning centers
   - Monitor and update a listing of the research priorities required to meet the needs of the operational tropical cyclone forecast and warning centers
   - Develop a succinct 10-year, multiagency research implementation plan that outlines specific strategies to address research priorities
   - Update the implementation plan (above bullet) as required (e.g., at least annually)

6.2.6 Education, Outreach, and Workforce Development

1. The agencies and organizations—public and private—involved with education, training, and outreach concerning the public's knowledge and appreciation of tropical cyclone impacts and the appropriate public responses to reduce those risks must never assume their task is done. These efforts must continue, and they must be accorded the priority they deserve **(section 3.7.3)**.
2. An area of extreme importance for improving tropical cyclone forecasts is advancing data assimilation and tropical cyclone NWP modeling systems. An important example of a deficiency in workforce development is that the United States is not producing enough new personnel with the education and training required for improving tropical cyclone forecasts via advanced data assimilation and numerical modeling systems. Resolving this deficiency will require strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities **(section 3.7.3)**.

6.3 Recommendations

The JAG/TCR developed recommendations that follow logically from some of the key findings identified above. The recommendations are listed in table 6-2.

Figure 6-1, which is associated with recommendations 1 and 2, illustrates the focused research, collaborations, and increased resources that are required and envisioned to lead to essential tropical cyclone prediction improvements over the next decade. Every component represented in

Table 6-2. JAG/TCR Recommendations

No.	Category	Recommendation	Section 6.2 Reference
1	**Tropical cyclone NWP modeling**	The continued development and implementation of the next-generation tropical cyclone forecast systems, such as the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, to improve tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state/storm surge, and precipitation should be a high priority for the Nation.	6.2.3: 1,2
		a. Development and transition of research to operations: (1) The development efforts of the next-generation hurricane forecast systems should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies.	6.2.3: 2
		(2) Sufficient human and infrastructure[a] resources should be provided to support development of advanced data assimilation and NWP modeling systems (see figure 6-1).	6.2.3: 2a
		(3) An interagency working group, under the auspices of the OFCM, should be formed to develop a plan to support the tropical cyclone NWP program. The plan should: (a) include procedures to enhance the flow of relevant research focused on improvements to the operational NWP systems; (b) improve the conduit by which the academic community could be involved in the next-generation hurricane model development and testing (e.g., through the JHT and DTC) and (c) account for having sufficient human and infrastructure[a] resources for development work and transition of research to operations activities, including sufficient resources to support collaborative ventures (see figure 6-1).	6.2.3
		b. Operations: Sufficient human and infrastructure[a] resources, including the capability to run ensembles with the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, should be provided to NCEP/EMC and FNMOC for their operational NWP tropical cyclone model programs.	6.2.4: 1
2	**Tropical cyclone research and research coordination**	a. **Research** (1) The JAG/TCR recommends strong support for activities focused on the tropical cyclone research priorities identified in chapter 5.	6.2.5: 1a
		(2) Results of social science research need to be an integral part of the hurricane forecast and warning program. With increased funding, a possible venue to pursue social science research questions is through the Joint Hurricane Testbed (without compromising current projects).	6.2.5: 1a
		(3) Sufficient and sustained funding is needed for analyses of field experiment data sets.	6.2.5: 1b
		b. **Research Coordination.** An element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to perform the tasks described in section 6.2.1, paragraph #2. The JAG/TCR recommends that this coordination requirement and development of a research implementation plan be satisfied through the OFCM infrastructure.	6.2.5: 2

3	**Strategic plan for tropical cyclone observations**	Through the OFCM infrastructure, a strategic plan for improved tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.) needs to be developed. The plan should consider observations and observing strategies for tropical cyclone forecaster needs, data assimilation for NWP models, and NWP model diagnostics and verification.	6.2.2: 1
4	**Tropical cyclone warning program review**	NOAA (including OFCM), along with Federal agencies, should continue to review and improve the Nation's hurricane warning program.	6.2.4: 2
5	**Education, out-reach, and work-force development**	a. Education, training, and outreach efforts concerning the public's knowledge and appreciation of tropical cyclone impacts must continue, and they must be accorded the priority they deserve. b. To resolve the deficiency within this Nation in producing enough qualified (educated) personnel with the requisite NWP modeling education and training, there needs to be strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities.	6.2.6: 1 6.2.6: 2

[a] Infrastructure resources are related to items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems.

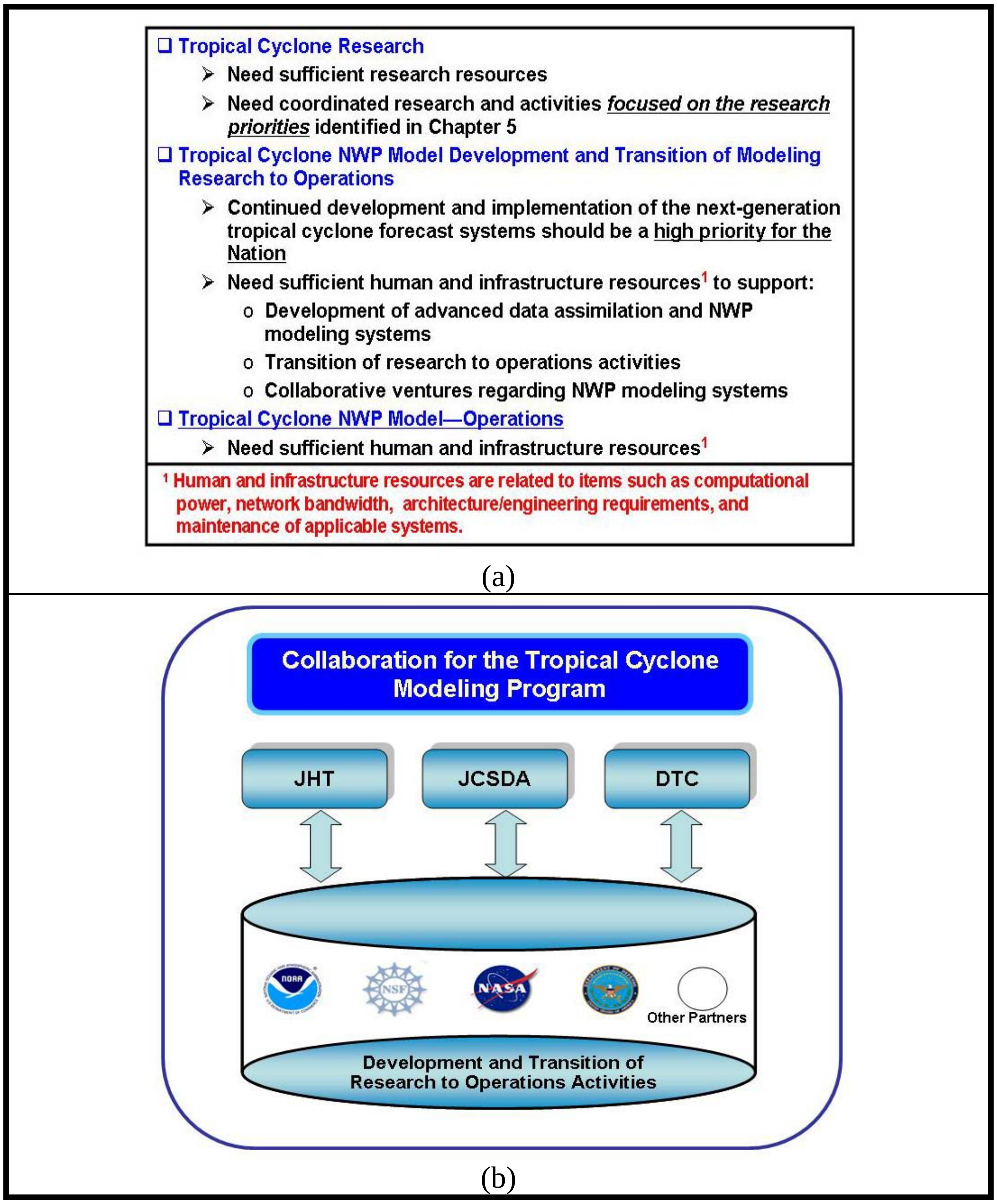


Figure 6-1. Illustration of recommendations 1 and 2.

figure 6-1a is absolutely essential to ***maximize the benefits for the Nation***. The activities for tropical cyclone model development and for transition to operations ***will be the keystone for successful R&D.*** These R&D and operational transition activities are the proving ground and implementation process for all of the tropical cyclone research categories and topics. Results from a broad spectrum of government and academic initiatives will require significant planning, scientific and technical evaluations, coordination and testing, and implementation activities. The envisioned tropical cyclone modeling program will therefore need significant infrastructure with major testing resources and substantial workforce to achieve the savings in life and property expected from the research results. Each collaboration entity represented in figure 6-1b contributes to the overall improvement in modeling capability. For example, the JCSDA serves a key role in expediting the assimilation of data from new satellite-based observing systems and instruments into operational models used to prepare forecasts and warnings.

6.4 Resource Estimates Associated with Recommendations

Table 6-3 summarizes new investments (funding increases above currently projected levels) that are associated with the JAG/TCR recommendations and are required to continue advancing tropical cyclone science and operational capabilities. These investments are the best estimates of the JAG members, based on their combined experience with current and past budgets for tropical cyclone research and development

- The ***development*** of advanced data assimilation ***and*** NWP modeling systems is vital to further improving the Nation's tropical cyclone forecasting capability. The tasks associated with the development of these systems will require additional resources to tackle the myriad of complex, manpower-intensive work that needs to be accomplished. Funding to significantly enhance tropical cyclone ***transition of research to operations*** activities and capabilities will be the keystone for successful R&D. As mentioned in section 6.3, these functions are the proving ground and implementation process for all of the tropical cyclone research categories and topics **(table 6-2, recommendation 1a)**.
- Sufficient human and infrastructure resources need to be provided to the tropical cyclone ***operational*** NWP modeling centers (i.e., NCEP/EMC and FNMOC), including sufficient computing power to sustain and enhance the tropical cyclone forecast and warning program. Obviously, moving to higher resolution, coupled NWP models will require increased computing power. As an example, NOAA's high performance computing experts estimate that increasing hurricane model resolution to 1 km would be 14,580 times more computationally expensive. This enhancement would take over 28 years to achieve at current budget levels/strategies.[1] This underscores the vital need to significantly enhance current funding levels of the Nation's operational tropical cyclone NWP models. As mentioned above, the human and infrastructure resource investments must account for the two U.S. NWP centers providing operational guidance for informed critical decisions (i.e., the two centers, NCEP/EMC and FNMOC, that plan to run advanced, coupled models and apply consensus and ensemble techniques for operational tropical cyclone guidance) **(table 6-2, recommendation 1b)**.
- The atmosphere/ocean research priorities are described in Section 5.1. The investments included in this category are expected to provide results for transitioning into operations through the hurricane testbed process (e.g., JHT, JCSDA, DTC, NCEP/EMC, NRL/FNMOC) and later in the education and outreach category. Therefore, the investments are shown increasing/decreasing in the associated categories as results mature and feed into the transition and operations activities **(table 6-2, recommendation 2)**.

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[1] Personal communication from Frederick Toepfer, NOAA Environmental Modeling Program Manager, to Mark Welshinger, OFCM.

Table 6-3. Additional Resource Estimates ($ millions above Current Plan) Associated with the JAG/TCR Recommendations[a]

Rec. No.	Recommendation Summary	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17
1a	Development of advanced data assimilation *and* NWP modeling systems; Transition of research to operations	30	30	30	30	30	30	30	25	25	25
2a	Atmospheric- and ocean-related research, including analyses of field experiment data sets	15	15	15	15	15	10	10	10	10	10
	SUBTOTAL ***Research, Model Development, and Transition to Operations***	45	45	45	45	45	40	40	35	35	35
1b	Operational NWP computing (NCEP *and* FNMOC)	30	30	30	30	30	30	30	30	30	30
	SUBTOTAL ***Previous Subtotal Plus Operational NWP Computing***	75	75	75	75	75	70	70	65	65	65
2a	Social science research	10	10	10	10	10	5	5	5	5	5
	TOTAL	**85**	**85**	**85**	**85**	**85**	**75**	**75**	**70**	**70**	**70**

[a]The estimates do not include some significant *operational* acquisition costs (e.g., to plan, build, launch, and support an ocean surface vector wind satellite system).

- Analyses of field experiment data sets will require consistent funding throughout the next decade. Initially, a large effort will be needed to harvest and analyze the information from past, current, and continuing field experiments. When new observing platforms and sensors are available, their data sets will require analyses and integration with the results from heritage systems **(table 6-2, recommendation 2)**.
- Social sciences will require strong research emphasis in the early funding years to help bring multidisciplinary talents to bear on these important aspects of research described in section 5.3. As this research matures, its results will feed into the testbed process and will require greater emphasis in the education and outreach category **(table 6-2, recommendation 2)**.

The following general factors for research investments are relevant to all of the resource estimates presented in table 6-3:

- Investments in each of the research categories are not mutually exclusive. Research in any of the areas is expected to help leverage investments in other areas, to the overall benefit of tropical cyclone prediction accuracy, and in the application of the predictions by decisionmakers.
- Each of the research categories includes some research that may also be supported by studies or experiments in other research areas or in transition into operational activities where the research results are applied.
- Proposed budget figures are increased or decreased with time, based on expected increases in knowledge and understanding and subsequent improvements in operational applications that implement the results of the new knowledge and understanding.
- The proposed research funds may be distributed among all agencies that conduct tropical cyclone research or research on the impacts of tropical cyclones on the U. S. population and resources at risk.

6.5 Summary

Coastal population growth and land development have resulted in a dramatic rise in the assets at stake that could be affected by tropical cyclones. Approximately fifty percent of Americans now live within 50 miles of a coastline (NRC 1999) and are thus potentially exposed to the wrath of a landfalling hurricane. Annual U.S. hurricane losses average about $10 billion (Pielke et al. 2007). In a recent analysis of hurricane damages from 1900 to 2005, Pielke et al. (2007) noted that their normalization method agrees with insurance industry data in projecting a doubling of economic losses from landfalling hurricanes every ten years.

One important contribution to avoiding loss of lives and reducing risk and vulnerability to hurricane landfall and tropical cyclone movement is highly accurate meteorological forecasts that can be used to ensure that credible warnings are issued in a timely manner. In addition, the public and military operations being threatened must have confidence in those warnings, understand them, and take the appropriate actions to protect property and evacuate when necessary. Further improvements to the Nation's tropical cyclone forecast and warning service are feasible, within reach, and ***valuable investments for our safety, security, and economic well-being***.

This comprehensive plan: (1) reviewed the tropical cyclone R&D community; (2) examined the current capabilities and limitations of the Nation's tropical cyclone forecast and warning system; (3) summarized the operational needs of the tropical cyclone forecast and warning centers—TPC/NHC, CPHC, and the JTWC—and the planned capabilities to meet the needs; (4) identified tropical cyclone research priorities to aid in meeting the operational needs; and (5) presented a comprehensive roadmap of activities to further improve the effectiveness of the Nation's tropical cyclone forecast and warning service during the next decade and beyond.

Vast improvements in tropical cyclone prediction are attainable with focused research efforts; enhanced transition of research to operations capabilities; strong interagency partnerships, coordination, and planning; and ***most importantly, sufficient resources***—both human and infrastructure. The capability to gain skill in forecasting rapid intensity changes and to improve predictions of hurricane intensity and structure, sea state/storm surge, and precipitation is currently on the horizon, much as improving hurricane track was two decades or so ago. The ultimate goal is to prevent loss of life and injuries and to reduce the Nation's vulnerability to these potentially devastating storms. This goal can and must be accomplished for the good of the Nation.

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APPENDIX A
SUMMARY OF SATELLITE DATA USED IN NCEP'S OPERATIONAL DATA ASSIMILATION SYSTEMS

- **HIRS sounder radiances**
- **AMSU-A sounder radiances**
- **AMSU-B sounder radiances**
- **GOES sounder radiances**
- **GOES, Meteosat, GMS winds**
- **GOES precipitation rate**
- **SSM/I precipitation rates**
- **TMI precipitation rates**
- **SSM/I ocean surface wind speeds**
- **ERS-2 WS ocean surface wind vectors**
- **SeaWinds ocean surface wind vectors**
- **AVHRR SST**
- **AVHRR vegetation fraction**
- **AVHRR surface type**
- **Multi-satellite snow cover**
- **Multi-satellite sea ice**
- **SBUV/2 ozone profile and total ozone**
- **AIRS**
- **MODIS winds**
- **Altimeter sea level observations (ocean data assimilation and wave data assimilation system)**

Note: Refer to Appendix Q for the acronyms used in this appendix.

Polar orbiting platforms used in NCEP's operational data assimilation systems include high-quality data from functioning instruments on the following platforms:

- **NOAA polar orbiting satellites** (e.g., HIRS, AMSU-A, AMSU-B, AVHRR)
- **Defense Meteorological Satellite Program (DMSP);** for example: SSM/I
- **NASA;** for example:
  - **TRMM** (e.g., TMI)
  - **QuikSCAT** (e.g., SeaWinds)
  - **Aqua** (e.g., AMSU-A, AIRS, MODIS)
  - **Terra** (e.g., MODIS)
- **European Remote Sensing Satellite (ERS)**—for example:
  - **ERS-2 (**e.g., WS [Wind Scatterometer])

NOTES

- Atmospheric observations (all instruments in the above table except altimeter observations) are used by:
  - NCEP Global Data Assimilation System (GDAS)
  - NCEP Regional Data Assimilation System (RDAS)

  (Provided they meet the data cutoff times of 1:15 for the RDAS and 2:45 for the GDAS)
- Sea Surface Temperature (SST) retrievals are used by all atmospheric weather models for a daily lower boundary condition.
- Ocean observations (altimeter observations in table above) are used in NCEP's:
  - Global Ocean Data Assimilation System (GODAS) for climate forecasting
  - Real-Time Ocean Forecast System (RTOFS) for daily ocean forecasting
  - Global Wave Forecast System

APPENDIX B
IMPORTANT UPGRADES TO GLOBAL MODELS AND OPERATIONAL USE OF HIGH-RESOLUTION REGIONAL MODELS

Improvement in hurricane track forecasts has been well documented over the past three decades. Figure B-1 shows the reduction of the 72 hour official track error of the TPC/NHC over this period from 400 nm to less than 200 nm. The improved skill closely follows the continuous advancement of operational numerical models and their enhanced forecast capabilities.

The documentation of model track skill originated with CLIPER in the 1970s, a statistical model based on climatology and persistence, which became the benchmark for track skill for all future model track forecasts (Neuman 1972). An improvement of track skill continued in the 1980s with the use of a hybrid model that combined statistical techniques with background fields from NOAA's global model (e.g., the NHC-83, NHC-90 [Neuman and McAdie 1991]), the development of a barotropic model (VICBAR) for operations, a one level advection model (BAMS), and a quasi-lagrangian dynamical model (QLM) that ran at NCEP in the late 1980s and early 1990s. These early models all helped define the downward linear trend into the early-mid 1990s to reduce the forecast errors at all forecast times. The description and performance characteristics of these early track models are described in DeMaria (1997); McAdie and Lawrence (2000).

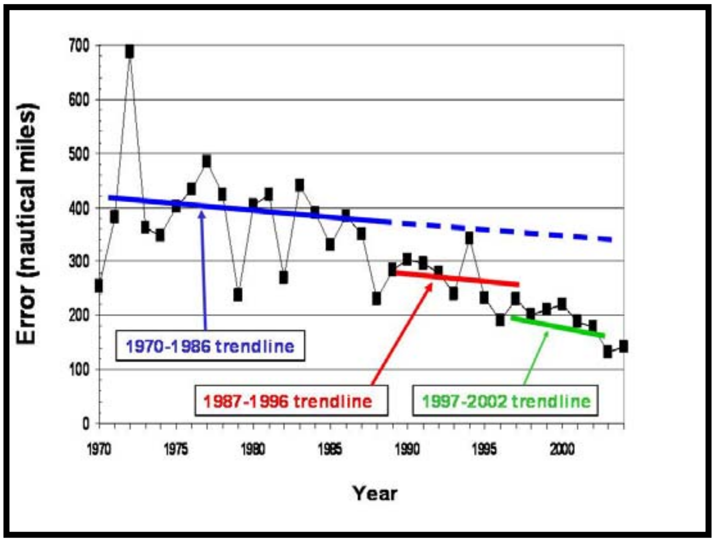


Figure B-1. TPC/NHC 72-Hour Track Forecast Errors, Atlantic Basin

As shown in Figure B-1, a pronounced acceleration in track forecast skill occurred in the mid-1990s with increased use of global models (e.g., the Global Forecast System (GFS; formerly the MRF/AVN) run at the National Centers for Environmental Prediction (NCEP); the Navy Operational Global Atmospheric Prediction System (NOGAPS) run at Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the United Kingdom Meteorological Office global model (UKMO)). The increase in forecast skill is tied to the availability of global observations (e.g., satellites), an advancement of global modeling numerical techniques that could maximize the usefulness of these data, and increased sophistication in representing model physics to provide routine high quality global analyses.

Since the early 1990s, the horizontal resolution of the NOGAPS global spectral model has tripled while its vertical resolution has nearly doubled. For example, from 1989 to1994, the NOGAPS model resolution was T79L18 (~165 km horizontal resolution, 18 vertical levels), using the Arakawa-Schubert convective parameterization scheme (Arakawa-Schubert 1974) ; from 1994 to 2000, the NOGAPS model resolution was either T159L18 or T159L24 (by 1998), using the Arakawa-Schubert convective parameterization scheme. From 2000 to 2002, the NOGAPS model resolution was T159L24, using the Emanuel convective parameterization scheme (Emanuel 1991, Emanuel and Zivkovic-Rothman 1999). Finally, from 2002 to the present, the resolution of the NOGAPS model has been T239L30, using the Emanuel convective parameterization scheme. Similar upgrades to other global models also occurred.

There were other important upgrades to the global models, and a few examples follow. To represent the hurricane scale, a bogus vortex was developed by Lord (1993) and incorporated in the NCEP global model. The direct use of satellite radiances replaced the use of retrievals in the GFS data assimilation system at NCEP in 1995 (Derber and Wu 1998). The assimilation of high density multispectral GOES-8 winds (Velden et al. 1997) into NOGAPS was initiated at FNMOC in 1996 (Goerss et al. 1998).

Although global model forecasts were advancing to provide better track forecasts, after the devastation of Hurricane Andrew in 1992 in South Florida and a clear inability of the global models to forecast the catastrophic landfall winds, a resurgence in developing high-resolution dynamical hurricane models became a focus not only for improving track forecasts but also offered promise for providing the higher resolution forecast models needed to address hurricane intensity forecasts. Research for more than two decades since the late 1970s, led by the pioneering effort of Yoshio Kurihara at NOAA's Geophysical a Dynamics Laboratory (GFDL), led to the development of a movable nested grid hurricane model (Kurihara and Bender 1980). The TPC/NHC requested that the high resolution, nested, movable GFDL model be evaluated to assess its performance in a semi-operational mode at the TPC/NHC in 1993. The seminal GFDL forecasts of Hurricane Emily and the recurvature of this storm off the outer banks of North Carolina in 1993 led to a pioneering collaboration between NOAA research and NOAA operations.

For the 1994 hurricane season, the GFDL model was monitored for operational performance. Due to its promising performance in providing higher track skill for the Atlantic and East Pacific basins than all other operational models, the GFDL model was transitioned into NCEP operations for the 1995 hurricane season. A version of the GFDL that is run at FNMOC, the GFDN, became operational in May 1996 (Rennick 1999). Although many transitional modeling and code obstacles existed at the time to transition a research model into operations, the joint efforts of the NCEP Environmental Modeling Center (EMC) and GFDL became a defining collaboration that has endured to the present.

With continuous yearly upgrades to the GFDL model, which were aligned with the upgrades to the NCEP global model, the GFDL model became the top track performance model and the mainstay for hurricane forecast guidance at TPC/NHC (Kurihara et al, 1998). In carrying out the joint vision for operational performance standards, the close collaboration between EMC and

GFDL is considered one the most successful collaborations within NOAA and perhaps within the U.S. modeling community between research and operations.

As skillful track forecasts became more consistently deliverable to TPC/NHC, CPHC, and JTWC forecasters during the 1990s, particularly with the operational implementation of the GFDL and GFDN models, more attention became focused on improving intensity forecasts from dynamical models within the hurricane community. An aspect of addressing the intensity issue required the coupling of the atmosphere with the ocean. To meet this requirement, the University of Rhode Island (URI) offered an ocean model that could be readily coupled to the GFDL model (Bender et al. 2001). The coupled GFDL model was run on 163 forecasts during the 1995–98 seasons (Bender and Ginnis 2000). The coupling of the atmosphere with the ocean improved intensity forecasts, with the mean absolute error in the forecast of central pressure reduced by about 26 percent compared to the operational (non-coupled) GFDL model.

The coupled GFDL model became operational in 2001. It provided an upgrade to the GFDL system for hurricane scenarios where changes in sea surface temperatures (SSTs) were important to intensity changes. This effort formed unique three-way collaborations between operational hurricane modeling at EMC, NOAA research, and academia. With support through the USWRP, this close working collaboration has continued to the present.

To date, the coupled GFDL model has become the benchmark for performance against which the future operational NCEP hurricane model—the Hurricane Weather and Research Forecast system (HWRF)—will be measured for track forecast skill and forecast consistency.

APPENDIX C
RESEARCH MODELS

The NASA GEOS-5 Atmospheric Model and Data Assimilation System

The Global Modeling and Assimilation Office (GMAO) at the NASA Goddard Space Flight Center is developing a new atmospheric data assimilation system (DAS) to synthesize the large volume of observations from Earth Observing System (EOS) satellites and other satellites. This system will be used for a global atmospheric reanalysis of the satellite era as well as to generate products in support of NASA instrument teams. The reanalysis, referred to as the Modern Era Retrospective-analysis for Research and Applications (MERRA),[1] supports NASA's Earth science interests by placing the current suite of research satellite observations in a climate context and by providing the science and applications communities with state-of-the-art global analyses.

The DAS consists of the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model coupled to the Gridpoint Statistical Interpolation (GSI) analysis scheme being developed by NCEP/EMC and GMAO.

The GEOS-5 atmospheric model is a weather-and-climate-capable model using the finite-volume dynamical core (Lin, 2004). In developing GEOS-5, attention has focused on the representation of moist processes (see http://gmao.gsfc.nasa.gov/systems/geos5/). The moist physics package uses a single phase prognostic condensate and a prognostic cloud fraction. Two separate cloud types are distinguished by their source: *"anvil" cloud* originates from detraining convection, and *large-scale cloud* originates from a PDF-based condensation calculation. Ice and liquid phases for each cloud type are considered. Once created, condensate and fraction from the anvil and statistical cloud types experience the same loss processes: evaporation of condensate and fraction, auto-conversion of liquid or mixed phase condensate, sedimentation of frozen condensate, and accretion of condensate by falling precipitation. Development of GEOS-5 was guided by a realistic representation of tracer transports and stratospheric dynamics. The ozone analysis of the DAS is input to the radiation package along with an aerosol climatology. GEOS-5 is coupled to a catchment-based hydrologic model (Koster et al. 2000) and a sophisticated multi-layer snow model (Stieglitz et al. 2001).

The GSI analysis solver was developed at NCEP to support inhomogeneous and anisotropic 3D background error covariances (e.g., Wu et al., 2002; Derber et al. 2003; Purser et al. 2003). The data streams currently assimilated by the DAS are listed in table C-1. The DAS is currently being used to test the impact of data selection strategies for AIRS radiance data and the impact of MODIS derived motion vector winds on weather prediction skill. A clear advantage of NASA's use of the GSI solver is the relative ease of transition of new techniques to operational models.

For MERRA and for regular products, the system will use a 0.5° resolution model and analysis, with 72 levels to 0.01 hPa. The GEOS-5 model is being run globally at 0.25° horizontal resolution to generate 5-day forecasts of tropical cyclone activity as a contribution to the MAP06

[1] MERRA website is http://gmao.gsfc.nasa.gov/merra/.

project (http://map06.gsfc.nasa.gov). The model is being initialized with the 0.5° DAS. This project will provide a critical test of the weather capabilities of the model and DAS.

Table C-1. Observation Data Sources and Parameters Used as Input to the NCEP DAS

Conventional Data	Surface ship and buoy observations
Radiosondes	SSM/I rain rate and wind speed
Pibal winds	TMI rain rate
Wind profiles	QuikSCAT wind speed and direction
Conventional aircraft reports, ASDAR, MDCARS	
NEXRAD radar winds	**Satellite Data**
Dropsondes	TOVS 1b radiances
GMS, METEOSAT, cloud drift IR and visible winds	DMSP SSM/I radiances
MODIS clear sky and water vapor winds	GOES sounder T_B
GOES cloud drift IR winds	Aqua/AIRS radiances (150 channels)
GOES water vapor cloud top winds	Aqua/AMSU-A radiances
Surface land observation	SBUV2 ozone (Version 8 retrievals)

The Florida State University Global Model and Multimodel Superensemble

The Florida State University (FSU) global model (Krishnamurti et al. 1991) uses a spectral transform method with semi-implicit time differencing to solve the dynamic equations. The model has a horizontal grid resolution of T126 (~80 km) and uses 14 layers in the vertical between roughly 50 and 1000 hPa. An array of physical parameterization schemes is employed for shallow and deep convection, dry convective adjustment, surface fluxes, planetary boundary layer mixing, short and longwave radiation, interaction of clouds with radiation, and surface energy balance. The model is initialized from large-scale analyses from the European Center for Medium Range Weather Forecasting (ECMWF) with 0.5 ° horizontal resolution and 28 vertical levels. Precipitation estimates from NASA's Tropical Rainfall Measuring Mission (TRMM) and Defense Meteorological Satellites Program Special Sensor Microwave Imager (SSMI) satellites are used as input for physical initialization to improve the initial representation of precipitation processes in the model. The FSU model has shown good success in predicting hurricane tracks (Williford et al. 1998).

A significant advance in hurricane prediction research came with the development of the FSU multimodel superensemble forecast system (Krishnamurti et al. 1999; 2000a, 2000b; 2001). This system utilizes track and intensity forecasts from several global and regional forecast models including NCEP's GFS global model, the U.S. Navy's NOGAPS, the ECMWF global model, the FSU global model, and the GFDL hurricane forecast model, in addition to several simpler dynamical and statistical models used by NHC. A key part of the multimodel superensemble is the training phase, in which prior forecasts and observations are used to derive linear regression–based statistical coefficients. During the forecast period, the superensemble forecasts are constructed using these statistical coefficients and current multimodel forecasts. Williford et al. (2003) showed that the superensemble method performed well in 1999.

MM5

The Pennsylvania State University—National Center for Atmospheric Research mesoscale model is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulations. It was developed as a community mesoscale model and the Fifth-Generation model (MM5) is the latest in a series developed from a mesoscale model used by Richard Anthes at Pennsylvania State University in the early 1970's, later documented by Anthes and Warner (1978). Since that time, it has undergone many changes designed to broaden its use. These include (i) a multiple-nest capability; (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale; (iii) multitasking capability on shared- and distributed-memory machines; (iv) four-dimensional data-assimilation capability; and (v) expanded physics options. This model has been used extensively by the research community to conduct both idealized and real-case simulations in order to study the dynamics and physics of hurricanes, often at very high horizontal grid resolution (~1-6 km), as well as to examine the impacts of various observations on hurricane simulations via data assimilation. Such studies have examined (a) the genesis of hurricanes; (b) the influence of shear on storm intensity and precipitation distribution; (c) the organization of upward motion in the hurricane eyewall and the role of buoyancy; (d) the sensitivity of hurricane intensity and precipitation to boundary layer, cumulus, and microphysical parameterizations; (e) vortex Rossby wave dynamics; (f) the impact of atmosphere-ocean coupling; (f) techniques for inserting bogus vortices for model initialization; (g) and satellite data assimilation. While use of this model has led to significant advances in our understanding of hurricanes, its relevance to operational forecasting has been limited because of the large differences between the MM5 model and operational models and the lack of a pathway for transition of research results to operations. With the advent of the WRF model, use of the MM5 model is expected to significantly decline.

WRF

The Weather Research and Forecasting (WRF) Model is the next-generation mesocale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), NOAA/NCEP, the NOAA Global Systems Division of the Earth System Research Laboratory (ESRL) (formerly the Forecast Systems Laboratory), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration.

WRF features two dynamic cores, the Advanced Research WRF (ARW) core developed at NCAR and the Nonhydrostatic Mesoscale Model (NMM) core developed by NCEP. The NMM is being implemented operationally as the core of the HWRF and is described in section 4.4.2. The ARW core is based upon equations that are fully compressible and nonhydrostatic. The horizontal grid has Arakawa C-grid staggering with a vertical coordinate based on terrain-following hydrostatic pressure. Time integration uses a 3rd order Runge-Kutta scheme with smaller time steps for acoustic and gravity-wave modes. Current data assimilation capabilities are experimental and are based upon a 3-dimensional variational (3D-VAR) data assimilation system (Barker et al. 2004). Four-dimensional variational data assimilation (4D-VAR) is also under development.

Application of the ARW model generally follows that of MM5: It is used to study the dynamical and physical processes related to hurricane genesis, intensification, rainfall, landfall, and extratropical transition. In addition to basic research, NCAR has implemented the ARW model as an experimental hurricane prediction system run in real time in 2004 and 2005. Forecasts in 2004 and 2005 used the same grid spacing and physics options. A 2-way nested configuration was used that features a 12 km outer fixed domain with an inner 4 km mesh. During 2004, the 4 km nest was fixed in space and contained 450x500 points in the north-south and east-west directions, respectively. The location of the 4 km domain was chosen to contain the storm throughout the 48 h forecast period. In 2005, a feature-following capability was added that positions the nest at the location of the minimum 500 hPa geopotential height within a radius of the last position of the vortex center (or within a radius of the first guess, when first starting). The repositioning occurs every 15 simulation minutes, and the width of the search radius is based on the maximum distance the vortex can move at 40 m s^{-1}.

On the 12 km domain, the Kain-Fritsch cumulus parameterization was used, while the inner domain used no parameterization. Both domains used an explicit microphysics scheme that predicts only one cloud variable (water for temperatures greater than 0ºC and ice for temperatures less than 0ºC) and one precipitation variable, either rain or snow (again thresholded on 0ºC). Both domains use the Yonsei University (YSU) scheme for the planetary boundary layer (Noh et al. 2001). This is a first-order closure scheme that is similar in concept to the scheme of Hong and Pan (1996), but in comparison tests it appears less biased toward excessive vertical mixing.

The forecasts were integrated from 00 UTC and occasionally at 12 UTC during the time when a hurricane threatened landfall within either 48 h (2004) or 72 h (2005). During 2004, both domains were initialized directly from the NCEP Global Forecast System (GFS) model with no additional data assimilation or balancing. In 2005, forecasts were initialized using the GFDL model, with the GFS used only when the GFDL was unavailable.

Evaluation of the skill of the forecast system is ongoing, but several seasons of forecasts with a stable model configuration and initialization technique will likely be required to assess forecast skill effectively. An advantage of the ARW over MM5 is that, because both the ARW and NMM WRF use a similar modeling framework, transitioning research results to operations is easier. However, any techniques or model physics developed for the ARW must be implemented within and fully tested with the NMM core.

APPENDIX D

2005 FORECASTS AND MODELS USED AT THE TPC/NHC AND CPHC

ID	Name/Description[1]	Type	Timeliness (Early/Late)	Parameters Forecast
OFCL	Official NHC or CPHC forecast			Trk, Int
CLP5	CLIPER5 (Climatology and Persistence model)	Statistical baseline	E	Trk
SHF5	SHIFOR5 (Climatology and Persistence model)	Statistical baseline	E	Int
A98E	NHC98 (Atlantic)[2]	Statistical-dynamical	E	Trk
P91E	NHC91 (Pacific)	Statistical-dynamical	E	Trk
BAMS	Beta and advection model (shallow layer)	Single-layer trajectory	E	Trk
BAMM	Beta and advection model (medium layer)	Single-layer trajectory	E	Trk
BAMD	Beta and advection model (deep layer)	Single-layer trajectory	E	Trk
LBAR	Limited area barotropic model	Single-layer regional dynamical	E	Trk
GFDL	NWS/Geophysical Fluid Dynamics Laboratory model	Multi-layer regional dynamical	L	Trk, Int
GFSO	NWS/Global Forecast System (formerly Aviation)	Multi-layer global dynamical	L	Trk, Int
UKM	United Kingdom Met Service model	Multi-layer global dynamical	L	Trk, Int
NGPS	Navy Operational Global Prediction System	Multi-layer global dynamical	L	Trk, Int
GFDN	Navy version of GFDL	Multi-layer regional dynamical	L	Trk, Int
CMC	Environment Canada global model	Multi-level global dynamical	L	Trk, Int
ETA	NWS/Eta	Multi-level regional dynamical	L	Trk, Int
AFW1	Air Force MM5[2]	Multi-layer regional dynamical	L	Trk, Int
OFCI	Previous cycle OFCL, adjusted	Interpolated	E	Trk, Int
GFDI	Previous cycle GFDL, adjusted	Interpolated-dynamical	E	Trk, Int
GFSI	Previous cycle GFS, adjusted	Interpolated-dynamical	E	Trk, Int
UKMI	Previous cycle UKM, adjusted	Interpolated-dynamical	E	Trk, Int
NGPI	Previous cycle NGPS, adjusted	Interpolated-dynamical	E	Trk, Int
GFNI	Previous cycle GFDN, adjusted	Interpolated-dynamical	E	Trk, Int
AEMI	Previous cycle AEMN, adjusted	Consensus	E	Trk, Int
SHIP	Statistical Hurricane Intensity Prediction Scheme (SHIPS)	Statistical-dynamical	E	Int
DSHP	SHIPS with inland decay	Statistical-dynamical	E	Int
AEMN	GFS ensemble mean	Consensus	L	Trk, Int
GUNA	Average of GFDI, UKMI, NGPI, and GFSI	Consensus	E	Trk
CONU	Average of at least 2 of GFDI, UKMI, NGPI, GFSI, and GFNI	Consensus	E	Trk
ICON	Average of GFDI and DSHP	Consensus	E	Int
FSSE	FSU Super-ensemble[2]	Weighted consensus	E	Trk, Int
GUNS	Average of GFDI, UKMI, NGPI	Consensus	E	Trk

1. Items were used in 2005 by both TPC/NHC and CPHC unless otherwise footnoted (and highlighted in blue).
2. Item was used only at TPC/NHC in 2005.

APPENDIX E

2005 FORECASTS AND MODELS USED AT THE JTWC

ID	Name/Description	Type	Timeliness (Early/Late)	Parameters Forecast
JTWC	Official JTWC forecast			Trk, Int
GFSO	NWS/Global Forecast System (formerly Aviation)	Multi-layer global dynamical	L	Trk, Int
GFSI	Previous cycle GFS, adjusted	Interpolated-dynamical	E	Trk, Int
JAVN	CDR Mike Fiorino (NHC) vortex tracker applied to GFSO *	Multi-layer global dynamical	E	Trk, Int
JAVI	Previous cycle JAVN, adjusted *	Interpolated-dynamical	E	Trk, Int
UKM	United Kingdom Met Service model	Multi-layer global dynamical	L	Trk, Int
UKMI	Previous cycle UKM, adjusted	Interpolated-dynamical	E	Trk, Int
JUKM	CDR Mike Fiorino (NHC) vortex tracker applied to UKM *	Multi-layer global dynamical	E	Trk, Int
JUKI	Previous cycle JUKM, adjusted *	Interpolated-dynamical	E	Trk, Int
NGPS	Navy Operational Global Prediction System	Multi-layer global dynamical	L	Trk, Int
NGPI	Previous cycle NGPS, adjusted	Interpolated-dynamical	E	Trk, Int
JNGP	CDR Mike Fiorino (NHC) vortex tracker applied to NGPS *	Multi-layer global dynamical	E	Trk, Int
JNGI	Previous cycle JNGP, adjusted *	Interpolated-dynamical	E	Trk, Int
GFDN	Navy version of GFDL	Multi-layer regional dynamical	L	Trk, Int
GFNI	Previous cycle GFDN, adjusted	Interpolated-dynamical	E	Trk, Int
AFW1	Air Force MM5	Multi-layer regional dynamical	L	Trk, Int
AFWI	Previous cycle AFW1, adjusted *	Interpolated-dynamical	E	Trk, Int
COWP	Coupled Ocean Atmosphere Prediction System *	Multi-layer regional dynamical	E	Trk, Int
COWI	Previous cycle COWP, adjusted *	Interpolated-dynamical	E	Trk, Int
EGRR	United Kingdom Met Service model *	Multi-layer global dynamical	E	Trk, Int
EGRI	Previous cycle EGRR, adjusted *	Interpolated-dynamical	E	Trk, Int
JGSM	Japan Meteorological Agency Global Spectral Model *	Multi-layer global dynamical	E	Trk, Int
JGSI	Previous cycle JGSM, adjusted *	Interpolated-dynamical	E	Trk, Int
JJGS	CDR Mike Fiorino (NHC) vortex tracker applied to JGSM *	Multi-layer global dynamical	E	Trk, Int
JJGI	Previous cycle JJGS *	Interpolated-dynamical	E	Trk, Int
JTYM	Japan Meteorological Agency Typhoon Model *	Multi-layer regional dynamical	E	Trk, Int
JTYI	Previous cycle JTYM, adjusted *	Interpolated-dynamical	E	Trk, Int

ID	Name/Description	Type	Timeliness (Early/Late)	Parameters Forecast
TCLP	Australia Bureau of Met Tropical Cyclone Limited Area Prediction System *	Multi-layer regional dynamical	E	Trk, Int
TCLI	Previous cycle TCLP, adjusted *	Interpolated-dynamical	E	Trk, Int
WBAR	University of Munich (Harry Weber) Barotropic Model *	Single-layer global dynamical	E	Trk
WBAI	Previous cycle WBAR, adjusted *	Interpolated-dynamical	E	Trk
CONW	Average of at least 2 of AFWI, AVNI, COWI, EGRI, GFNI, JGSI, JTYI, NGPI, TCLI, WBAI *	Consensus	E	Trk, Int
SBAM	Beta and advection model (shallow layer) initialized from NOGAPS *	Single-layer trajectory	E	Trk
MBAM	Beta and advection model (medium layer) initialized from NOGAPS *	Single-layer trajectory	E	Trk
FBAM	Beta and advection model (deep layer) * initialized from NOGAPS	Single-layer trajectory	E	Trk
STIP	CIRA/NESDIS Statistical Typhoon Intensity Prediction System *	Statistical-dynamical	E	Int
STID	CIRA/NESDIS Statistical Typhoon Intensity Prediction System (Decay Model) *	Statistical-dynamical	E	Int
ST5D	5 Day Statistical Intensity Forecast (STIFOR) *	Statistical-dynamical	E	Int
ST10	CONW Statistical Intensity Prediction Scheme *	Statistical-dynamical	E	Int
PTRO	Météo France Model *	Multi-layer regional dynamical	E	Trk
KBAR	Korea Meteorological Agency Barotropic Model *	Single-layer global dynamical	E	Trk
KBAI	Previous cycle KBAR, adjusted *	Interpolated-dynamical	E	Trk
KREG	Korea Meteorological Agency Regional Model *	Single-layer regional dynamical	E	Trk
KREI	Previous cycle KREG, adjusted *	Interpolated-dynamical	E	Trk
K426	Korea Meteorological Agency Global Model (low resolution) *	Multi-layer global dynamical	E	Trk
K42I	Previous cycle K426, adjusted *	Interpolated-dynamical	E	Trk
K213	Korea Meteorological Agency Global Model (high resolution) *	Multi-layer global dynamical	E	Trk
K21I	Previous cycle K213, adjusted *	Interpolated-dynamical	E	Trk

* Denotes models used exclusively at JTWC in 2005.

APPENDIX F
TRACK GUIDANCE MODEL ERRORS FOR 2005

The number of cases ("# Cases" at bottom of each table) indicates the number of TPC/NHC, CPHC, or JTWC forecasts represented in the error computation.

Table F-1. Homogeneous Comparison of Selected Subset of **Atlantic Basin** Early Track Guidance Model Errors (n mi) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	31.0	54.2	77.3	100.2	146.1	195.6	248.4
CLP5	46.9	100.3	162.3	211.9	271.4	341.9	457.9
GFSI	35.6	60.2	85.3	116.3	198.3	275.7	359.6
GFDI	33.9	57.7	78.9	103.9	163.3	253.6	337.4
GFNI	37.1	66.1	96.8	129.6	207.9	299.4	405.4
UKMI	38.1	65.9	93.9	118.5	169.5	216.2	263.1
NGPI	34.7	61.6	90.3	118.8	178.0	236.3	324.5
GUNA	29.1	50.1	72.5	96.1	148.0	194.7	249.9
CONU	29.4	50.6	74.0	97.7	150.2	197.3	257.1
FSSE	29.3	49.5	72.1	96.1	156.6	219.8	261.9
AEMI	35.7	60.7	85.9	113.4	181.8	240.6	264.0
# Cases	398	358	319	268	183	110	71

Table F-2. Homogeneous Comparison of Selected Subset of **Eastern Pacific Ocean Basin** Early Track Guidance Model Errors (n mi) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	28.0	48.0	65.9	79.4	103.6	119.0	132.8
CLP5	34.6	71.0	109.8	146.9	215.0	262.4	319.9
GFSI	34.2	60.4	87.4	113.6	176.0	238.2	256.8
GFDI	32.0	57.1	78.4	97.6	153.1	218.0	288.9
GFNI	41.5	74.9	104.5	125.5	161.2	206.4	244.0
UKMI	36.9	63.3	89.8	113.0	173.2	221.6	297.6
NGPI	38.4	71.2	97.9	123.3	174.6	220.6	267.1
GUNA	27.5	45.9	63.6	77.6	108.3	128.1	147.5
CONU	28.7	48.9	67.3	80.6	108.9	131.7	152.1
AEMI	34.0	61.2	88.8	117.8	176.8	236.0	265.8
BAMS	35.6	63.5	94.9	125.7	182.4	235.8	293.4
BAMM	34.4	58.0	82.2	107.5	148.8	181.5	227.7
BAMD	36.9	65.3	94.1	120.8	169.0	225.2	256.0
LBAR	32.6	69.3	116.2	164.4	255.7	337.9	437.1
P91E	34.6	66.6	100.1	136.3	227.5	318.8	456.4
# Cases	172	149	135	119	93	73	53

Table F-3. Heterogeneous Comparison of Selected Subset of **Northwest Pacific Ocean** Basin Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	40	61	81	102	156	231	284
CONW	36	55	73	94	142	207	272
AFWI	45	78	115	156	279	--	--
AVNI	37	61	85	115	191	296	393
COWI	44	78	118	161	255	--	--
EGRI	46	76	108	139	211	252	306
GFNI	44	74	103	130	204	287	381
JGSI	38	61	80	99	141	234	--
JTYI	38	61	84	113	171	--	--
NGPI	43	70	96	119	182	278	360
TCLI	45	78	117	158	246	253	275
WBAI	49	83	117	154	228	--	--
# Cases	543	503	452	403	312	176	119

Table F-4. Heterogeneous Comparison of Selected Subset of **North Indian Ocean** Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	42	62	84	116	118	133	134
CONW	41	65	91	116	123	154	185
AFWI	46	77	107	138	112	--	--
AVNI	44	60	77	94	91	84	69
COWI	40	57	66	83	112	--	--
EGRI	45	70	98	122	229	272	79
GFNI	51	67	88	114	166	279	405
JGSI	34	52	77	113	213	--	--
JTYI	45	76	121	187	317	--	--
NGPI	46	71	93	121	78	95	107
TCLI	57	96	141	179	203	--	--
WBAI	58	113	174	237	197	--	--
# Cases	77	67	56	49	18	10	8

Table F-5. Heterogeneous Comparison of Selected Subset of **Southern Hemisphere** Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**
(Comparison at 96 and 120 h are against CONW.)

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	41	69	91	114	199	--	--
CONW	40	67	94	117	207	248	292
AFWI	58	103	136	176	274	--	--
AVNI	44	75	111	146	223	310	394
EGRI	45	74	95	137	259	325	366
GFNI	51	89	122	147	210	282	373
NGPI	45	80	118	148	242	333	409
TCLI	52	91	134	149	338	--	--
WBAI	55	108	165	211	321	--	--
# Cases	239	213	192	169	41	--	--

APPENDIX G
INTENSITY GUIDANCE MODEL ERRORS FOR 2005

Although not computed operationally, included for reference in tables G-1 and G-2 is a simple intensity consensus model (ICON) that is an average of GFDI and DSHP. In each table, The number of cases ("# Cases" at bottom of each table) indicates the number of TPC/NHC, CPHC, or JTWC forecasts represented in the error computation.

Table G-1. Homogeneous Comparison of Selected Subset of **Atlantic Basin** Early Intensity Guidance Model Errors (kt) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	7.8	11.9	14.4	16.1	19.3	17.8	20.1
SHF5	10.8	17.2	20.6	21.9	24.9	26.4	23.8
GFDI	9.7	14.1	16.8	18.0	21.1	23.6	24.1
SHIP	10.2	15.9	19.0	19.8	21.6	22.3	23.6
DSHP	9.0	12.9	15.5	17.7	20.8	20.2	23.8
FSSE	8.6	12.7	15.4	17.4	21.2	23.1	23.0
ICON	8.8	12.4	14.7	16.3	19.5	20.2	21.9
# Cases	430	401	356	312	231	161	112

Table G-2. Homogeneous Comparison of Selected Subset of E**ast Pacific Ocean Basin** Early Intensity Guidance Model Errors (kt) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	6.0	10.2	13.9	16.5	18.5	19.0	19.9
SHF5	7.0	11.7	15.4	18.5	20.1	20.1	19.0
GFDI	7.4	11.5	14.7	17.0	20.4	20.0	17.2
SHIP	6.6	10.6	13.9	16.6	19.4	20.5	22.1
DSHP	6.3	10.1	13.4	16.0	19.3	20.5	22.1
ICON	6.3	9.8	12.5	14.5	17.7	17.3	16.5
# Cases	247	220	190	165	129	102	85

Table G-3. Heterogeneous Comparison of **Western North Pacific Ocean** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	7.2	11.6	14.8	17.6	23.4	25.7	26.6
CONW	9.4	16.4	22.1	25.8	29.7	30.8	28.2
AFWI	11.2	19.0	24.4	27.3	30.0	--	--
AVNI	10.6	18.5	24.8	29.5	35.9	39.5	38.3
GFNI	9.3	15.1	20.4	23.5	24.5	24.3	23.8
JGSI	10.6	18.3	23.8	27.3	33.2	47.0	--
JTYI	9.2	15.2	20.0	23.6	27.0	--	--
NGPI	11.3	18.6	24.1	28.4	33.8	34.4	32.8
TCLI	9.6	16.6	21.6	24.6	27.3	44.5	59.0
ST5D	7.8	13.1	17.8	20.7	25.5	26.3	24.9
STIP	8.2	14.0	17.8	20.8	25.5	28.4	26.6
# Cases	543	503	452	403	312	176	119

Table G-4. Heterogeneous Comparison of **North Indian Ocean** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	4.8	8.1	11.4	13.0	21.4	11.0	11.3
CONW	7.1	11.6	12.9	13.5	14.5	15.3	5.7
AFWI	7.7	14.5	18.5	21.1	25.6	--	--
AVNI	7.0	11.5	14.5	16.7	14.9	12.4	9.0
GFNI	8.2	13.3	16.0	16.3	13.2	16.2	14.0
JGSI	8.9	12.9	17.5	19.7	26.0	--	--
JTYI	8.0	15.3	19.5	22.8	23.5	--	--
NGPI	7.9	12.7	13.6	15.3	15.6	17.4	7.8
TCLI	9.0	13.8	16.6	19.0	18.5	--	--
ST5D	6.8	11.6	12.2	14.5	13.2	16.6	9.5
STIP	9.6	17.8	25.1	28.2	28.6	--	--
# Cases	77	67	56	49	18	10	8

Table G-5. Heterogeneous Comparison of **Southern Hemisphere** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**
(Comparison at 96 and 120 h are against CONW)

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	9.4	15.7	21.7	25.5	32.9	--	--
CONW	10.5	19.0	25.4	29.5	34.7	32.2	35.7
AFWI	11.1	20.1	28.0	32.8	16.8	--	--
AVNI	11.8	20.7	27.3	32.7	44.8	36.4	40.3
GFNI	10.0	17.7	23.5	26.8	25.3	27.7	38.6
NGPI	12.4	21.6	28.5	32.4	39.5	38.2	41.3
TCLI	13.7	19.5	22.2	23.7	23.0	--	--
ST5D	10.3	17.5	22.4	24.6	29.6	25.9	24.5
# Cases	239	213	192	169	41	140	106

APPENDIX H
ARTICLE FROM *NOAA MAGAZINE*

NOAA IS ENCOURAGING EVERYONE TO PREPARE FOR HURRICANE SEASON

July 30, 2006 — NOAA is ready as we enter the peak of the North Atlantic Hurricane Season and we want to make sure you are as well. While NOAA will again provide the best possible forecasts, it is vital that everyone living in hurricane prone areas be prepared. Max Mayfield, director of the NOAA National Hurricane Center says, "The message for everyone is the same, whether we have an active season or a below-normal season, you've got to have a plan in place and you've got to be ready to implement that plan. Remember one hurricane hitting where you live is enough to make it a bad season."

How is NOAA Prepared for Hurricane Season

This year, NOAA committed more than $300 million dollars to track and forecast hurricanes. In FY 2007, NOAA requested an additional $109 million dollars for hurricane-related investments. Currently, NOAA is focusing on further improving hurricane track and intensity forecasting through better observations, enhancing its modeling efforts (including those related to storm surge and inland flooding) and the continuation of Joint Hurricane Testbed to advance the transfer of new research and technology into operational hurricane prediction.

Improving NOAA equipment is also critical. NOAA aircraft, the W-P3 Orions and the Gulf Stream IV, provide essential observations and data critical to the NOAA National Hurricane Center forecasters and supplement the U.S. Air Force Reserve reconnaissance flights. The $14.2 million dollars NOAA received in FY 2006 supplemental appropriations to improve future aircraft service will add an additional W-P3 in 2007, and upgrade the radar and instrumentation on all of NOAA's aircraft.

NOAA also works year-round with federal, state and local emergency managers; educating them about weather effects from hurricanes, while they educate NOAA about response issues and their challenges. It is a constant learning process and the key is working together to ensure that the public takes appropriate action this hurricane season.

Most preparedness activity and outreach takes place outside hurricane season. In May of 2006, as part of NOAA's ongoing mission to enhance economic security and national safety, the NOAA National Weather Service again led its annual Hurricane Awareness Tour — this year focusing on Gulf Coast states. The tour helped raise awareness about the potential effects from a hurricane landfall with FEMA, local governments, emergency managers, schools, the public and the media working as a team to increase hurricane awareness and encourage preparedness in this vulnerable area of the nation.

APPENDIX I
NPOESS SATELLITE DATA PERTINENT TO TROPICAL CYCLONE ANALYSIS AND FORECASTING

This appendix reviews the NPOESS sensors and data that are pertinent to tropical cyclone analysis and forecasting. The expectations of use are derived from extrapolations of current practices for both analysis and NWP models. As noted in the footnotes associated with the discussions regarding the Conical Microwave Imager/Sounder and Radar Altimeter, the exact specifications and future acquisition of both of these sensors are in doubt/jeopardy.

Visible/Infrared Imager/Radiometer Suite (VIIRS)

- Polar-Orbiting VIS/IR Imagery
  - Not currently used directly in NWP systems except for sea surface temperature (SST) estimates (see next bullet). In the future, it may provide some useful information after substantial development effort.
- IR SSTs
  - VIIRS provides retrievals (currently) and radiances (in the future) for SST estimates. Technology will evolve rapidly over next 5 years so that in the NPOESS era, direct use of radiances will provide the best SST information.

Crosstrack Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS)

- Temperature and moisture retrievals
  - Temperature and moisture retrievals are not used either in analysis or in NWP models.
- Radiances
  - IR (CrIS) and microwave (ATMS) radiances are used in data assimilation to provide essential temperature and moisture information for initializing hurricane forecast models.

Conical Microwave Imager/Sounder (CMIS)[2]

- For analysis, a microwave imager/sounder can view tropical cyclone inner-core structure often obscured by upper-level clouds and thus masked in visible and infrared imagery.
- For analysis, a microwave imager/sounder can derive column integrated atmospheric water vapor over the oceans, also known as total precipitable water (TPW). TPW measurements are useful for the analysis of tropical cyclone intensity trends. TPW can also be derived using IR and microwave radiances through data assimilation.
- A microwave imager/sounder can provide surface wind information as well as integrated moisture information for analysis in non-precipitating regions. For analysis, surface wind and rain rate information are the only quantities currently used from microwave imager. Rain contamination is an important quality control issue for both analysis and NWP.

[2] CMIS has been terminated; a new Microwave Imager/Sounder will be competed—not available until C2 (i.e., 2016 at the earliest).

- The radius of 50 kt winds is a critical parameter for ship routing and the radius of 34 kt winds are important for coastal evacuations because these storm-response activities must be completed before the arrival of gale force winds.
  - Microwave estimates of surface winds suffer in measuring high winds and are contaminated by heavy rain
  - Microwave radiances may contribute to statistical intensity prediction models.
  - For NWP, current practice is to derive wind speeds from imagery. However, in the future, microwave radiance information will be used directly to provide a cleaner signal for data assimilation.
- Integrated moisture estimates are useful for the analysis of tropical cyclone intensity trends.
  - Integrated moisture can also be derived using IR and microwave sounder radiances through data assimilation.

- A microwave imager/sounder can provide intermittent analysis of rainfall rate and some cloud properties such as liquid water.
  - However, it does not provide time-continuous information in general. Impact on analysis depends critically on time continuity of coverage (i.e., number of satellites, time between overpasses).
  - This information may be useful in future for NWP models.
  - Similar information can be provided by ATMS.
- A microwave imager/sounder may provide intermittent analysis of tropospheric warm core structure, rain rate, some cloud properties, and approximate wind structure (using a diagnostic model) due to direct overpasses.
    - It does not provide time-continuous information in general. Impact on analysis depends critically on time continuity of coverage (i.e., number of satellites, time between overpasses).
  - Rain rate and cloud properties may be useful in future for NWP models.

Radar Altimeter (ALT)[3]

- Radar altimetry measures sea surface height and wave heights.
- Many studies have shown that the ocean's subsurface thermal structure plays an important role in tropical cyclone intensification. The subsurface structure can often be deduced from satellite altimetry data.
  - The modeling of the oceanic heat content (OHC) shows that the ocean energy available to the storm can vary considerably, depending on the subsurface ocean structure. The OHC can be estimated using a combination of sea surface temperature and ocean altimeter measurements.
- For NWP, altimeter measurements are critical to providing information (through the ocean and wave data assimilation process) to coupled atmosphere-ocean-wave hurricane NWP models.

[3] The NPOESS ALT, a previously baselined sensor, has been placed into a Deferred/Government Furnished Equipment category. The ALT sensor will not be on NPOESS unless an external government agency agrees to sponsor the acquisition of the sensor and provides it to the NPOESS IPO.

APPENDIX J
METOP SATELLITE DATA PERTINENT TO TROPICAL CYCLONE ANALYSIS AND FORECASTING

This appendix reviews the MetOp sensors and data that are potentially pertinent to tropical cyclone analysis and forecasting. The expectations of use are derived from extrapolations of current practices for both analysis and NWP models.

Infrared Atmospheric Sounding Interferometer (IASI)

IASI is one of the most advanced onboard instruments measuring infrared (IR) radiation emitted from the surface of the Earth to derive data of unprecedented accuracy and resolution on humidity and atmospheric temperature profiles in the troposphere and lower stratosphere. It also can measure some of the chemical components playing a key role in climate monitoring, global change, and atmospheric chemistry.

The Microwave Humidity Sounder (MHS)

MHS acquires measurements at various altitudes of atmospheric humidity, including rain, snow, hail and sleet, and temperature by measuring microwave radiation emitted from the surface of the Earth.

Advanced Scatterometer (ASCAT)

ASCAT, an enhanced follow-on instrument to the highly successful scatterometers flown on ESA's ERS-1 and ERS-2 satellites, measures wind speed and direction over the ocean. Its six antennas allow for simultaneous coverage of two swaths on either side of the satellite ground track, providing twice the information of the earlier instruments. ASCAT also contributes to activities in areas as diverse as land and sea ice monitoring, soil moisture, snow properties, and soil thawing.

Advanced Microwave Sounding Units (AMSU-A1 and AMSU-A2)

The AMSU instruments measure scene radiance in the microwave spectrum. The data from these instruments are used in conjunction with the High-resolution Infrared Sounder (HIRS) instrument to calculate the global atmospheric temperature and humidity profiles from the Earth's surface to the upper stratosphere. The data are also used to provide precipitation and surface measurements including snow cover, sea ice concentration, and soil moisture.

High-resolution Infrared Radiation Sounder (HIRS/4)

HIRS/4 is a 20-channel radiometric sounder measuring radiance in the IR spectrum. Data from HIRS/4 are used in conjunction with data from the AMSU instruments to calculate the atmosphere's vertical temperature profile and pressure from the Earth's surface to about 40 km altitude. HIRS/4 data are also used to determine ocean surface temperatures, total atmospheric ozone levels, precipitable water, cloud height and coverage, and surface radiance.

APPENDIX K
NCEP DATA ASSIMILATION DEVELOPMENT

1. Advanced Data Assimilation Techniques

Recently, new techniques have been developed to improve data assimilation. Broadly speaking, these techniques may be classified in three categories: 4D-VAR, Ensemble Data Assimilation (EDA), and Situation-Dependent Background Errors (SDBE). A short description of these three techniques follows.

4D-VAR

The 4D-VAR technique has the following advantages:

- All observation increments over the data window are considered at their observing time.
- The impacts of all observations on the model solution are realized at the observing time in the model.
- 4D-VAR allows for some time and space variability of the background error, although efforts to implement this degree of freedom have been rudimentary so far, even at ECMWF.
- In principle, the resulting analysis is a model solution so that it is a balanced, model-adjusted state. In practice, this ideal balance is not achieved because of inconsistencies introduced by simplifications and approximations.

The disadvantages of 4D-VAR are the following:

- In addition to needing a 3D-VAR framework, 4D-VAR requires approximately three times more software, including a tangent linear and adjoint versions of the forecast model. Every change to the model (e.g., physics, dynamics) will impact the 4D-VAR system directly. Any inconsistencies in the entire 4D-VAR system will cause it to perform suboptimally. These interrelationships may slow development of the entire forecast system.
- Operational maintenance and change-management of a 4D-VAR system is much more difficult, due to its complexity and larger volume of code (see above). Code management costs will increase as will coordination time between scientists working on different parts of the system.
- A full (no approximations) 4D-VAR system is 10-30 times more expensive computationally than 3D-VAR. 4D-VAR systems with approximations or simplifications are generally 2–5 times more expensive than 3D-VAR. Examples of simplifying approximations currently used at operational NWP centers include performing the analysis at lower horizontal resolution and using a simplified assimilating model (e.g., no physics or simplified physics).

In addition to the examples noted above, there are many ways of simplifying a 4D-VAR system. One possible simplification involves the "model" used in the 4D-VAR. It has been customary to use the same forecast model as in the free forecast. Therefore, simplifications have been made in the model physics or in horizontal/vertical resolution relative to the forecast model. However, a fresh look at the 4D-VAR problem may be in order. It may be feasible to construct a simple model for observation increments that can become part of the 4D-VAR technique. This model would remove the need for using the full free forecast model and its accompanying tangent linear and adjoint models.

Ensemble Data Assimilation

In EDA, the most likely atmospheric state is produced by finding the linear combination of ensemble forecast realizations that best matches the available observations. With EDA, background errors can be estimated directly from the ensemble at every analysis time and throughout the forecast domain. In a fully interactive EDA system, the ensemble perturbations are derived from the analysis error covariance. In this way, information from both the analysis and ensemble are used in a consistent manner. Although EDA is a relatively new technology, it is being vigorously pursued by about half a dozen groups in the research community, including a one-person effort at NCEP/EMC. The consistent use of information by the analysis and ensemble generation techniques is the major goal of an EDA-based system. However, it is yet to be demonstrated that this can be done reliably in an operational setting. A comparison of various EDA schemes is currently being sponsored by the THORPEX program.

EDA has the following advantages:

- No ancillary model components such as tangent linear and adjoint models are required; therefore, the code infrastructure is reduced considerably.
- The analysis code can be simpler, although in practice this may not necessarily be the case.
- There is a natural information feedback between the ensemble and data assimilation systems, which has not been fully explored in the 4D-VAR context. Unfortunately, some preliminary investigations by ECMWF in this area have been disappointing, so a lot more work needs to be done.
- Ensemble forecasts scale very well on massively parallel computers and, therefore, are very efficient to run operationally.

EDA has the following disadvantages:

- It is much less mature in practical applications than 3D-VAR. There are still many unknowns regarding ensemble construction, stability of background error formulation, and the impact of model error—particularly, any model bias. Many of the studies showing extremely optimistic results have been done with simulated data or without any large data source (e.g., satellite data).
- The technique appears to be very sensitive to the characteristics of the background (model) error, even more than 3D-VAR and 4D-VAR.

- Costs are proportional to the ensemble size and resolution. An ensemble run at full horizontal and vertical resolution would be highly desirable, although some cost reduction can be achieved by running the ensembles at lower resolution.
- The ensemble generation technique is critical; short term (3–6 hour) ensemble characteristics have not been well characterized.
- It is critical that the ensembles span the entire possible range of analysis states. If observations lie outside the ensemble envelope, extrapolation errors will be potentially fatal (i.e., could cause a major bust).

Situation-Dependent Background Errors

It is widely recognized that the major outstanding analysis problem is improved formulation of the background error part of the analysis equation. Many improvements over the past 10 years have been in this area, including a major upgrade to the ECMWF system. Nonetheless, 3D-VAR systems have background error formulations that are constant in time and geographically varying in a very limited way (e.g., latitudinal and vertically varying only, derived empirically from the model forecast climatology). The SDBE approach attacks the fundamental analysis problem directly and is particularly relevant to the hurricane problem. Some early work on this was done at ECMWF, the Met Office (METO), but was abandoned in favor of a simplified 4D-VAR.

One of the most significant modeling challenges to improve numerical forecasts of hurricane structure and intensity in high-resolution models is the initialization of the hurricane vortex. To advance this effort, a local 3D-VAR using SDBE covariances is being developed at EMC to initialize the hurricane core circulation in the HWRF using real-time airborne Doppler radar from NOAA's WP-3D aircraft and the newly funded instrument upgrade package on the NOAA Gulfstream IV aircraft (see section 3.1.1)**.** For storms approaching landfall, the data assimilation will also make use of the coastal WSR-88D high-resolution radar data. The NCEP Gridpoint Statistical Interpolation (GSI) now contains coding structures intended for admission of SDBE and will be exploited in the HWRF to initialize the hurricane core through development of flow-dependent algorithms. Developing SDBE using extensions to the GSI has the following advantages:

- It addresses directly the most fundamental part of the analysis problem.
- There would be direct continuity with previous work, including diagnostics, performance statistics, and other infrastructure software, and ease of comparison and diagnosis that comes with incremental change.
- The methodology is affordable now in a development and testing mode, while resources can be garnered for final testing and operational implementation in 1–3 years.
- The methodology is innovative and has a good chance of succeeding.
- It can be applied most advantageously in a 4D-VAR context.
- It can incorporate information from ensemble forecast runs.

The preferred development strategy for an NCEP Global and Regional Advanced Data Assimilation System (GRADAS) is, first and foremost, to develop SDBE within the GSI. 4D-

VAR extensions to the GSI, using a simple model for observation increments, will also be developed for improved use of high time-resolution observations such as surface and radar data and satellite imagery. This approach will result in systematic and incremental augmentations of the current NCEP global and regional analysis code and produce a simplified 4D-VAR that can also use ensemble-based information.

2. EMC's Data Assimilation Priorities

The following data assimilation priorities at EMC are associated with development of the above strategy:

- Improving the background error covariances and their evolution for the atmosphere, ocean, and land
- Assessing the impact of atmosphere, ocean, and land model errors and biases
- Identifying the key variables to be measured for NWP, including the requirements of accuracy and resolution in time and space and the tradeoffs between resolution and areal coverage
- Development of strategies to extract maximum meteorological information from the data (e.g., adaptive thinning, "super-obbing," recursive filters, etc.)
- Specifying the observation errors, especially in sensitive regions such as the inner core, and for surface observations in steep topography
- Development of techniques for optimal use of spatially dense correlated observations
- Development of adaptive quality-control techniques
- Development of assimilation techniques for available quantities (e.g., Doppler line-of-sight winds, air-sea fluxes, trace gases, aerosols)
- Modeling of radiative interactions with microphysics and aerosols

3. Data Assimilation Challenges for the Tropics and Hurricanes

Data assimilation for the tropics and hurricanes includes the following specific challenges:

- **Balance equations**: In the tropics (and for mesoscale in general), balance is dominated by moist processes and is much more complex than for the larger scales. Failure to properly treat the balance issues will result in a rapid loss of useful information at the beginning of the forecast. The increase in nonlinearity due to moist processes makes the tropical/hurricane problem more difficult to solve.
- **Analysis variables:** To accurately analyze variables in the tropics such as cloud liquid water and cloud ice, a balance has to be achieved and all the fields involved need to be initialized. This means that the surface and ocean fields must be correctly specified. The ability to achieve a realistic balance is not as straightforward as for the larger scales.
- **Background error covariance:** For the tropics, it is essential to have circulation-dependent error covariances, but they are difficult to determine. For example, the structure of the background error covariances for cloud and surface fields are almost

certainly dependent on small-scale dynamics that are not well known. Furthermore, it is critical to include in the background error covariances the relationships between the variables (e.g., water vapor and clouds).

4. Focused Data Assimilation Efforts Dealing with the Coupled Ocean Model

The coupled ocean model data assimilation efforts will focus on these items:

- Upper ocean and mixed layer as being of primary importance
- Skin temperature, which is a primary measurement from satellites
- Bulk water temperatures obtained from ship observations (the satellite retrievals are calibrated to the bulk temperature)
- Profiles of the thermal (and salinity) structure and mixed layer depth that are provided by floats and expendable conductivity temperature and depth probes

APPENDIX L
NCEP GLOBAL MODEL DEVELOPMENT

1. NCEP Global Model Development

This appendix describes an evolutionary plan for the NCEP global model. A number of external considerations are described, since they must be included in any long-range planning. These considerations include the emerging Earth System Modeling Framework (ESMF), the separate evolution of the model adiabatic dynamics and physics components, a short review on the basics of forecast model techniques, the concept of primary and secondary models, forecast system diversity, and interaction with other NOAA modeling groups for both the weather and climate applications.

The Global Forecast System (GFS) has many critical applications and functions in the NCEP operational job suite and is the cornerstone of NCEP's suite. Some of these forecast applications are noted below, with explicit relevance to hurricanes highlighted in bold type:

1. Global weather (1–16 days) with many applications such as Aviation, medium-range (3–8 days) precipitation and severe weather, **hurricane tracks**
2. **Initial and boundary conditions for hurricane regional model (i.e., HWRF)**
3. Boundary conditions for North American run
4. Boundary and initial conditions and background field for the Regional Spectral Model
5. Driver for ocean wave models and, in the future, other ocean models
6. Ozone distribution and transport and, in the future, other atmospheric constituents
7. **Background field for global data assimilation system**
8. **Ensemble system model (to include hurricane tracks)**
9. Coupled Climate Forecast System (CFS) model

The predecessor to the current NCEP GFS was developed in the late 1970's and was first implemented in August 1980. This model was based on the spectral representation for all forecast variables. In response to increased computing resources and changing computer architecture at NCEP, the GFS has evolved to higher resolution, both horizontally and vertically, and a more modular code structure. The current horizontal resolution is T382, or approximately 35 km; vertically there are 64 layers in a domain from the surface to 0.2 hPa (approximately 55 km). The GFS adiabatic dynamics and physics require application of Fourier and Legendre transforms to convert between spectral and gridpoint spaces. Advective processes are computed on the transform grid from spectral coefficients. A sigma (normalized pressure) vertical coordinate in current used (September 2004). A hybrid sigma-pressure coordinate option is included in the operational code and will be fully tested for operations in FY2005. The time integration scheme is a three-time-level leap-frog scheme with semi-implicit integration. Physical parameterizations and nonlinear dynamics computations are applied on a reduced Gaussian grid for computational economy. Changes to the physical parameterizations occur on the average of twice per year, with changes to the adiabatic dynamics much less frequently.

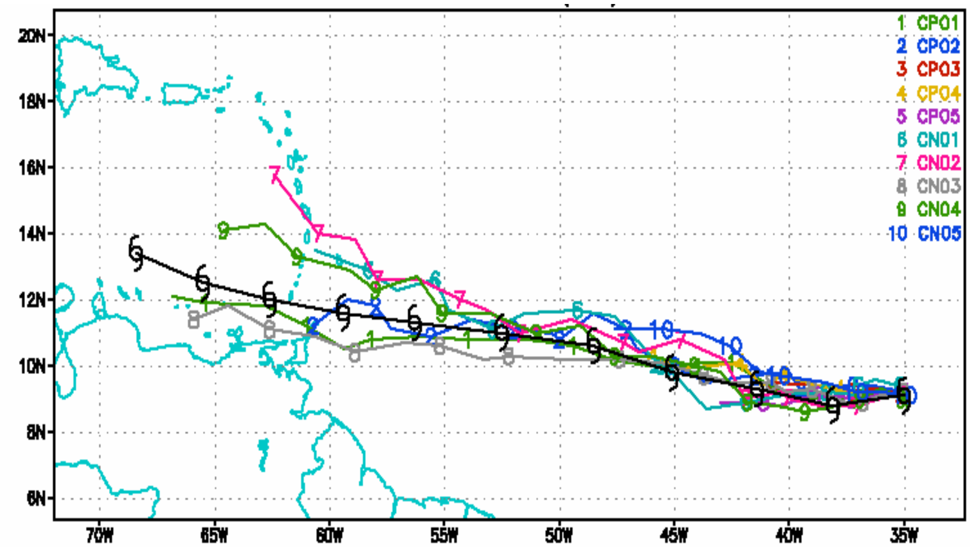
Ensembles and Forecast System Diversity

When initial and model related errors are well captured, ensemble forecasts can convey case-dependent variations in forecast uncertainty. Currently no other methods can provide such information. Variations in forecast uncertainty can have a significant impact on users. Small expected errors in the track of a hurricane (figure L-1a), for example, call for a different emergency response from a case when the possible tracks cover a larger area of the coast (figure L-1b). Therefore, all uncertain forecast information must be presented in a probabilistic or other format that conveys the associated forecast uncertainty.

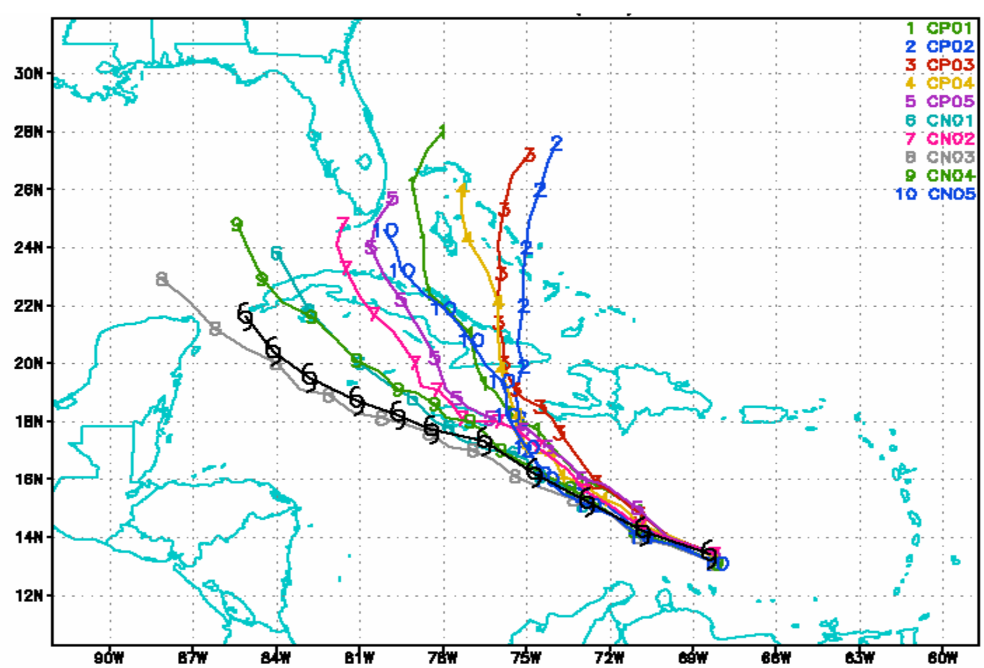
Ensembles can be formed in a number of ways. One can collect single forecasts generated by different NWP centers. Methods have also been devised to simulate initial and model-related errors. Today, in addition to a single higher resolution forecast, most NWP centers, including NCEP, also generate their own set of global ensemble forecasts. The NCEP Global Ensemble Forecast System (GEFS) recently underwent two major changes that are significant for hurricane forecasting. First, with an implementation in 2005, the initial perturbations related to tropical storms were revised. With the use of the hurricane relocation algorithm, the position of the tropical storms is no longer perturbed, and the perturbations in the magnitude and shape of the storms are better controlled (figure L-1). These changes further improved the track prediction performance of the GEFS system. As figure L-2 shows, there was a significant reduction in the error of the ensemble mean track. Importantly, the spread in the ensemble also was reduced to a level that now closely matches that of the error. This is an indication of a well-calibrated track forecasting system that is statistically reliable and can generate probabilistic forecasts that are consistent with observations. With these changes, the performance of the ensemble mean track exceeds that of the higher resolution Global Forecast System (GFS) averaged over the 2005 Atlantic hurricane season (figure L-3, courtesy of Jim Goerss, U. S. Navy) for all lead times, beginning with 12 hours (not shown in figure L-2). However, the ensemble mean forecast errors were still higher than the multi-model consensus CONU for all forecast periods.

The second change is related to the implementation of a multi-center ensemble approach that is aimed at optimally combining ensembles generated first in North America (North American Ensemble Forecast System, NAEFS, currently NCEP and Meteorological Service of Canada ensembles are available, FNMOC and possibly UK MetOffice ensembles to be added later). The NAEFS effort includes the exchange of all ensemble members generated by the participating centers for a large number of variables; the optimal combination of information from the different ensembles; the statistical bias correction of many of the variables; and the expression of the forecasts in terms of climatological percentiles, based on the NCAR-NCEP reanalysis data, allowing for a simple downscaling of the forecasts.

NCEP is interested in working with the hurricane user community in developing new and improved products based on the NAEFS and other ensemble data. Bias-corrected and downscaled probabilistic high wind, precipitation and other products are examples of the opportunities for providing more diverse and informative products generated automatically for the user community. Plans are also being considered for using the ensemble approach in limited area (WRF) hurricane ensemble forecasting.



(a)



(b)

Figure L-1. Two forecast examples for Hurricane Ivan generated with the 2005 version of the NCEP Global Ensemble Forecast System. The ensemble in figure L-1a indicates a case with relatively small track uncertainty while that in figure L-1b shows a case with large uncertainty. Such information can be critical in emergency management applications.

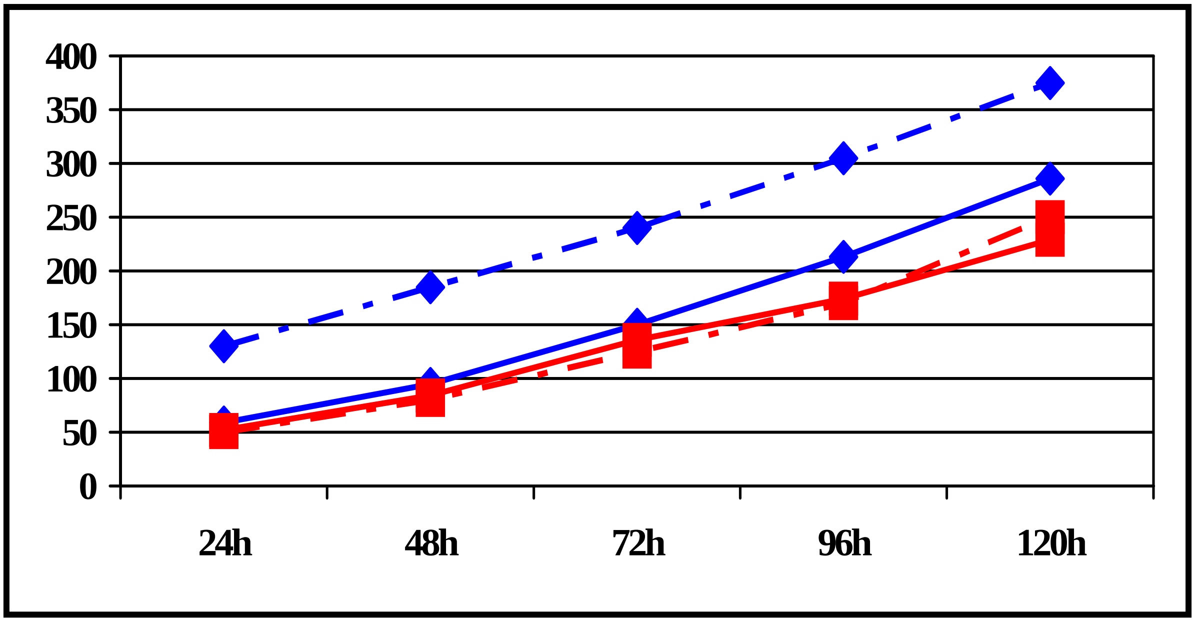


Figure L-2. Track error of (solid lines) and spread around the ensemble mean forecast (dashed lines) for 8/23-10/1 2004 Atlantic storms with the then operational (blue) and since implemented (red) versions of the NCEP Global Ensemble Forecast System. The closely matching error and spread curves indicate an ensemble forecast system that is statistically reliable for tropical storm prediction applications.

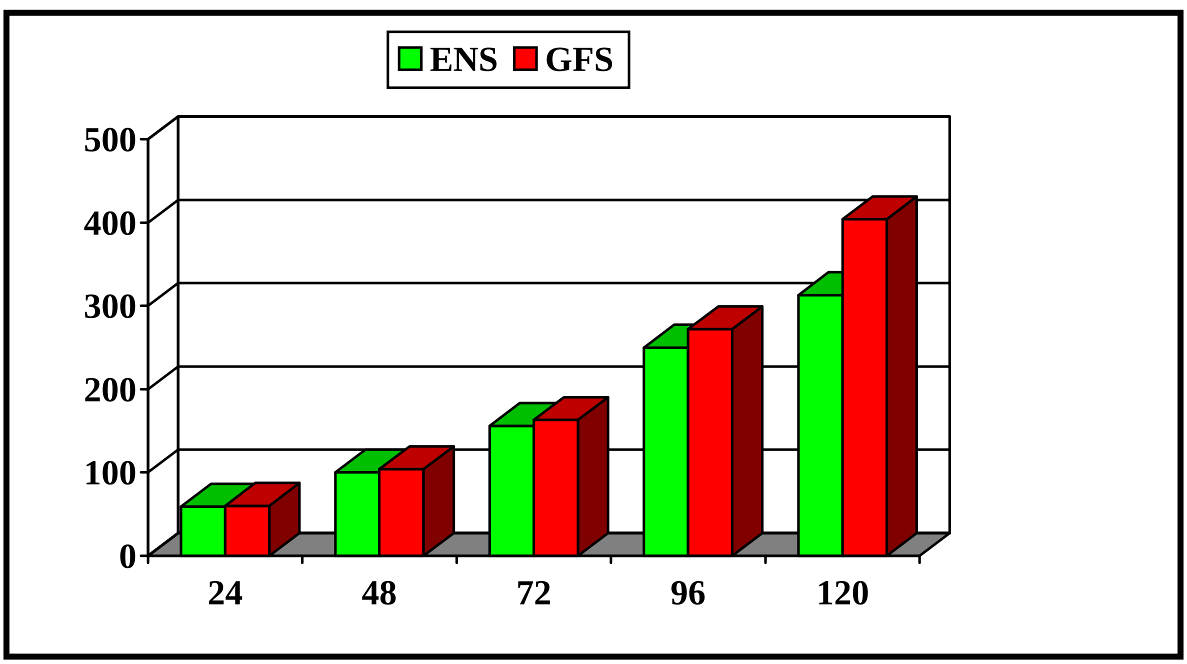


Figure L-3. NCEP global ensemble mean (green) and Global Forecast System (GFS, red) tropical storm track forecast errors (nm) averaged over the 2005 Atlantic Hurricane season. The error in the ensemble mean track is lower than that in the high-resolution single forecast at all lead times. Of interest, the computational cost of generating either the lower resolution ensemble or the higher resolution single forecast is similar. (Courtesy of Dr. James Goerss, U. S. Navy.)

ESMF and the Common Modeling Structure

The ESMF is a multi-agency project to develop both a model superstructure and infrastructure. The superstructure is defined as a set of standards that allow new components to be coupled together with minimal impact on remaining components. Components may be defined as complete models (e.g. ocean model) or parts of a complete model (e.g. dynamics, physics, or parts of each). The infrastructure is a set of portable, reusable utility routines that can be used across different models.

Both superstructure and infrastructure must be flexible enough to allow evolution of NCEP's models and general enough to accommodate both global and regional models and data assimilation modules for each application. It must also accommodate both primary and secondary models, some of which could originate from other parts of NOAA or from outside NOAA. ESMF-compatible code should be easily transferable to NCEP operations, given the high degree of modularity and portability standards inherent with ESMF.

2. Model Requirements

The next-generation NCEP global model must provide skillful guidance for all applications listed in the introduction to Appendix L, demonstrate at least the computational efficiency of NCEP's current global model and provide the flexibility to meet future demands. The following set of highly desirable global numerical model properties should be considered in developing NCEP's next-generation model.

Requirements for Dynamics

The next-generation NCEP model will evolve to one with the following properties:

"Same" Model for Global and Regional Applications

The model dynamics should be capable of representing both the global and mesoscale circulations in the atmosphere. The current resolution of the global model is ~35 km, which is very similar to the resolution of NCEP's regional model in September 2000. Other international NWP centers, such as the UK Met Office and the Canadian Meteorological Center (CMC), use the same dynamics for both global and regional models. This strategy facilitates the data assimilation applications since the model background properties are more consistent across various applications. It reduces code maintenance for complex communications strategies and dynamics algorithms, and it facilitates the inevitable march to improved forecasts through higher horizontal and vertical resolution.

Non-hydrostatic Option through a "Switch"

If a single dynamics is required for both global and mesoscale applications, then the ability to switch efficiently between hydrostatic and nonhydrostatic dynamics is critical. Although non-hydrostatic dynamics for global applications appears necessary at horizontal resolutions of below 10-12 km, this resolution will not be feasible operationally for many years to come. However, the experience gained at regional forecasting, where full non-hydrostatic dynamics is now operational, can be useful provided the same dynamics structure is used. Moreover, some improvements to the vertical velocity calculation may provide an improved dynamical response to convective heating, even at coarser resolution. This is an area of active research.

ESMF standards

As stated above, ESMF standards will enhance portability and reuse of software, provide a common modeling structure, and thereby decrease the time needed to bring in model components from outside NCEP (provided they are ESMF-compatible). This common modeling structure can be used to provide a more unified system for running NCEP's operational global and regional forecast systems.

Two-Way Nesting

A well-designed, two-way nesting capability is required if a single model structure is going to be used for both global and regional models. One-way nesting is used to drive NCEP's North American run. However, at this time, the global and regional models are separate modules with very different dynamics and physics. An earlier forecast from the global model supplies the boundary conditions for the regional model, which is run before the global model. In the future, when NPOESS satellite data is available with shorter latency than current data, it may be possible to drive the North American model (and others) with concurrent boundary conditions from NCEP's global model. At an even further stage of development, a two-way nesting capability may be possible if the global and regional models have a common dynamics and physics. The full, two-way nested configuration for global forecasting is an area of active research at this time.

Conservative Scheme for Adiabatic Dynamics

The dynamics should be formulated to conserve, in a domain-integrated sense, as many of the quantities in the continuous formulation of the equations as possible. First order quantities, such as mass, should be conserved as demonstrated by the continuous forecast equations. Moreover, the continuous equations can also be combined to demonstrate the conservations of quadratic quantities such as potential vorticity, total energy, and enstrophy under well-defined conditions (e.g., adiabatic, nondivergent flow). It appears desirable to have a discretization of the continuous equations that preserves these relationships, although there is not unanimous agreement on this issue. A scheme that does not formally conserve these quantities should still be tested and evaluated for its conservation properties. Such conservation may become increasingly important with the length of the forecast application.

Hybrid Vertical Coordinate and Vertical Discretization

A hybrid coordinate, with a terrain-following coordinate near the lower boundary but approaching an isentropic coordinate in the upper troposphere and stratosphere, may provide a better discretization of the dynamics, due to reduced vertical discretization errors. In addition, careful vertical discretization may be helpful in providing improved conservative properties for the dynamics. These are leading edge research problems, however, and considerable work is needed in this area.

Formal Accuracy

The formal accuracy of a particular numerical scheme is an important factor, although less formally accurate schemes with good conservation properties have been shown to be excellent schemes. In addition, as horizontal resolution increases, the influence of formal accuracy becomes less. One area of research concerns the discretization of physical processes, which can contribute positively to a more accurate solution.

Consistent Treatment of All Forms of Water Substance

The heat content and density of air and all forms of moisture needs to be accounted for in a consistent manner. Also, the impacts of water vapor and other gases on the gas constant and specific heat must be addressed consistently.

Conservation of Tracers, Including Moisture

The total quantities of tracers should be conserved in the absence of sources and sinks. The numerical schemes should not produce unrealistic quantities such as negative values.

Requirements for Physics

The GFS physics has been applied to daily, global weather forecasting, to Seasonal to Interannual (S/I) forecasting with the coupled Climate Forecast System (CFS), to regional mesoscale forecasting with the Regional Spectral Model (RSM), and to hurricane forecasting in the GFDL model. In the case of the CFS, the GFS physics produced coupled atmosphere-ocean simulations with very small (< 0.5 K) climate drift in the tropic. Furthermore, the GFS physics appears to have considerable skill in forecasting seasonal tropical wind shear, which is a major predictor of tropical cyclogenesis and convective activity in general.

The application of physical parameterizations for high horizontal and vertical resolution is an area of active research. Use of ultra-high resolution (1-2 km) nested models to capture the cloud-scale physics for a global model (also called "superparameterization") may prove fruitful for directing new development in the future. Assumptions common to current physical parameterizations, e.g., hydrostatic and isobaric processes, may prove limiting at resolutions below 10 km, in much the same way as the hydrostatic assumption is unsatisfactory for the adiabatic dynamics. The general application of physical parameterizations with general ("non-sigma") vertical coordinates also needs to be explored.

To facilitate and encourage more advanced research on global modeling, the NCEP GFS can be transformed into a more general system, while maintaining a strong heritage and connection to operations. In this way, incremental and controlled evolution can be achieved with reduced risk.

Requirements for Computational Efficiency

NCEP's job suite is defined by a time window for data assimilation, model integration and product generation; by the number of available computing processors; and by the speed of the computing interconnect fabric. The object is to produce the most accurate forecast within the allowable time window, provided the forecast system code is maintainable and upgradeable within resources available to EMC and its partners.

3. Model Development Strategies

At present, there are five principal strategic options for development of NCEP's next-generation dynamics:

1. Upgrade the current operational spectral model (sigma-pressure hybrid version)
2. Upscale the Non-hydrostatic Mesoscale Model (NMM) to global domain
3. Apply Semi-Implicit (SI) and Fully-Implicit (FI) Semi-Lagrangian (SL) formulation (Kar dynamics)
4. Adopt the Finite-Volume (FV) dynamics
5. Adopt the University of Wisconsin sigma-theta dynamics

To minimize future code rewriting and reorganization, these development efforts should take place within an ESMF-compatible structure. Preliminary work on such a structure has begun and is still evolving. Although it is currently unclear to what degree an ESMF-compatible structure can be suitable for operations, it should be able to house each of the above strategies, which are discussed in more detail below. To give a common beginning to all development efforts, the codes need to be placed into this structure as a first step. This step will make it easier for all participants to share code as soon as possible, will allow results to be compared more readily, and will save development time because the ESMF infrastructure codes will provide standard techniques for implementing message passing, other communications chores, standardized gridding, etc.

Evolve the current operational spectral model (sigma-pressure hybrid).

After placing the current operational, sigma-pressure hybrid spectral model into an ESMF-compatible structure, the model could be developed further by taking the following steps:

- Improve the accuracy of the vertical discretization
- Generalize the vertical coordinate, which can allow a sigma-theta option
- Add FISL and/or SISL capabilities
- Improve mass and thermodynamic consistency for all forms of water
- Continue to experiment with high-resolution downscaling using the RSM

This development strategy has the following advantages:

- Strong continuity with operations will allow evolutionary progress.
- An ESMF-compatible structure is being constructed and tested.
- Spectral method potentially has the most accurate horizontal dynamics formulation.
- Tracers are already included, although they are not in the most economical or even the most desirable form.

- A regional model (the RSM) has already been constructed and tested; it is part of the Short-Range Ensemble Forecast (SREF) system.

This strategy has the following disadvantages:

- The computational efficiency on higher resolution, limited area domains may decrease for spectral models, due to the overhead in converting from grid to spectral space with a smaller number of grid points.
- A nesting technique will require additional code support since different spectral functions must be used for the global and regional applications.
- Adding fully implicit time differencing and SL advection to increase the time step will involve major changes to code structure and require considerable resources.
- In all likelihood, introduction of FISL and/or SISL techniques will reduce conservation properties.

Upscale NMM to Global Domain

The NMM became the primary regional model at NCEP on June 13, 2006, when the Gridpoint Statistical Interpolation (GSI) system was coupled with the NMM in the Weather Research and Forecasting (WRF) system structure. The NMM can be converted into a global model on a latitude-longitude grid by filtering the smallest waves near the poles to ensure computational stability (as in many Eulerian gridpoint models on a sphere). A second strategy is to integrate the model on two separate domains using mercator grids, with a coupling mechanism between the domains for information transfer. Using the ESMF-compatible structure, coupling may be facilitated. For participation in this global model development project, the following steps must be taken:

- Place the NMM into the ESMF-compatible structure
- Either (a) add low pass filters in the polar regions to allow longer time steps or (b) couple domain components on two mercator grids (bi-mercator [BM] technique)
- Consider the possibility of a stretched grid (as already done by CMC) for global and regional applications
- Continue to develop dynamics in response to requirements stated in Section II

This development strategy has the following advantages:

- The NMM dynamics is very scalable and has been shown to run efficiently and to give good quality forecasts on a regional domain.
- The NMM uses a hybrid sigma-pressure vertical coordinate already.
- The NMM currently allows a non-hydrostatic option via a switch.
- Global upscaling through low pass filtering in polar regions is a known technology, but may not be without risk.

This strategy has the following disadvantages:

- Upscaling the NMM dynamics from regional to global introduces some risk, but this may be mitigated by introducing global model physics into the NMM. Nevertheless, thorough testing will be required because of the large number of new weather regimes that must be forecast skillfully, such as the tropics and the Arctic.
- Resources will need to be expended to move the NMM into the NCEP ESMF-compatible modeling structure.
- The BM strategy is innovative, but it is also high risk because of the possible inconsistencies of the evolving model solutions on separate grids and the problem of extracting regional boundary conditions where the grids are stitched together.

Apply Semi-Implicit (SI) and Fully-Implicit (FI) Semi-Lagrangian (SL) Formulation (Kar)

This formulation uses a FI or SI formulation of the non-advective, nonlinear terms in the full dynamics equations. In addition, SL advection can be used consistently with the SI or FI formulation. Using both of these techniques together can allow increased efficiency through longer time steps, but not without additional of significant computational overhead. Initial results using a shallow water model have been very encouraging, and development of a 3D hydrostatic FISL model is well underway. Application of these techniques to operational-grade models, such as the GFS and the NMM, can be done more efficiently by using these models in an ESMF-compatible framework which other members of the group are using. For participation in this global model development project, the following strategic options could be taken:

1. Formulate, apply and restructure the NMM and/or GFS to use SI, FI and SL techniques
2. Continue to develop the FISL and SISL shallow water formulations into a full, 3D, operational grade model

Option 1 is preferred since the work required to develop, test, and implement a new, operational grade model is estimated to be less. Application of FISL or SISL techniques could be directed at either the NMM or GFS. The result of this application will be a totally different type of model, which may have a good combination of accuracy and computational efficiency. SL techniques have, however, no formal conservation guarantee of mass or dynamical quantities, although the impact of exact conservation alone may not be of critical importance. Considerable research, using isentropic diagnostics, needs to be done. It should be noted that ECMWF uses a spectral-SL scheme for forecasts in daily and seasonal time domains.

This development strategy has the following advantages:

- The code and scripting surrounding the GFS or NMM models can be used to house the FISL and SISL dynamics so that it need not be developed for a new model.
- The new techniques can be compared cleanly within the operational GFS or NMM frameworks.

- If successful, the new techniques will result in an evolved model with increased efficiency and most, if not all, of the same good characteristics of NCEP's current operational model.

This strategy has the following disadvantages:

- The work necessary to restructure the GFS and/or NMM for efficient operation on parallel computing architectures, is large. It will involve new strategies and code for defining haloes in the GFS.
- The formal non-conservation of mass may be troublesome for NCEP's Seasonal-to-Interannual climate forecast mission.

Adopt the Finite-Volume (FV) Dynamics

The FV dynamics has been tested at NASA/GSFC, GFDL, and NCAR for climate applications and, more recently, for data assimilation using NCEP's GSI code. The FV dynamics may have better conservative properties than other SL formulations. While NASA/GSFC has had some experience using the FV model in a cycled data assimilation system, this system has not yet achieved the same maturity in testing as NCEP's system.

This development strategy has the following advantages:

- Substantial community testing has been done for climate applications.
- Community support should be available from GMAO and possibly GFDL.
- Conservation properties may be improved over traditional SL schemes.

This strategy has the following disadvantages:

- The FV model has not yet been fully demonstrated for NWP and data assimilations.
- The work to downscale this model to a regional application is underway but not complete.
- A non-hydrostatic formulation of this model is under development but not currently available.
- A generalized coordinate version is not yet available.

Adopt the University of Wisconsin Dynamics

The University of Wisconsin (UW) dynamics is a specific implementation of a sigma-theta hybrid coordinate, which has potentially very nice conservation properties. Detailed score comparisons with NCEP's GFS, which have been made for the past two years, show that the UW model has comparable 500 hPa height scores and improved moisture verification scores when NCEP's physics are used. More detailed comparisons, including tropical forecast skill, will be useful to demonstrate the potential advantages of the hybrid coordinate. Thus, the UW model will be run by UW personnel on NCEP's computer for comparisons using NCEP's verification suite. This activity should produce improved understanding of the impacts of dynamics formulations on global forecasts at different time and space scales.

This development strategy has the following advantages:

- The model has some potentially nice conservation properties.
- Side-by-side testing can be useful in understanding the behavior of NCEP's model.

This strategy has the following disadvantages:

- This model is not supported.
- The model's computational efficiency and program structure are unknown.
- The model has not been fully tested for the broad variety of NCEP's applications.
- The formal accuracy of this model may be less than second order.

4. The Chosen Strategy

It is currently unclear whether either the spectral or gridpoint discretizations will be ultimately superior or whether neither will demonstrate a clear advantage. Among international weather centers, both spectral (ECMWF, Japan Meteorological Agency) and gridpoint (Met Office, Canada) methods are used. However, a spectral method has only been used at the Japan Meteorological Agency for both global and regional applications, where both methods are required. It appears that the most popular choice is a gridpoint method, either through direct nesting or a stretched grid technique. It should be recalled that spectral models still evaluate advective processes on a grid, so that the choice of discretizing the advection boils down to representing horizontal gradients from spectral coefficients, from horizontal interpolations in a SL technique, or from finite difference approximations from grid values.

The chosen strategy is to consolidate EMC model development efforts into three projects as follows:

1. Develop an ESMF-compatible Prototype Framework (PF), which will run the latest version of the NCEP Global Forecast System (GFS)
2. Upscale the NMM to a global domain and incorporate SISL and FISL techniques
3. Generalize the PF to incorporate the NMM as both a global and regional model

The outcome of the above strategy will determine the longer term work (2007–2011). If preliminary projects for producing operational, ESMF-compatible systems are successful, this will enable efficient testing of "multi-model" strategies as well as expanding the suite of operational products to include ocean prediction, environmental monitoring (e.g., CO_2, aerosols), marine ecosystem monitoring and prediction, hydrological prediction, water and air quality monitoring and prediction, and space weather forecasting.

APPENDIX M
SOME FUTURE WORK PLANNED FOR THE HWRF AIR-SEA-LAND-HURRICANE PREDICTION SYSTEM

1. The following additional tasks are associated with WAVEWATCH III:

   - Include new stress and flux parameterizations in the wave model for use in coupling with the HWRF model as necessary and feasible.
   - Include shallow water (surf zone) physics parameterizations in the WAVEWATCH III model, utilizing established parameterizations from models such as Simulating WAves Nearshore (SWAN) and STeady State spectral WAVE (STWAVE). Note that the multi-grid version of WAVEWATCH III that is presently under development at NCEP already includes the capability of drying (movement over land) and wetting (back over water) of grid points.
   - Expand WAVEWATCH III to include irregular and/or unstructured grid approaches for the use in coastal areas. This approach will provide wave forcing for inundation models at the local resolution of such models. In the first approach, a full time-resolving model will be considered. Such a model may be excessively expensive for operational use and is intended mainly to demonstrate the physical feasibility of coupled modeling of waves and surges
   - Economical modeling of waves on irregular and/or unstructured grids may require implicit propagation schemes and/or the use of a quasi-steady approach. Implementation of such approaches in WAVEWATCH III can build upon established techniques for coastal wave models.

2. The work underway on HYCOM modeling with interaction with the ADCIRC team at NOS includes the following activities:

   - Body tides and the complicated problem of including tidal boundary conditions at the open boundaries of the domain have been implemented in HYCOM. Calibration of the tides is underway.
   - Simulations during hurricane events from HYCOM alone. These simulations show adequate skill in storm surge predictions while using operational GDAS winds. The surge estimates from the Real Time Ocean Forecast System (RTOFS) can be used as a first guess of the surge and serve to guide the deployment of the ADCIRC model in areas for which detailed advance knowledge of inundation is useful.
   - In December 2005, the HYCOM-based RTOFS for the Atlantic became operational. The work done on the tides in HYCOM was essential to this development. For hurricane events, the model has a resolution of 4-7 km. Daily fields of nowcast and forecasts of sea surface elevations and transports are now available to provide open boundary conditions to ADCIRC. Air-sea fluxes and wave fields from real-time and historical storms generated by this system are used for testing and validation of the new hurricane system components.

- Strategies for coupling of HYCOM fields to the high-resolution NOS coastal models and the representation of coast line configuration and coastal bathymetry are currently underway. They include NOS requirements for wave-related fluxes in their coastal models.
- Work continues on including turbulent boundary layer effects in HYCOM due to the waves. A series of simulations will be carried out jointly with NOS to deal with problems related to open boundary nesting of HYCOM and ADCIRC for selected cases. In addition, work on improving the representation of tides in HYCOM will continue.

3. The additional planned work dealing with the HWRF, the Noah LSM, the prediction of the distribution of low level surface winds and rainfall amounts, and forecasting of stream and river flow and flood levels includes the following activities:

   - Couple the LSM with the movable, nested grid of the HWRF; investigate the impact of the Noah LSM on the prediction of the distribution of low level surface winds and rainfall amounts and the overall decay rate upon landfall. This will be contrasted with the simple one-layer slab model currently in the HWRF and the GFDL operational hurricane models.
   - Compare the predicted wind and rainfall amounts from HWRF with observations, including the proposed meso-network in Alabama by the U.S. Army. This will include present hurricanes as well as significant landfalling cases that have occurred over the past few years. Standard verification techniques for rainfall verification will be used, as well as new techniques designed especially for landfalling hurricanes (see section 3.4.5).
   - Initiate a project that will use the runoff output of the Noah LSM as input to various objective techniques to forecast river flow and flooding. Successful precipitation prediction by itself may be attractive, but the true importance of precipitation lies as an input to provide accurate forecasting of stream and river flow and flood levels. Traditionally, river and flood forecasts have not used hurricane model predictions of precipitation as input to predict river and flood forecasts. Evaluation of model-predicted wind and precipitation fields will continue.
   - Upgrade and change (as required) the HWRF model physics packages to improve skill of precipitation and wind fields, especially the distribution of low-level surface winds and precipitation. The upgrades and changes will be based on the aforementioned verification and evaluation of predicted precipitation and wind fields and their deviations from the observed fields determined from historical observations and the proposed meso-net data in Alabama. The predictability of intense destructive features will be evaluated through the use of ensemble and high-resolution forecasts.
   - Continue the evaluation of the effect of utilizing HWRF-determined runoff in the forecast of river flow and flooding. The evaluation will be contrasted with more basic forecasts utilizing precipitation without regard to moisture conditions of the underlying soil. The basic forecasts may include coarse resolution rainfall forecasts from simple models of climatological hurricane rainfall and forecaster-subjective methods of supplying QPF. In addition, further refinements will be made to other physics packages of HWRF to improve predictive skill.

APPENDIX N QUESTIONS FROM THE *AIR-SEA INTERACTIONS IN TROPICAL CYCLONES WORKSHOP*

(Shay et al. 2005)

Focused questions arose from the *Air-Sea Interactions in Tropical Cyclones Workshop* involving the collaboration of the hurricane air-sea community in addressing fundamental issues needed to advance the HWRF and other air-sea coupled hurricane models.

1. Where is the air-sea community on observing and modeling the oceanic and coupled response to tropical cyclones? What is the state-of-the-art in areas of air-sea interaction/boundary layer processes and upper ocean physics? What promising technologies are on the horizon? Will they be available over the next 2 to 5 years?
2. How can we maximize recently acquired data sets such as ONR-CBLAST, NSF/ NOAA Isidore/Lili, HFP, and MMS Georges data sets?
3. What are the relevant time/space scales at which models need to be resolved relative to intensity change?
4. What is the impact of oceanic coupling on forecasting the atmospheric structure and intensity?
5. How do we improve initialization schemes? How important are positive feedback regimes such as the Gulf Stream and the Loop Current on storm intensity and structure?
6. Can we use some of the work from GODAE for assimilation of satellite, drifter, and float data?
7. What observations are needed to improve mixing parameterizations? What about wave coupling to the OML and ABL?
8. What is the appropriate mix of observations needed to improve the ocean and air-sea boundary layer processes in oceanic or coupled models?
9. What metric(s) need to be implemented for consistent assessment of model(s) performance? For example, is showing intensity changes from models enough for a validation? How do we implement data and metrics in near-real time for forecasting needs?
10. What new real-time experimental plans need to be developed to support model forecasts? For example, sampling scenarios may differ over the Loop Current than the subtropical front in the North Atlantic.
11. Do we follow the life cycle of one storm, or observe two storms under differing oceanic conditions each year? Will this approach provide enough statistics to really improve the models?

12. How do we maximize use of GOOS float and ship-of-opportunity data? Will NDBC upgrades be useful? What about Coastal Ocean Observing Systems?
13. Do we rely on moored instrumentation or do we integrate time series from floats/drifters with snapshots from expendable sensors from aircraft?
14. Where do we see satellite remote sensing support going? What type of data will be useful in supporting experimental plans and data assimilation in models?

APPENDIX P
SOCIAL SCIENCE RESEARCH

Representative Research Questions
1. Warning Process
How does information flow from forecasters to various types of decision makers?
How should probabilistic forecasts be structured to promote public understanding?
Do people respond better to consistent forecasts with lower probabilities of accuracy, or should forecasters sacrifice consistency for reasonable accuracy?
Are terms like watch, warning, and surge well understood or should new terminologies be developed and tested?
Are current watch/warning lead times the most useful to responders?
What graphics and visualization techniques promote appropriate reactions?
Is the Saffir-Simpson scale adequate, or would a different or additional scale be more useful?
How can the level of danger from surge, rainfall, and inland flooding be conveyed effectively?
How do risk perceptions vary in heterogeneous populations?
How can warning messages target high-risk groups?
What are the consequences of broadcast media consolidation to the warning process?
Can local WFOs be used more effectively in the warning process?
2. Decision Making
What are the processes by which various user groups receive, interpret, and use forecasts and warnings?
How do end users handle conflicting messages?
How can NWS products and processes be improved to promote more effective decisions and responses?
How do forecast and warning messages influence timing in decision making?
What products and timing best meet the needs of various categories of businesses and organizations?
How do social vulnerability issues (gender, race, class) play out in risk perception and response?
How do formal and informal social networks affect response to warning messages?
What are the best methods for educating various user groups in the effective use of forecasts and warnings in their decision-making processes?
How do the cultures of various organizations involved in responding to forecasts and warnings encourage or impede change?
How can the forecast community understand and navigate the political processes involved in hurricane-related decisions?

Representative Research Questions
3. Behavioral Response
How can response and evacuation behavior best be modeled?
How do context and resources affect the timing of hurricane response among various user groups?
What are the lags between various warning messages and protective actions?
What changes in the warning process are likely to promote evacuation among those who should leave, while deterring unnecessary evacuation?
What are the effects of “false alarms” on future hurricane response among different user groups?
What are the effects of various warning methods and processes on traffic patterns?
How do media accounts of a hurricane event affect future behavior?
How can behavioral studies from various events be structured to allow for comparative research?
How can behavioral data bases be made available to researchers while protecting the identify of respondents?
4. Social Impacts and Valuation
How can relevant social costs be included in the economic analyses of hurricane impacts?
How can the methods and tools of social science be used to document long-term social and economic costs?
What are the costs and benefits of either shrinking the warning area or increasing lead times?
Can meaningful metrics be developed to measure the economic value of hurricane forecasts and warnings that take into account the quality of the forecast, the value of communication process variables, and the value of responsiveness?
Is it even relevant to put a value on improved forecasts separate from the entire communication and response process?
How can spatial data analysis most effectively result in a clearer understanding of hurricane impacts?
How can impact measurements take into account the relative value of losses to various segments of the affected population?

APPENDIX Q
LIST OF ACRONYMS

3D	three-dimensional
3D-VAR	Three-Dimensional Variational Data Assimilation
4DDA	Four-Dimensional Data Assimilation
4D-VAR	Four-Dimensional Variational Data Assimilation
ADCIRC	Advanced Circulation [Model]
ADOS	Autonomous Drifting Ocean Station
ADT	Advanced Dvorak Technique
AFB	Air Force Base
AFFO	Announcement of Federal Funding Opportunity
AFRC	U.S. Air Force Reserve Command
AFWA	Air Force Weather Agency
AGCM	atmospheric general circulation model
ALT	Radar Altimeter
AMOP	Administrative Model Oversight Panel
AMPR	Advanced Microwave Precipitation Radiometer
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer—Enhanced
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Meteorological Laboratory (of NOAA/OAR)
AOR	area of responsibility
APP	American Meteorological Society Policy Program
APR	Airborne Precipitation Radar
ARMR	Airborne Rain Mapping Radar
ARW	Advanced Research WRF
ASCAT	Advanced Scatterometer [MetOp-A satellite instrument]
ASOS	Automated Surface Observing Systems
ATCF	Automated Tropical Cyclone Forecasting System
ATMS	Advanced Technology Microwave Sounder
AVAPS	Airborne Vertical Atmospheric Profiling System
AVN	Aviation Model [NOAA/NCEP predecessor to GFS]
AXBT	Airborne Expendable Bathythermographs
AXCP	Airborne Expendable Current Profilers
AXCTD	Airborne Expendable Conductivity Temperature and Depth [probe]
BASC	Board on Atmospheric Sciences and Climate (of NAS/NRC)
BAT	Best Available Turbulence
BEI	Battlespace Environments Institute
BFRL	Building and Fire Research Laboratory (of NIST)

BIO	Biological Science Directorate [of NSF]
BOM	Australia Bureau of Meteorology
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CARCAH	Chief, Aerial Reconnaissance Coordination, All Hurricanes
CBLAST-DRI	Coupled Boundary Layers Air-Sea Transfer Departmental Research Initiative
CD	compact disk
CENR	Committee on Environment and Natural Resources (of NSTC)
CFS	Coupled Climate Forecast System
CHAT	Caribbean Hurricane Awareness Tour
CHL	Coastal and Hydraulics Laboratory (of USACE/ERDC)
CICS	Cooperative Institute for Climate Studies [University of Maryland]
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIOSS	Cooperative Institute for Oceanographic Satellite Studies [Oregon State University]
CIRA	Cooperative Institute for Research in the Atmosphere
CLIPER	Climatology and Persistence [Model]
C-MAN	Coastal Marine Automated Network
CMA	Chinese Meteorological Administration
CMC	Canadian Meteorological Center
CMIS	Conical Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
CNMOC	Commander, Naval Oceanographic and Meteorological Command
COAMPS®	Coupled Ocean/Atmosphere Mesoscale Prediction System
CONDUIT	Cooperative Opportunity for NCEP Data Using IDD Technology
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CPHC	Central Pacific Hurricane Center
CrIS	Cross-track Infrared Sounder
CSU	Colorado State University
CWB	Taiwan Central Weather Bureau
DAC	Drifter Data Assembly Center [of GDP]
DMSP	Defense Meteorological Satellite Program
DOC	U.S. Department of Commerce; Drifter Operations Center [of GDP]
DOD	U.S. Department of Defense
DPR	Dual-frequency Precipitation Radar
DR	[NAS/NRC] Disasters Roundtable
DTC	Developmental Testbed Center
DVD	digital video disk
EAS	Emergency Alert System
ECMWF	European Center for Medium-Range Weather Forecasting
EDA	ensemble data assimilation
EDOP	ER-2 Doppler Radar

EIR	enhanced infrared
EMC	[NOAA/NCEP] Environmental Modeling Center
ENG	Directorate for Engineering [of NSF]
ENSO	El Nino–Southern Oscillation
EOS	Earth Observing System
ERDC	U.S. Army Engineer Research and Development Center
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESMF	Earth System Modeling Framework
ESRL	Earth System Research Laboratory
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FASTEX	Fronts and Atlantic Storm-Track Experiment
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FEMA	Federal Emergency Management Agency
FISL	fully implicit semi-Langrangian
FNMOC	Navy Fleet Numerical Meteorology and Oceanography Center
FSU	Florida State University
GDAS	[NOAA/NCEP] Global Data Assimilation System
GDP	Global Drifter Program
GEO	Geosciences Directorate [of NSF]
GEOS	Goddard Earth Observing System
GEOSS	Global Earth Observation System of Systems
GFDL	Geophysical Fluid Dynamics Laboratory [NOAA/OAR]
GFDN	Geophysical Fluid Dynamics Laboratory Hurricane Prediction System—Navy version
GFO	[NOAA] Geosat Follow-On [mission]
GFS	[NCEP] Global Forecast System
GIS	geographical information system
GMAO	Global Modeling and Assimilation Office (of NASA/GSFC)
GMI	GPM Microwave Imager
GODAE	Global Ocean Data Assimilation Experiment
GODAS	Global Ocean Data Assimilation System
GOES	Geostationary Operational Environmental Satellite
GOOS	[NOAA] Global Ocean Observing System
GOOS	[NOAA] Global Ocean Observing System
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRADAS	Global and Regional Advanced Data Assimilation System
GSFC	NASA Goddard Space Flight Center
GSI	[NCEP] Gridpoint Statistical Interpolation [System]
HAMSR	High Altitude MMIC Sounding Radiometer

HAT	Hurricane Awareness Tour
HFSEWG	Hurricane Forecast Social and Economic Working Group
HHS	U.S. Department of Health and Human Services
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
HIRS	High Resolution Infrared Radiation Sounder
HIRWG	Hurricane Intensity Research Working Group [of NOAA/SAB]
HLT	Hurricane Liaison Team
HPC	Hydrological Prediction Center (of NOAA/NCEP); High Performance Computing [DOD]
HPCMP	High Performance Computing Modernization Program [DOD]
HRD	Hurricane Research Division (of NOAA/OAR/AOML)
HSAI	HPC [High Performance Computing] Software Applications Institute [institutes are sponsored by HPCMP]
HSE	[NSF] Task Force on Hurricane Science and Engineering
HUD	U.S. Department of Housing and Urban Development
HWRF	Hurricane Weather Research and Forecast [model] (see WRF)
HYCOM	Hybrid-Coordinate Ocean Model [NCEP]
IASI	Infrared Atmospheric Sounding Interferometer
ICMSSR	Interdepartmental Committee for Meteorological Services and Supporting Research
ICON	intensity consensus model
IDEA	Integrated Dynamics through Earth’s Atmosphere (joint NASA-NOAA initiative)
IEOS	Integrated Earth Observation System
IFEX	Intensity Forecasting Experiment
IHC	Interdepartmental Hurricane Conference
IPO	Integrated Program Office
IR	infrared
ISRO	Indian Space Research Organization
IT	information technology
IWGEO	Interagency Working Group on Earth Observations [replaced by US GEO]
IWRAP	Imaging Wind and Rain Profiling System
JAAWIN	Joint Air Force and Army Weather Information Network
JAG/TCR	Joint Action Group for Tropical Cyclone Research
JAXA	Japanese Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JHT	Joint Hurricane Testbed
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory
JTWC	Joint Typhoon Warning Center
KMA	Korean Meteorological Administration
kt	knot(s)
LSM	land surface model

MAP	Modeling, Analysis, and Prediction [Program]
MERRA	Modern Era Retrospective analysis for Research and Applications
MHS	Microwave Humidity Sounder
MJO	Madden-Julian Oscillation
MM5	Fifth-Generation Mesoscale Model
MMIC	monolithic microwave integrated circuit
MODIS	Moderate Resolution Imaging Spectroradiometer
MPAR	multifunction phased array radar
MRF	Medium Range Forecast model [NOAA/NCEP predecessor to GFS]
MTSAT	Multifunctional Transport Satellite (Japanese geostationary satellite)
MURI	Multidisciplinary Research Program of the University Research Initiative
MVOI	multivariate optimum interpolation
MWW3	Multi-grid WAVEWATCH III [ocean wave model]
NAE	National Academy of Engineering
NAMMA	NASA African Monsoon Multidisciplinary Activities
NARAC	National Atmospheric Release Advisory Center
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAVDAS	NRL Atmospheric Variational Data Assimilation System
NAVDAS-AR	NAVDAS Accelerated Representer
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NCOM	NRL Coastal Ocean Model
NDBC	National Data Buoy Center
NESDIS	[NOAA} National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NHOP	National Hurricane Operations Plan
NHP	National Hurricane Program (of FEMA)
NIST	National Institute of Standards and Technology
NLDAS	North American Land Data Assimilation System
NLETS	National Law Enforcement Telecommunications System
nmi	nautical mile(s)
NMM	Nonhydrostatic Mesoscale Model
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NOPP	National Ocean Partnership Program
NOS	[NOAA] National Ocean Service
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRL	Naval Research Laboratory
NRL-Monterey	Marine Meteorology Division [of NRL Ocean and Atmospheric Science and Technology Directorate]

NSB	National Science Board (of NSF)
NSF	National Science Foundation
NSSL	[NOAA] National Severe Storm Laboratory
NSTC	National Science and Technology Council
NWP	Numeric Weather Prediction
NWR	NOAA Weather Radio
NWS	National Weather Service
OAR	[NOAA] Office of Oceanic and Atmospheric Research
OBS	Ocean Battlespace Sensing S&T [ONR department]
ODAS	ocean data assimilation system
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
OHC	ocean heat content
OML	oceanic mixed layer
OMPS	Ozone Mapping and Profiler Suite
ONR	Office of Naval Research
OPC	Ocean Prediction Center [of NOAA/NCEP]
OSSE	observing system simulation experiment
OSTP	Office of Science and Technology Policy
OSU	Oregon State University
OSVW	ocean surface vector winds
PBL	planetary boundary layer
PDA	personal digital assistant
PDT	Prospectus Development Team [for USWRP]
POM	Princeton Ocean Model
QPF	quantitative precipitation forecasting
QuikSCAT	Quick Scatterometer
R&D	research and development
RAINEX	Rainband and Intensity Change Experiment
R-CLIPER	Rainfall Climatology and Persistence model
recco	reconnaissance code
RSM	Regional Spectral Model
RSMC	Regional Specialized Meteorological Center
RTOFS	Real Time Ocean Forecast System
RTP	Rapid Transition Project [in U.S. Navy/ONR R&D process]
S&T	Science and Technology
SAB	[NOAA] Science Advisory Board
SATCOM	satellite communications
SATCON	satellite consensus
SBIR	Small Business Innovative Research

SDBE	situation-dependent background errors
SDR	Subcommittee on Disaster Reduction [of NSTC/CENR]
SFMR	Stepped-Frequency Microwave Radiometer
SHIFOR	Statistical Hurricane Intensity Forecast [Model]
SHIPS	Statistical Hurricane Intensity Prediction Scheme
S/I	seasonal to interannual
SISL	semi-implicit semi-Lagrangian
SLOSH	Sea, Lake, and Overland Surge [Model]
SPC	Storm Prediction Center (of NOAA/NCEP)
SRA	Scanning Radar Altimeter
SREF	Short-Range Ensemble Forecast
SSI	spectral statistical interpolation
SSM/I	Special Sensor Microwave Imager
SSMI/S	Special Sensor Microwave Imager/Sounder
SST	sea surface temperature
STAR	Center for Satellite Applications and Research (of NOAA/NESDIS)
STI	Shanghai Typhoon Institute
STIP	Science and Technology Infusion Plan (NOAA)
STIPS	Statistical Typhoon Intensity Prediction Scheme
STTR	Small Business Technology Transfer
STWAVE	Steady State Spectral Wave
SWAN	Simulating Waves Nearshore
SWMF	Space Weather Modeling Framework
TAFB	Tropical Analysis and Forecast Branch (of NOAA/NCEP/TPC)
TCHP	tropical cyclone heat potential
TCSP	Tropical Cloud Systems and Processes
THORPEX	a component program of the WMO World Weather Research Programme
TMI	Tropical Microwave Imager
TPC	Tropical Prediction Center (of NOAA/NCEP)
TRaP	Tropical Rainfall Potential [method for estimating rainfall]
TRMM	Tropical Rainfall Measuring Mission
TSB	Tropical Support Branch (of NOAA/NCEP/TPC)
TUTT	Tropical Upper Tropospheric Trough
UAS	unmanned aircraft system
UCAR	University Corporation for Atmospheric Research
UKMO	United Kingdom Meteorological Office; also the UKMO global model
US GEO	United States Group on Earth Observations [of CENR, replaces IWGEO]
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
UW	University of Wisconsin
UW-CIMSS	Unversity of Wisconsin Cooperative Institute for Meteorological Satellite Studies

VIIRS	Visible/Infrared Imager Radiometer Suite
VOS	Voluntary Observing Ship [program]
WCR	warm core ring
WFO	National Weather Service Forecast Office
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting [modeling initiative]
WRF-ARW	Advanced Research WRF
WSUAV	Weather Scout Unmanned Aerial Vehicle
XBT	Expendable Bathythermograph
YIP	Young Investigator Program
YSU	Yonsei University