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.

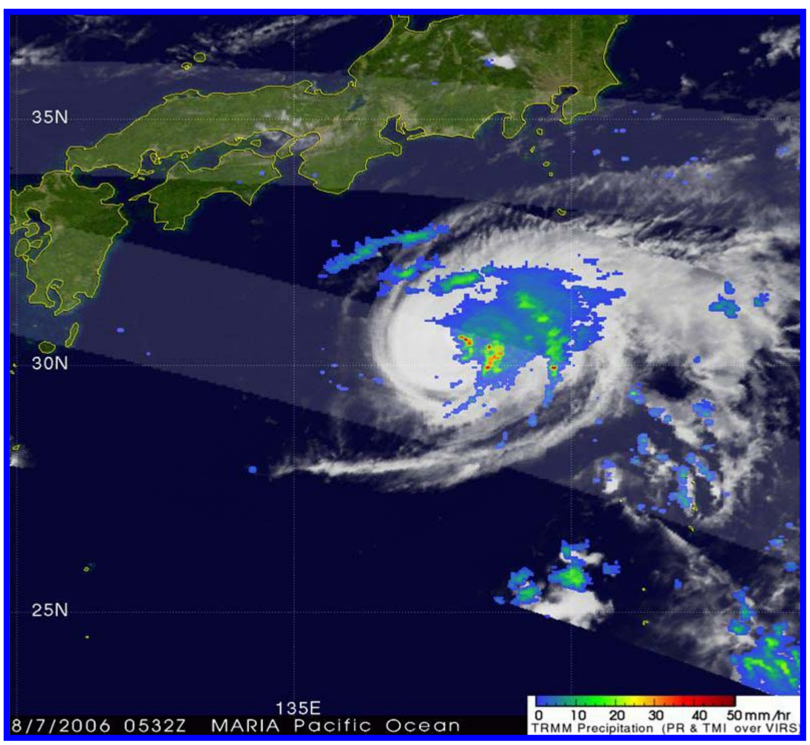

Figure 1-1. This image is made from data received from the NASA Tropical Rainfall Measurement Mission (TRMM) satellite showing Typhoon Maria closing in on Japan (August 7, 2006). Typhoon Maria subsequently weakened and passed just south of Tokyo Bay as a minimal tropical storm. Credit: NASA.

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).

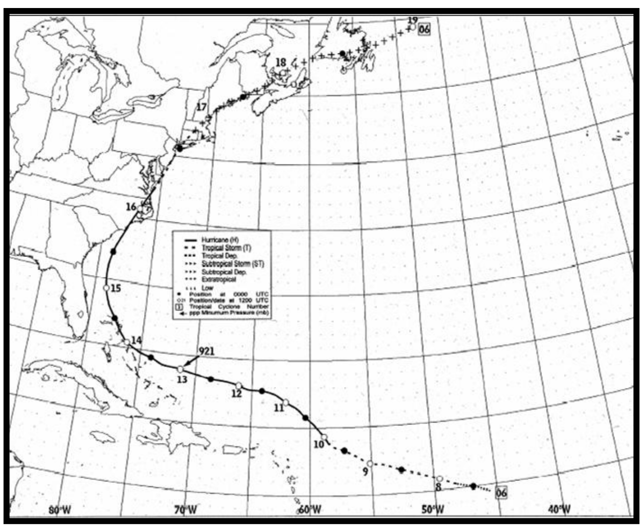

Figure 1-3. Best track position of Hurricane Floyd.

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

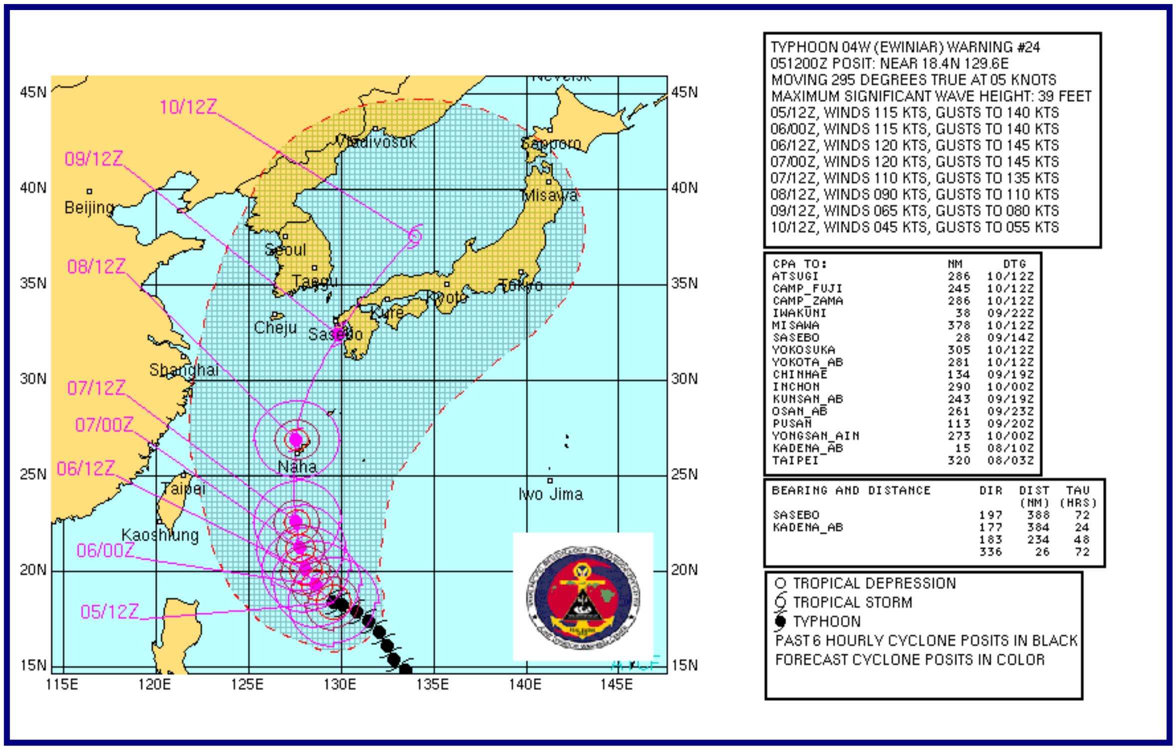

Figure 1-4. July 5, 1200 UTC, JTWC forecast indicating tropical cyclone passage over Sasebo in 96 hours.

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.)

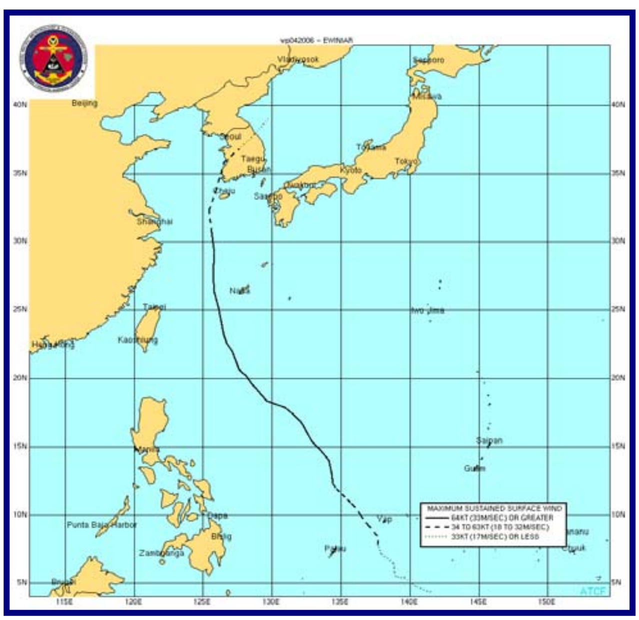

Figure 1-5. Overall track, Super Typhoon 04W (Ewiniar).

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).*

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

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

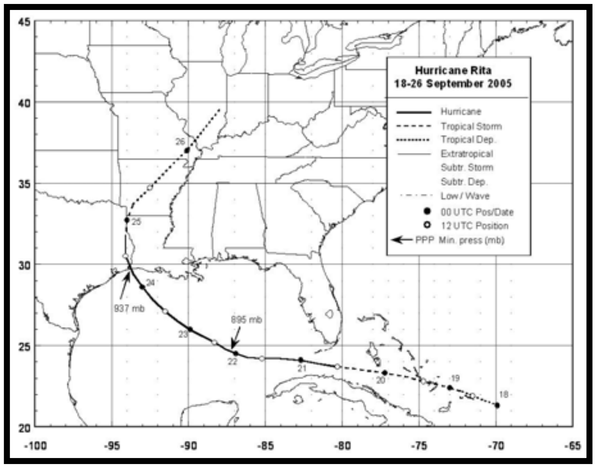

Figure 1-7. Best track position of Hurricane Rita.

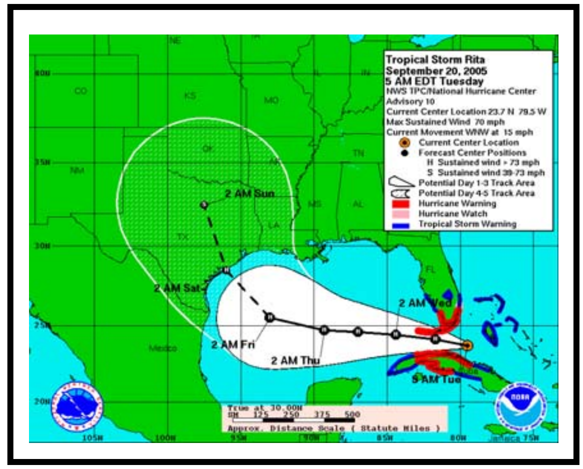

Figure 1-8. TPC/NHC Advisory #10 for Rita.

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

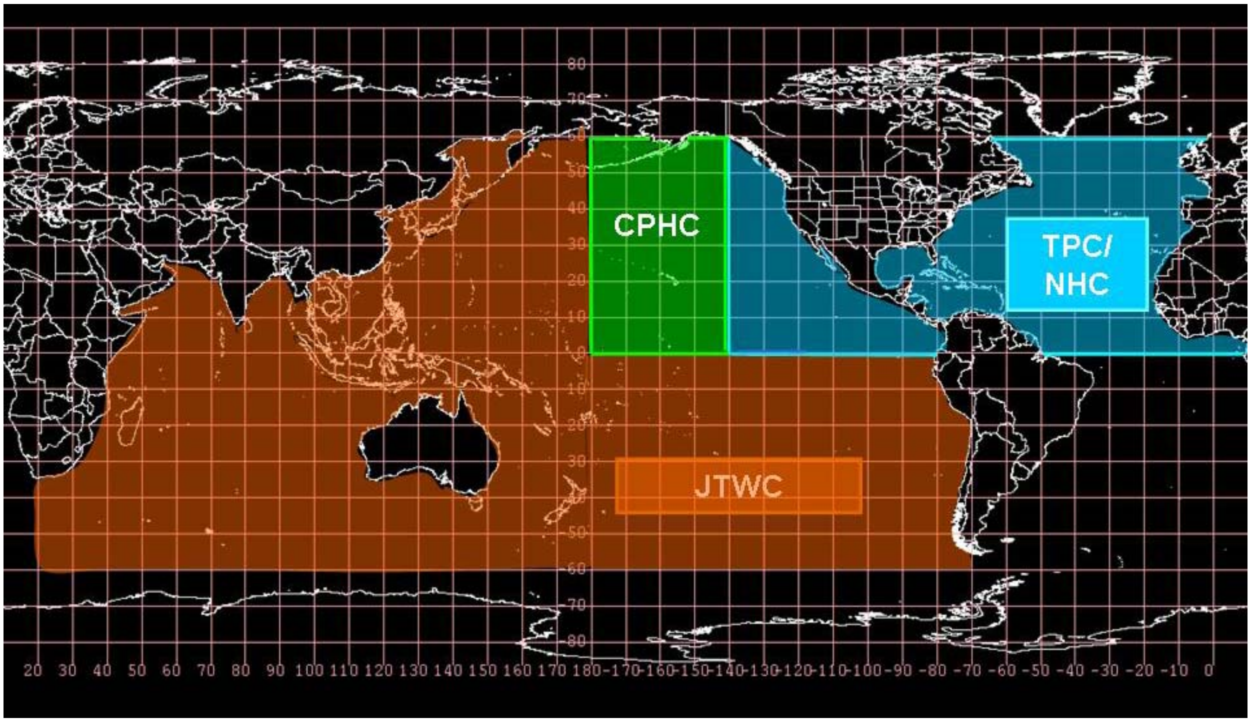

Figure 1-9. Areas of responsibility (AORs) assigned to the operational tropical cyclone forecast and warning centers. The JTWC AOR overlaps with those of the TPC/NHC and CPHC north of the equator in the central and north Pacific.

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 30/31° 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 30/31° 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