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

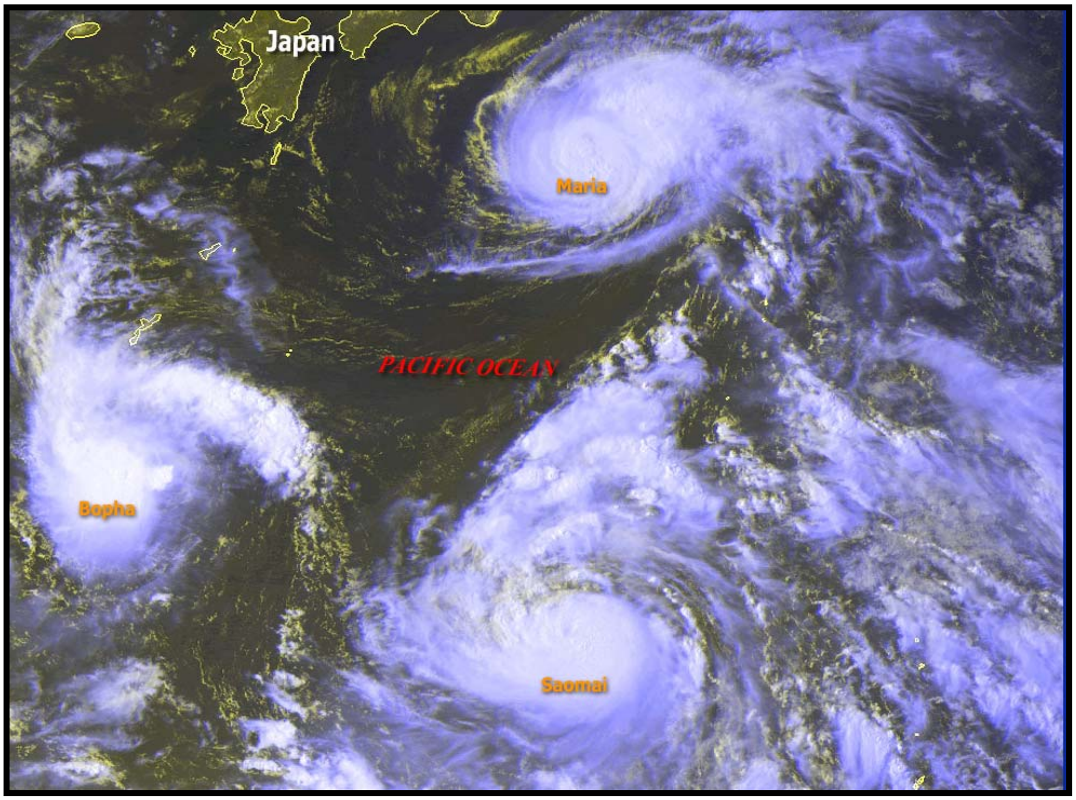
To meet the operational needs summarized in Table 4-1, focused efforts and sufficient investment in the four areas of advanced observations, advanced data assimilation technologies, advanced NWP models, and investment in human and infrastructure resources are critical to the future success of the Nation's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

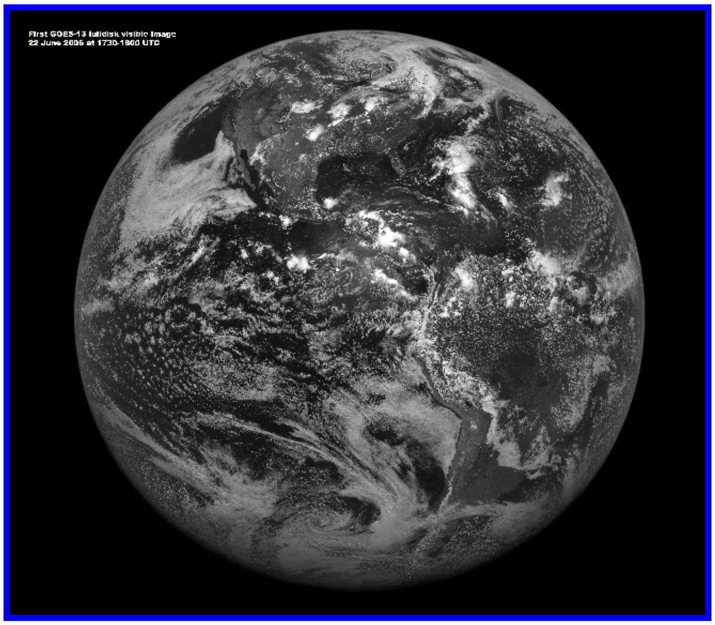


Figure 4-1. First GOES-13 full-disk visible image, June 22, 2006, 1730–1800 UTC. GOES-13 is the first of the GOES-N series of satellites. Credit: NOAA.

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.

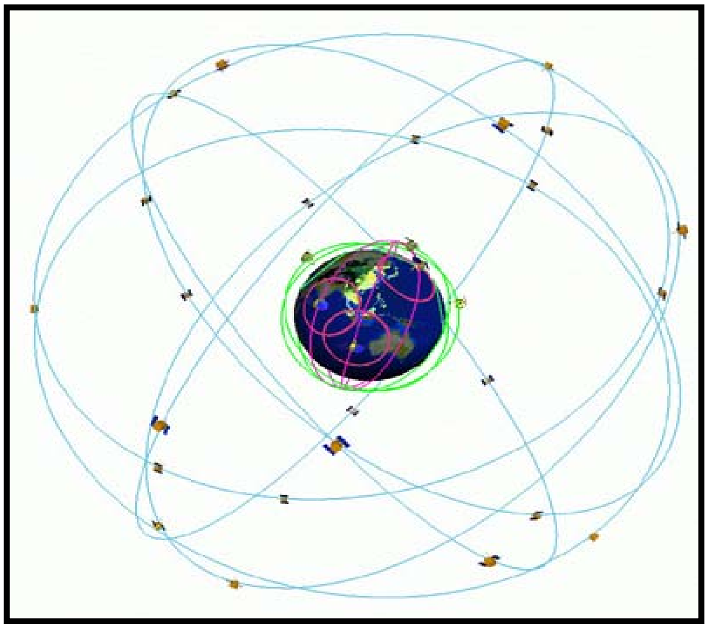


Figure 4-2. The constellation of six COSMIC satellites surrounded by satellites from the Global Positioning System, whose signals COSMIC will use. Credit: COSMIC Project Office.

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

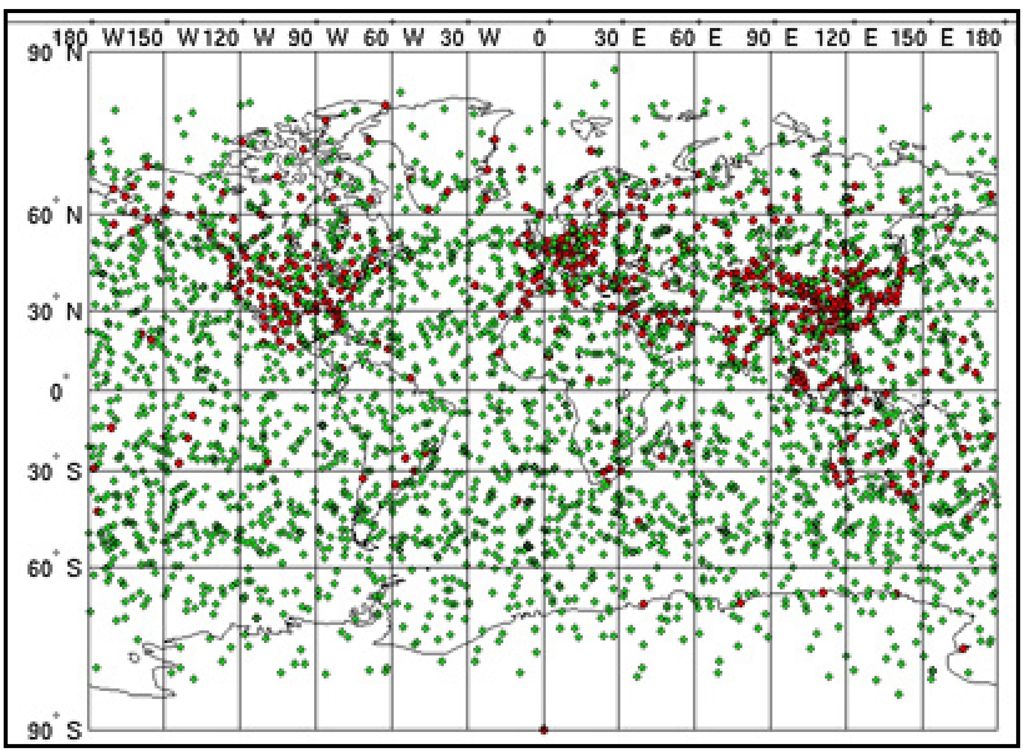


Figure 4-4. A comparison of the current global coverage of instruments launched via radiosondes each day (in red) with the expected coverage from the COSMIC satellite network in a 24-hour period (in green). Credit: COSMIC.

(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 <u>and</u> 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

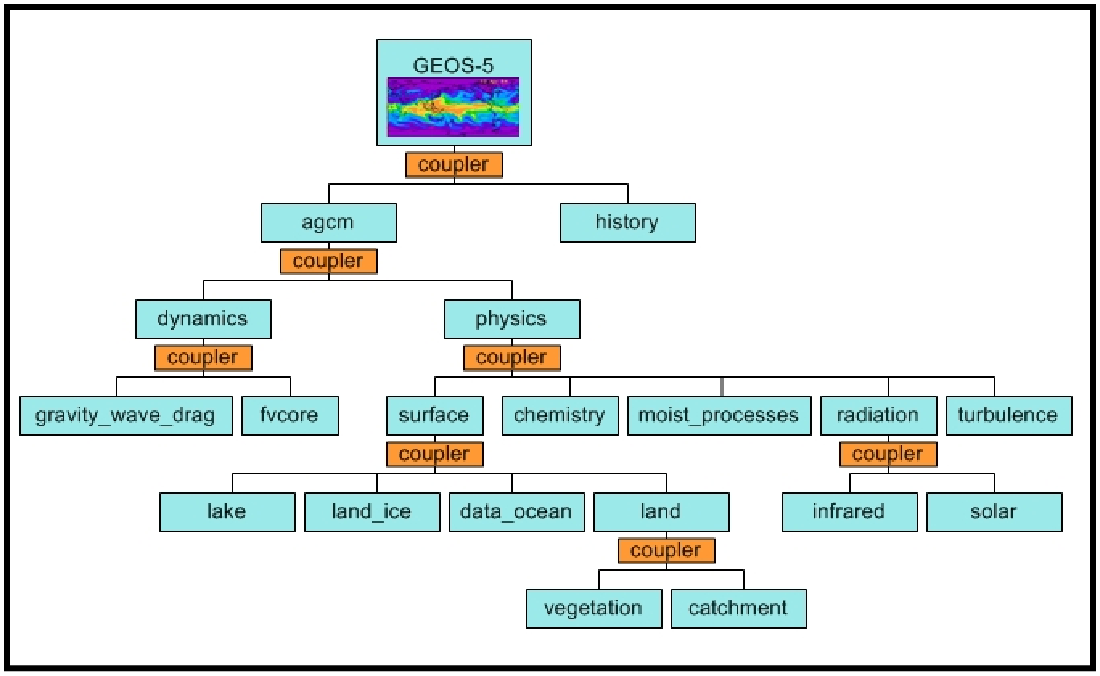


Figure 4-5. ESMF application example using NASA's GEOS-5 AGCM.

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

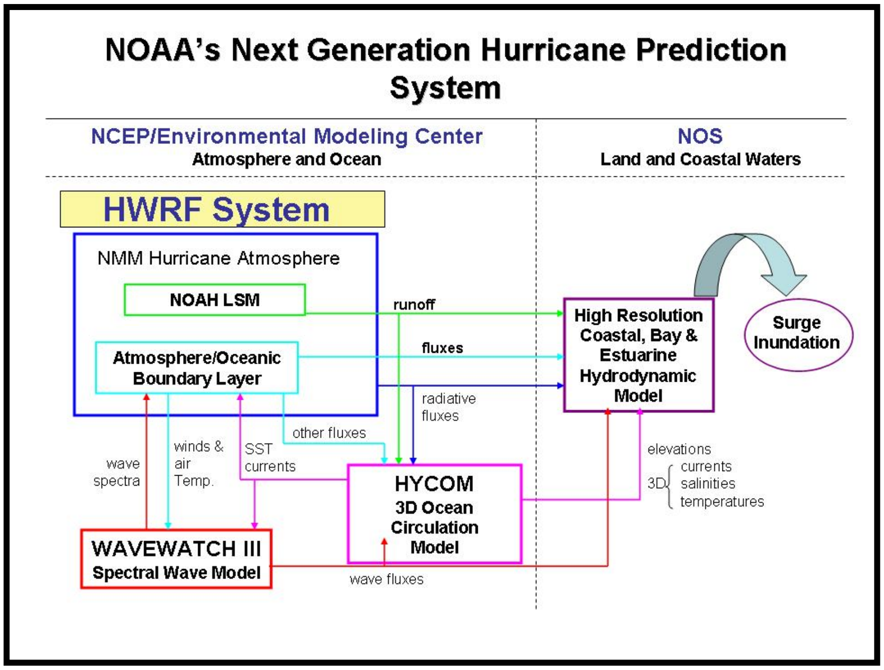


Figure 4-6. HWRF Air-Sea-Land Hurricane Prediction System.

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

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[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

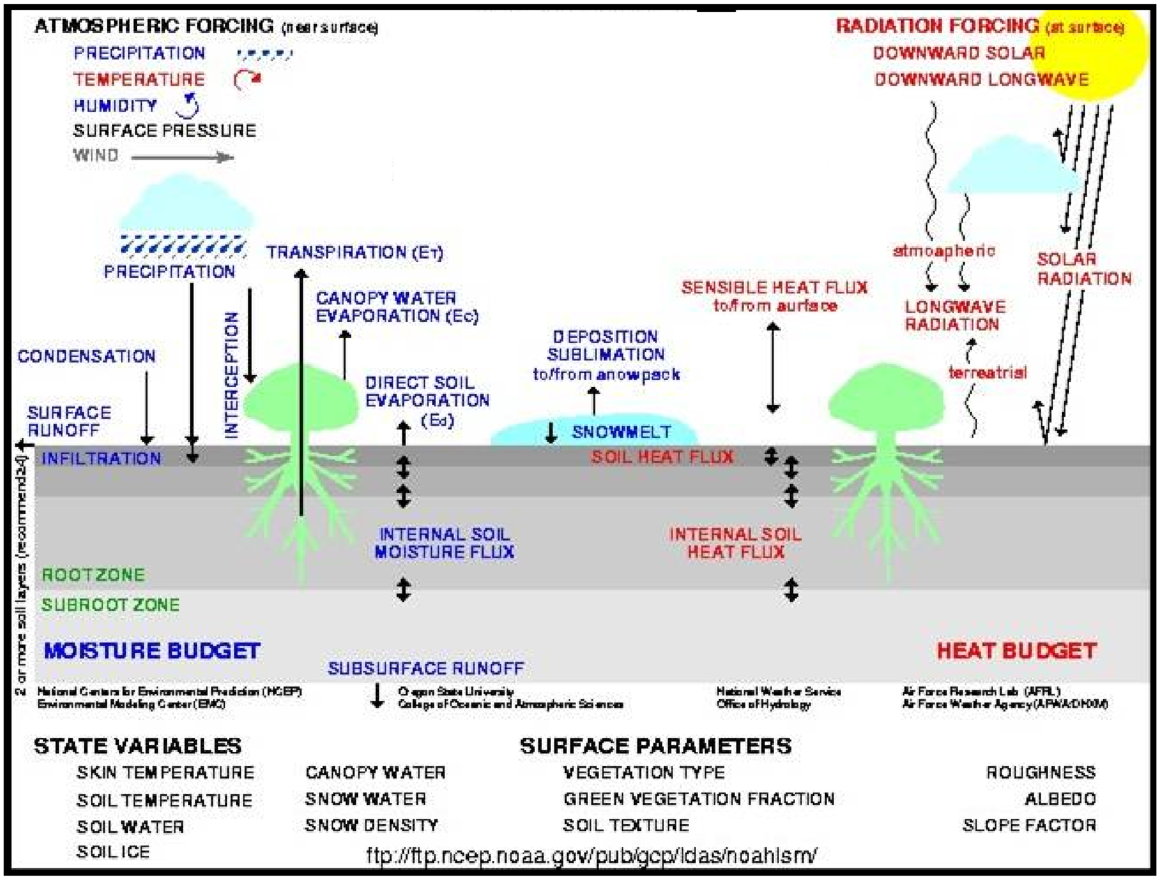

Figure 4-7. The Noah Land-Surface Model.

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.