3
CURRENT CAPABILITIES AND LIMITATIONS

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

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

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

3.1 Data Collection and Observations for Tropical Cyclone Fixing and Analysis

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

3.1.1 Operational and Research Aircraft for Observing Tropical Cyclones

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

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

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

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

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

AFRC WC-130J Aircraft

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

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

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

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

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

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

NOAA WP-3D Aircraft

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

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

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

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

* Installation underway, to be completed in 2008.

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

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

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

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

NOAA Gulfstream IV Aircraft

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

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

Other Research Aircraft and Instrumentation

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

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

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

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

3.1.2 Satellite Platforms, Instruments, and Data Streams

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

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

Satellite Data in Tropical Cyclone Analysis

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

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

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

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

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

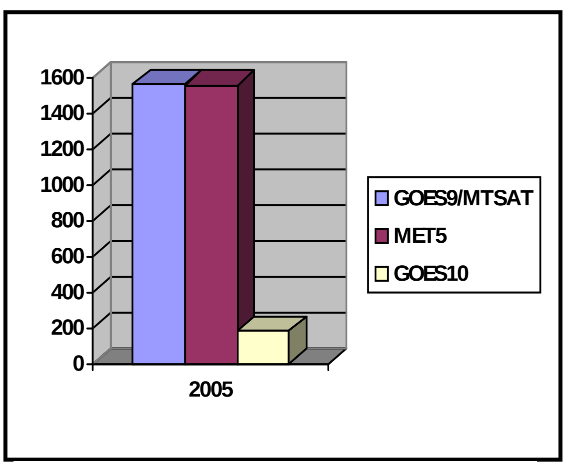

Figure 3-1. Geostationary satellite position and intensity fixes by JTWC during 2005.

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

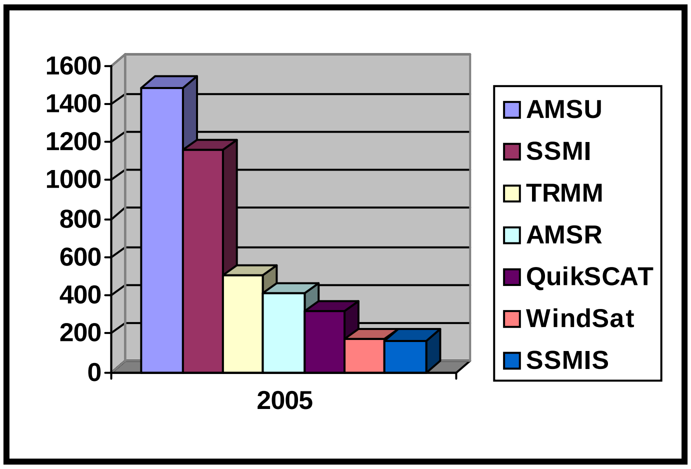

Figure 3-2. Microwave position fixes by JTWC during 2005.

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

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

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

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

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

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

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

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

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

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

Satellite Data in Tropical Cyclone Forecasting

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

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

3.1.3 Ocean Observations

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

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

Improving Observations of Ocean Thermal Structure

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

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

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

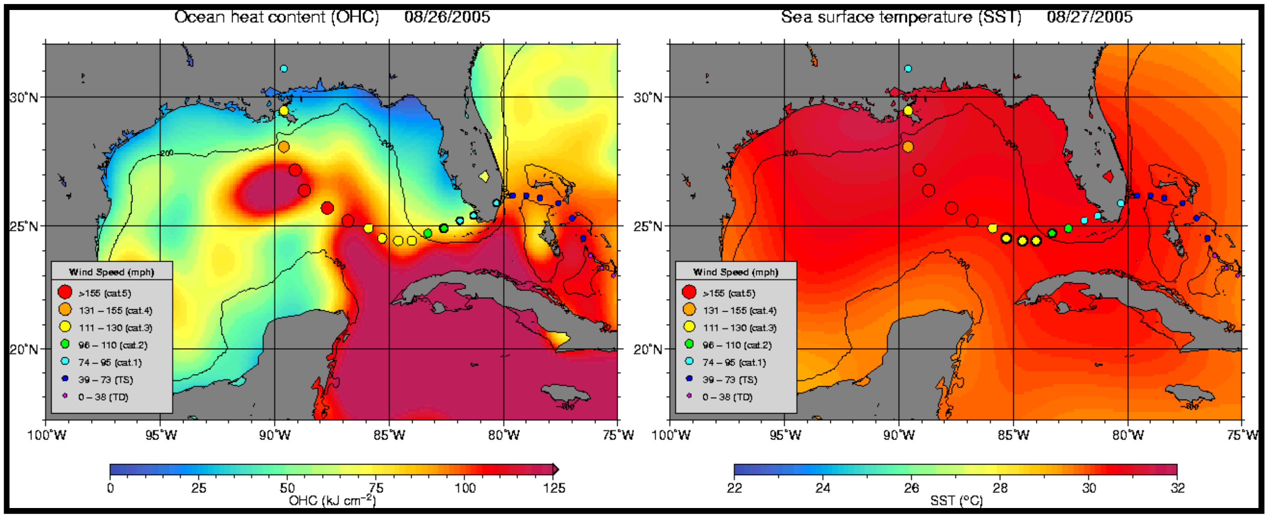

Figure 3-3. Comparison of altimeter-derived estimates of ocean heat content (left) and satellite-derived sea surface temperature (right). The circles of different colors indicate the track and intensity of Hurricane Katrina (Mainelli et al. 2006).

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

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

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

In Situ Ocean Observations

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

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

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

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

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

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

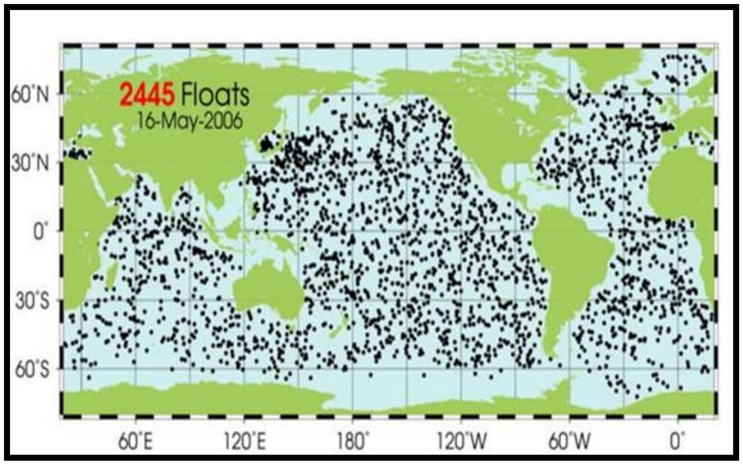

Figure 3-4. The Argo array.

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

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

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

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

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

3.1.4 Land-Based Surface Systems

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

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

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

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

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

3.1.5 Adaptive (Targeted) Observation Strategies

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

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

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

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

3.1.6 Observations of the Tropical Cyclone Inner Core

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

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

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

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

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

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

3.2 Statistical Analysis and Prediction Techniques

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

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

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

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

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

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

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

3.3 Numerical Models

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

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

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

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

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

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

3.3.1 Global Models

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

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

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

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

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

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

Table 3-5. Upgrades to the NOGAPS Model

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

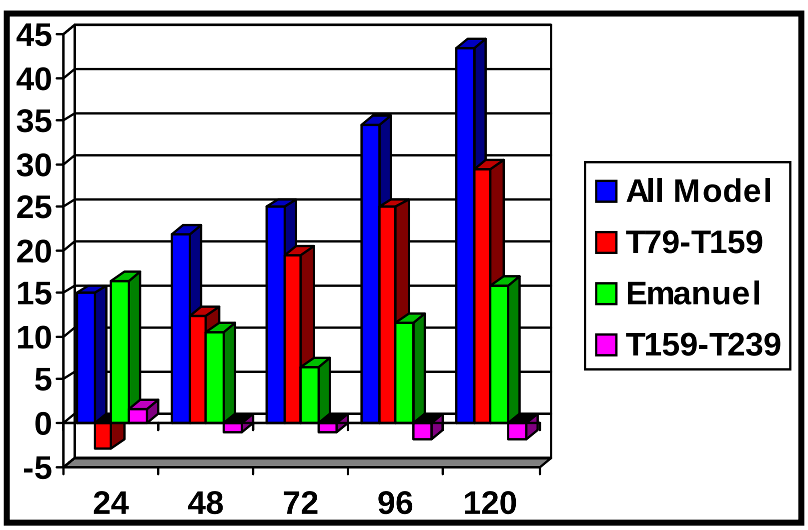

Figure 3-5. Percentage improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004.

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

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

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

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

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

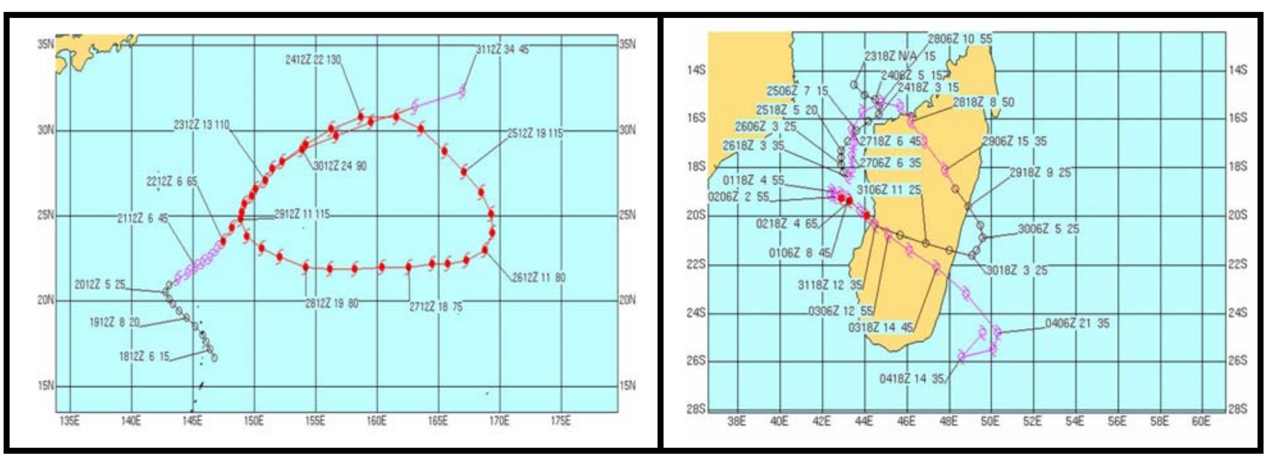

Figure 3-6. Two examples of erratically moving storms. Left: Tropical Cyclone Parma, October 18–31, 2003; Right: Tropical Cyclone Elita, January 23–February 5, 2004. Credit: JTWC.

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

3.3.2 High-Resolution Regional Models

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

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

Recent Improvements to the NOAA/NCEP GFDL Model

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

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

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

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

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

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

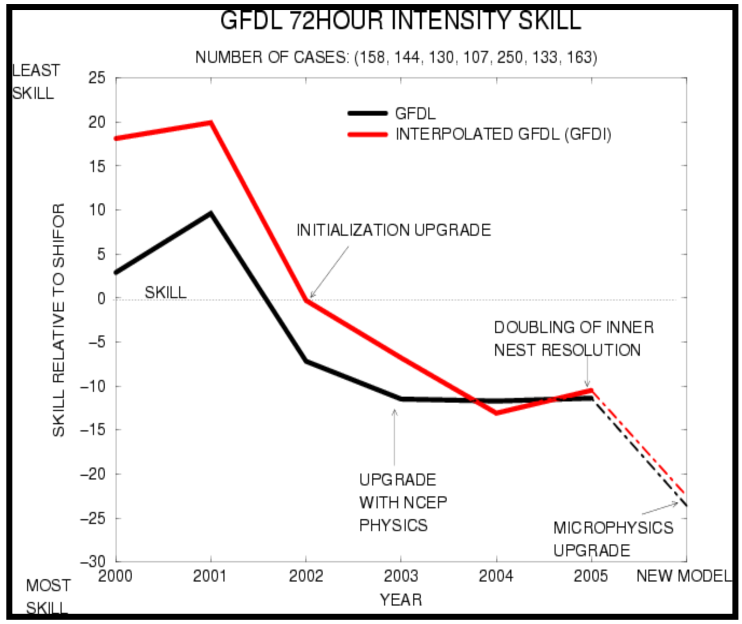

Figure 3-7. GFDL intensity skill (Atlantic basin) relative to SHIFOR since 2000. Also plotted is the intensity skill for 163 cases run with the 2006 version of the GFDL model (NEW MODEL).

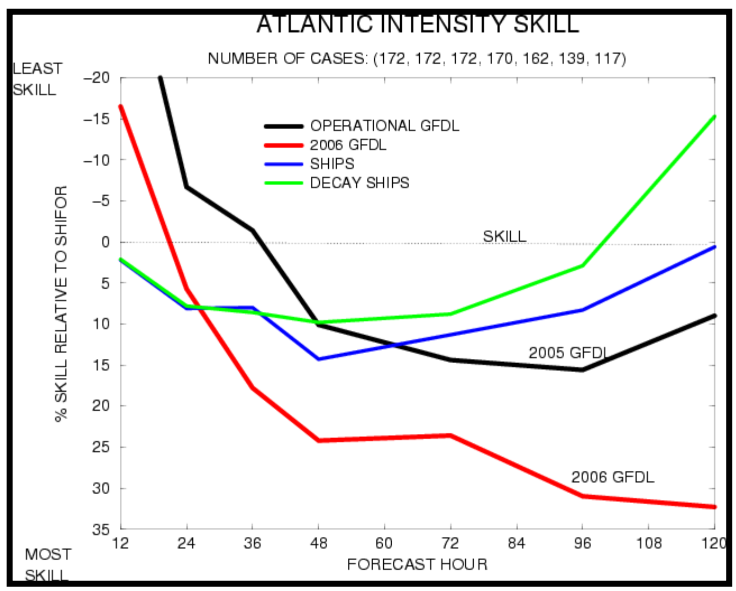

Figure 3-8. Comparison of intensity skill (Atlantic basin) between the 2005 operational GFDL model, the GFDL model made operational in 2006, and the statistical intensity models (SHIPS and DECAY SHIPS), run for select cases from the 2003-2005 hurricane seasons.

Improving the GFDL Air-Sea Momentum Flux Parameterization

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

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

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

Improving the GFDL Air-Sea Heat and Humidity Flux Parameterization

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

Preparing for the Next Generation of Hurricane Models

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

DOD's High-Resolution Regional Models

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

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

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

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

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

3.3.3 Ocean and Wave Models

Ocean Model

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

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

New Ocean Model Initialization Method

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

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

Wave Model

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

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

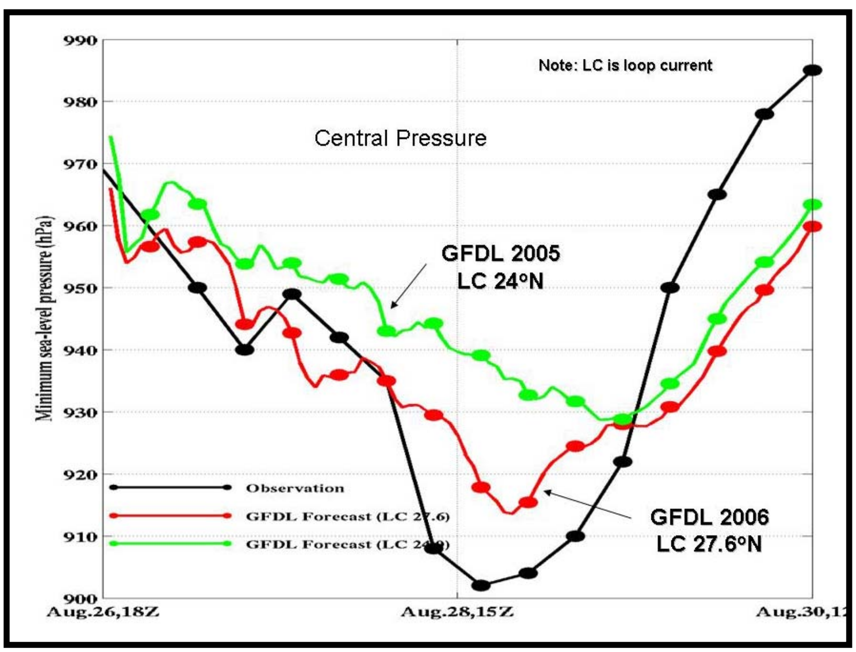

Figure 3-9. Positive impact of improved Loop Current initialization in the 2006 GFDL compared with the operational 2005 GFDL for Hurricane Katrina.

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

3.3.4 Data Assimilation Capability

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

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

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

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

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

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

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

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

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

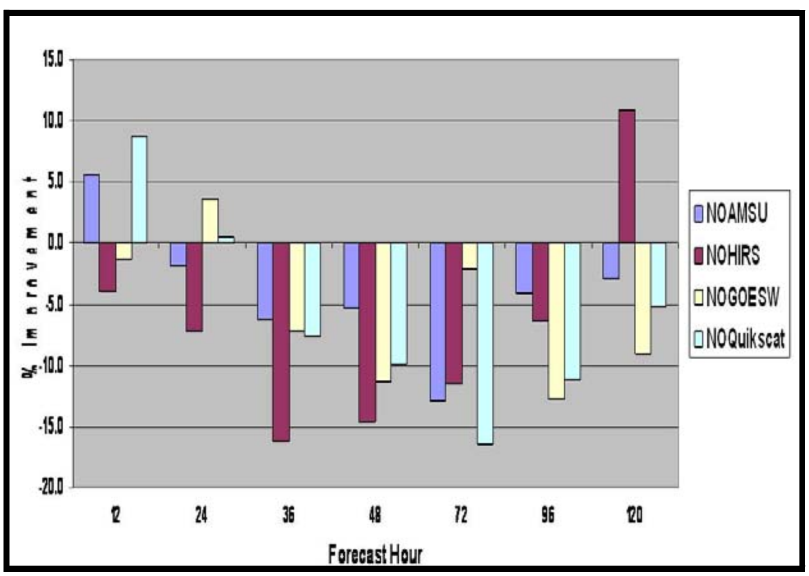

Figure 3-10. Negative impact of removing AMSU, HIRS, QuikSCAT surface wind data from the hurricane track forecast guidance in the Atlantic basin in 2003 (34 cases).

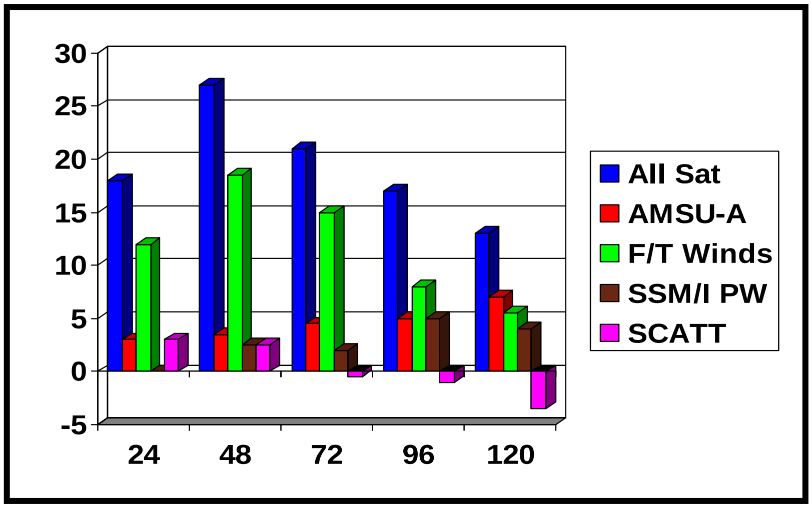

Figure 3-11. Percent improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004.

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

3.3.5 Use of Research Models

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

3.4 Forecasting and Warning

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

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

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

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

3.4.1 Track

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

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

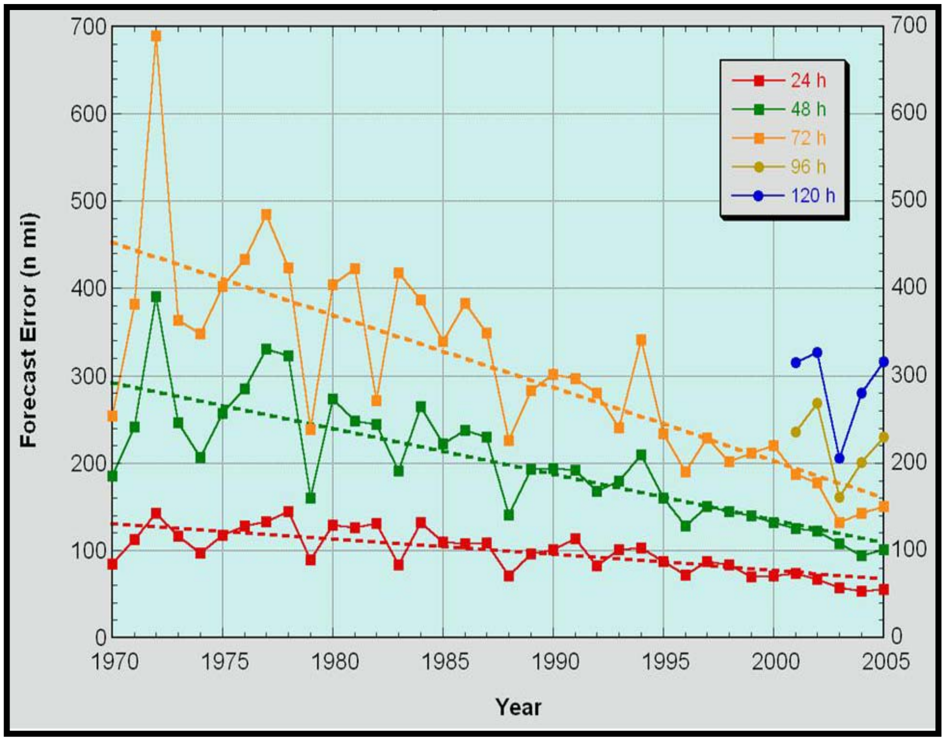

Figure 3-12. Annual average official track errors, with trend lines superimposed, for tropical storms and hurricanes in the Atlantic basin, 1970–2005.

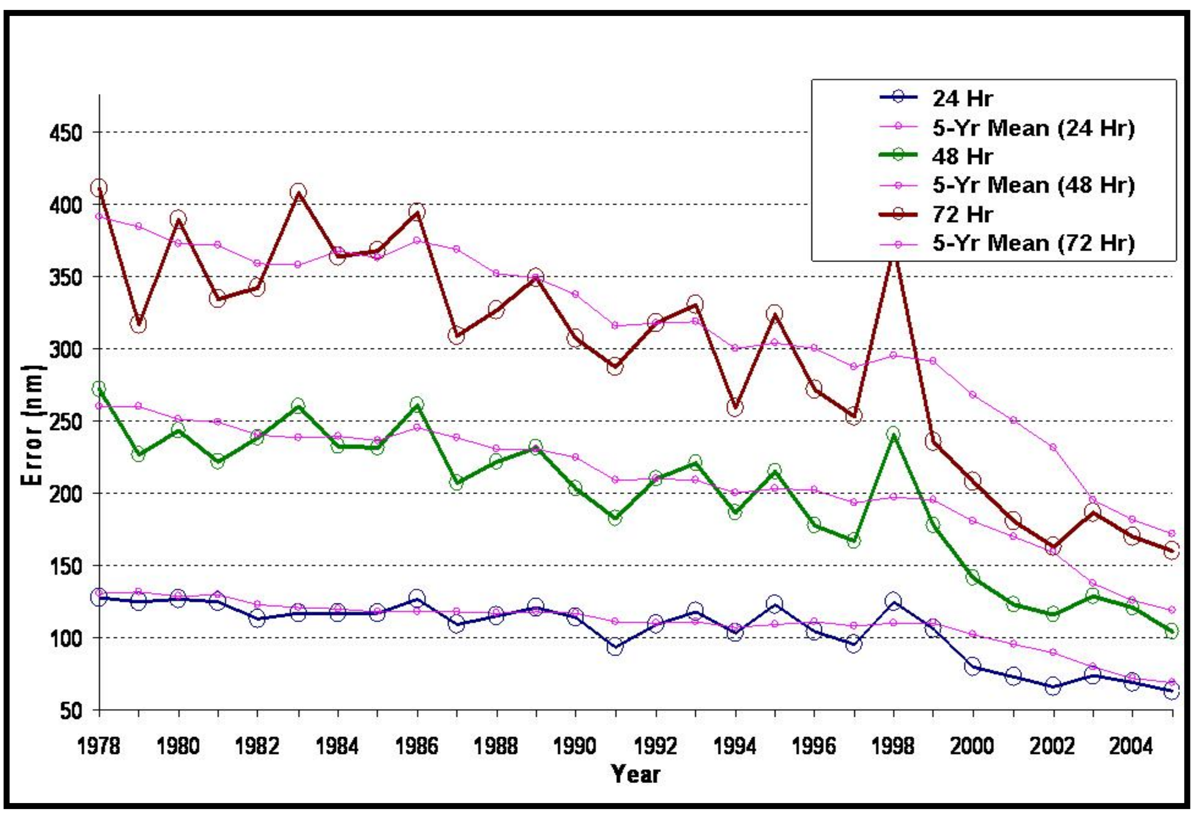

Figure 3-13. Mean track forecast error (nm) and 5-year running mean for 24, 48, and 72 hours for tropical cyclones in the western North Pacific Ocean, 1978–2005.

3.4.2 Consensus Forecasting

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

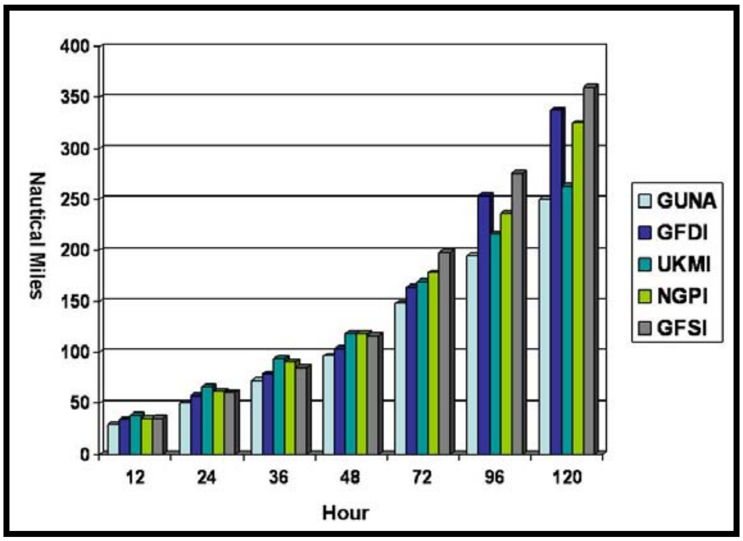

Figure 3-14. Atlantic basin track guidance model errors in nautical miles for 2005 of the GUNA model, a consensus model, and the individual models that are used to construct it.

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

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

3.4.3 Intensity and Structure

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

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

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

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

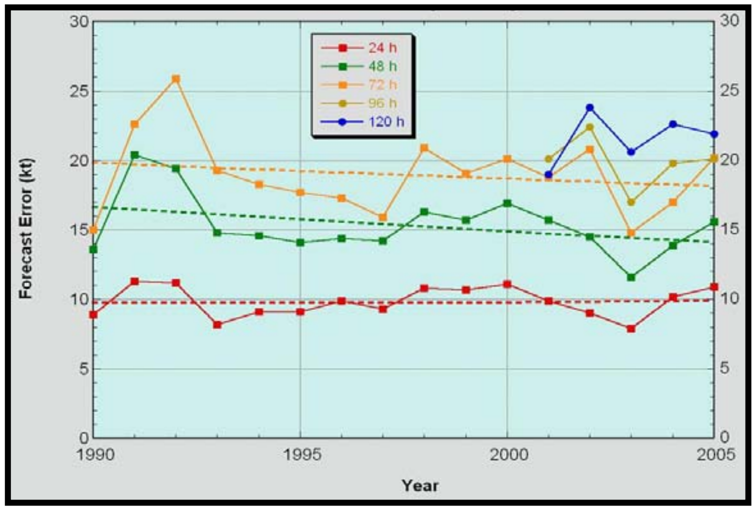

Figure 3-15. Annual average official intensity errors for the Atlantic Basin tropical cyclones for the period 1990-2005, with trend lines superimposed.

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

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

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

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

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

3.4.4 Sea State and Storm Surge

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

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

Sea State

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

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

Storm Surge

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

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

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

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

SLOSH requires the following meteorological inputs:

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

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

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

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

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

3.4.5 Precipitation and Fresh Water Flooding

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

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

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

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

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

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

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

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

A Scheme for Validating QPF from Landfalling Tropical Storms

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

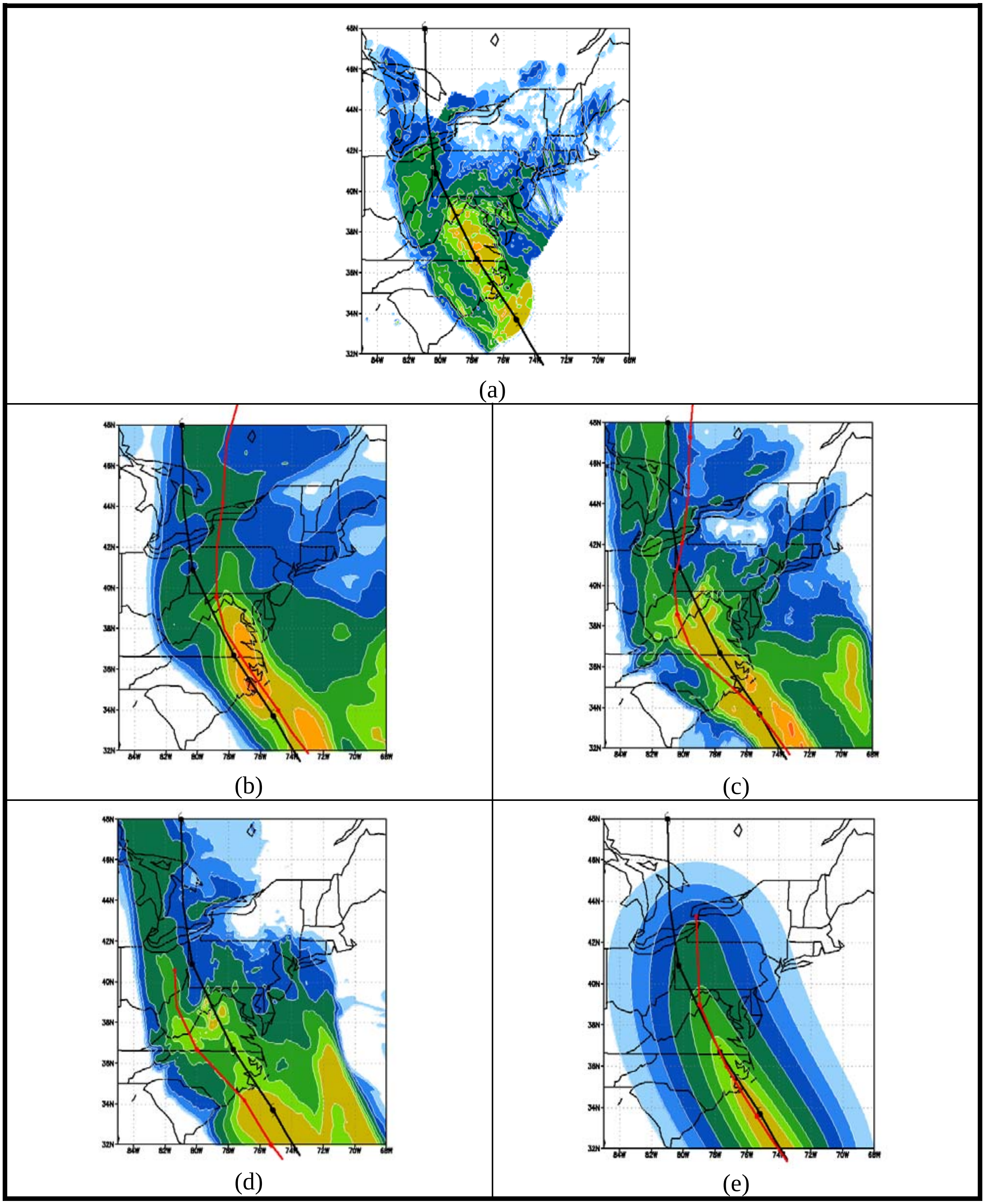

Figure 3-16. Plot of 72-h accumulated rain (shaded), 12 UTC 17 September to 12 UTC 20 September, 2003 for (a) Stage IV observations; (b) GFS; (c) GFDL; (d) Eta; (e) R-CLIPER.

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

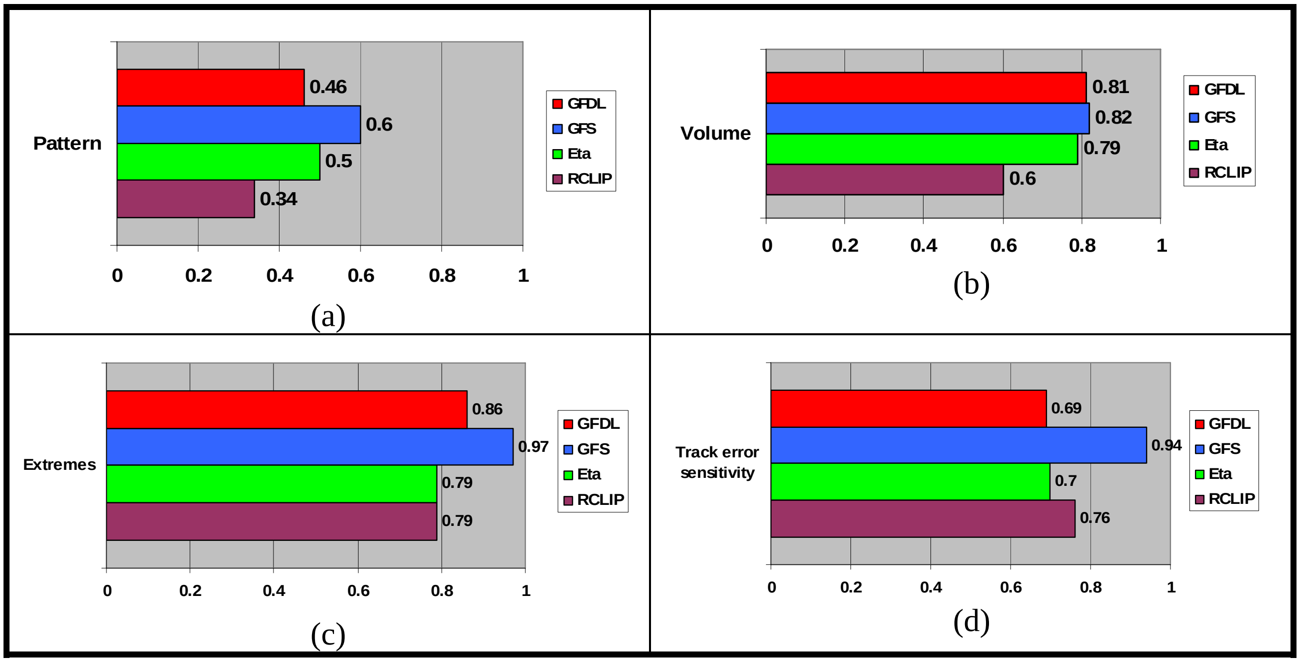

Figure 3-17. Comparisons of tropical cyclone QPF from different models showing how well they perform at (a) matching QPF patterns in the observed data; (b) matching extreme rainfall amounts, (c) matching the volume of observed rainfall, and (d) sensitivity of model QPF error to its storm track forecast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

Precipitation Forecasting

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

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

3.4.6 Severe Weather Activity

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

3.5 Tropical Cyclone Field Experiments

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

3.5.1 NASA-Sponsored Experiments

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

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

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

3.5.2 NSF-Sponsored Rainband and Intensity Change Experiment

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

3.5.3 NOAA-Sponsored Experiments

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

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

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

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

3.5.4 ONR-Sponsored Experiments

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

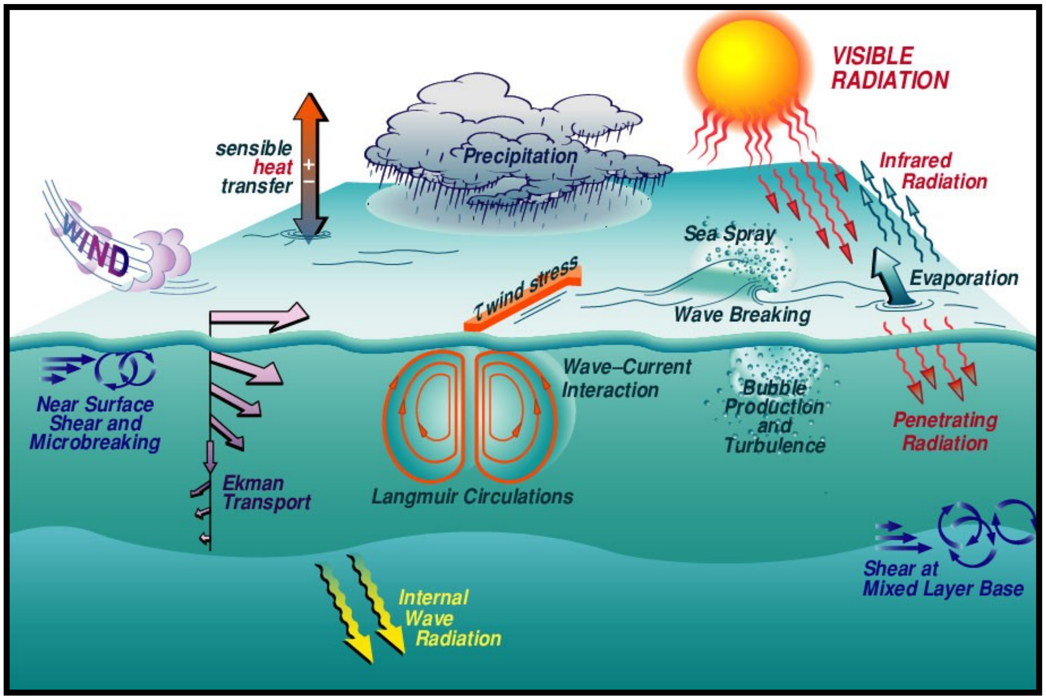

Figure 3-18. The hurricane component of CBLAST-DRI aimed to measure, analyze, understand, and parameterize air-sea fluxes in the hurricane environment. Credit: ONR.

3.5.5 Tropical Cyclone Field Experiments—Summary

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

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

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

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

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

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

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

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

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

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

3.6.2 The Joint Hurricane Testbed

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

JHT Transfer Process

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

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

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

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

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

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

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

JHT Transfer Projects since Inception

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

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

3.6.3 Transitioning ONR Research to Operations

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

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

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

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

3.6.4 The Transition Process at NCEP/EMC

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

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

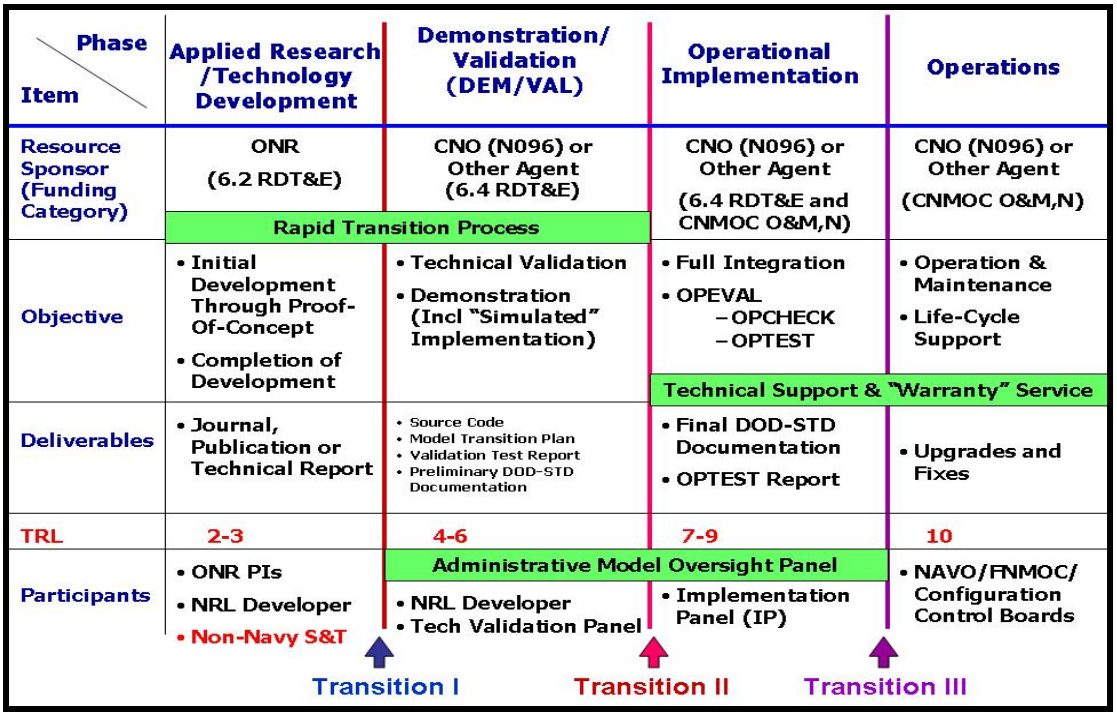

Figure 3-19. The U.S Navy/ONR process used to transition research to operations. CNMOC = Commander, Naval Oceanographic and Meteorological Command; CNO = Chief of Naval Operations; MOC = Fleet Numerical Meteorology and Oceanography Center; N096 = Oceanographer of the Navy; NAVO = Naval Oceanographic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

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

3.6.5 JCSDA: Transitioning New Data Assimilation Systems into Operations

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

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

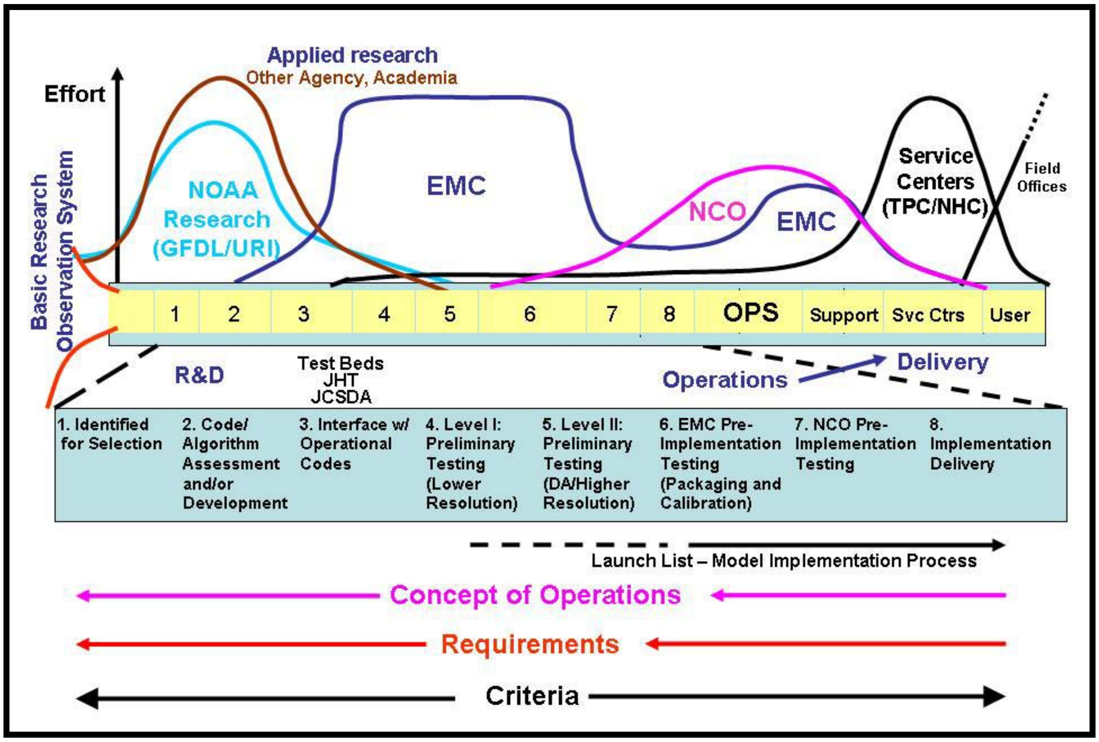

Figure 3-20. NCEP's role in transitioning research in models to operations through EMC processes.

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

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

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

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

3.7 Education, Training, and Outreach

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

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

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

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

Hurricane Awareness Tours

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

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

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

Hurricane Liaison Team

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

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

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

Other TPC/NHC Activities

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

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

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

NWS WFO Warning Coordination Meteorologist

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

World Wide Web

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

Newspapers and Magazines

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

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

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

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

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

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

Bulletins and Newsletters

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

Radio

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

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

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

Television

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

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

National Law Enforcement Telecommunications System

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

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

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

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

JTWC Annual Tour and Center Visits

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

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

Internet-Accessed Education, Training, and Outreach

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.7.3 Education, Training, and Outreach: Continued Efforts Needed

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

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

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

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

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

The BASC members suggested the following approach:

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

[7] The White House, 2006: *The Federal Response to Hurricane Katrina: Lessons Learned*, www.whitehouse.gov/reports/katrina-lessons-learned/, chapter 1, pg. 9.

[8] Draft output from the BASC Strategic Planning Retreat, Woods Hole, MA, 2006.

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

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

Some Key Issues and Questions:

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

3.8 Summary

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

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

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