# 2
# THE TROPICAL CYCLONE R&D COMMUNITY

## 2.1 Tropical Cyclone R&D as a Community Effort

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

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

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

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

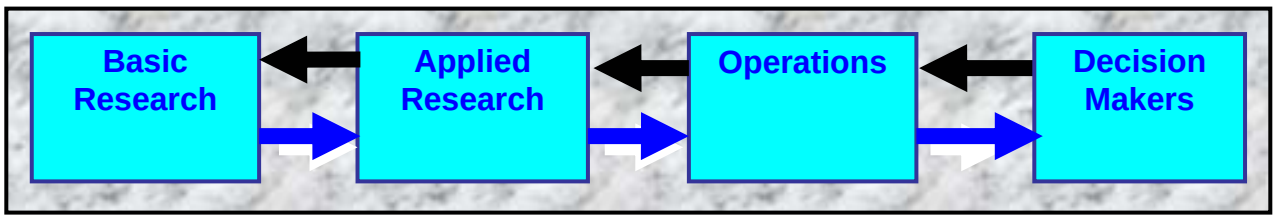


**Figure 2-1.** Representation of the flow of requirements (black arrows) and the transfer of knowledge and information (blue arrows) within the tropical cyclone community of practice.

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

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

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

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

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

### 2.2.1 NOAA

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

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

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

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

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

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

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

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

the past two decades in forecasting hurricane track. The work of the HIRWG and its interaction with the JAG/TCR are described further in section 2.8.8.

### 2.2.2 National Science Foundation

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

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

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

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

### 2.2.3 Department of Defense

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

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

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

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

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

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

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

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

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

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

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

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

### 2.2.4 National Aeronautics and Space Administration

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

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

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

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

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

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

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

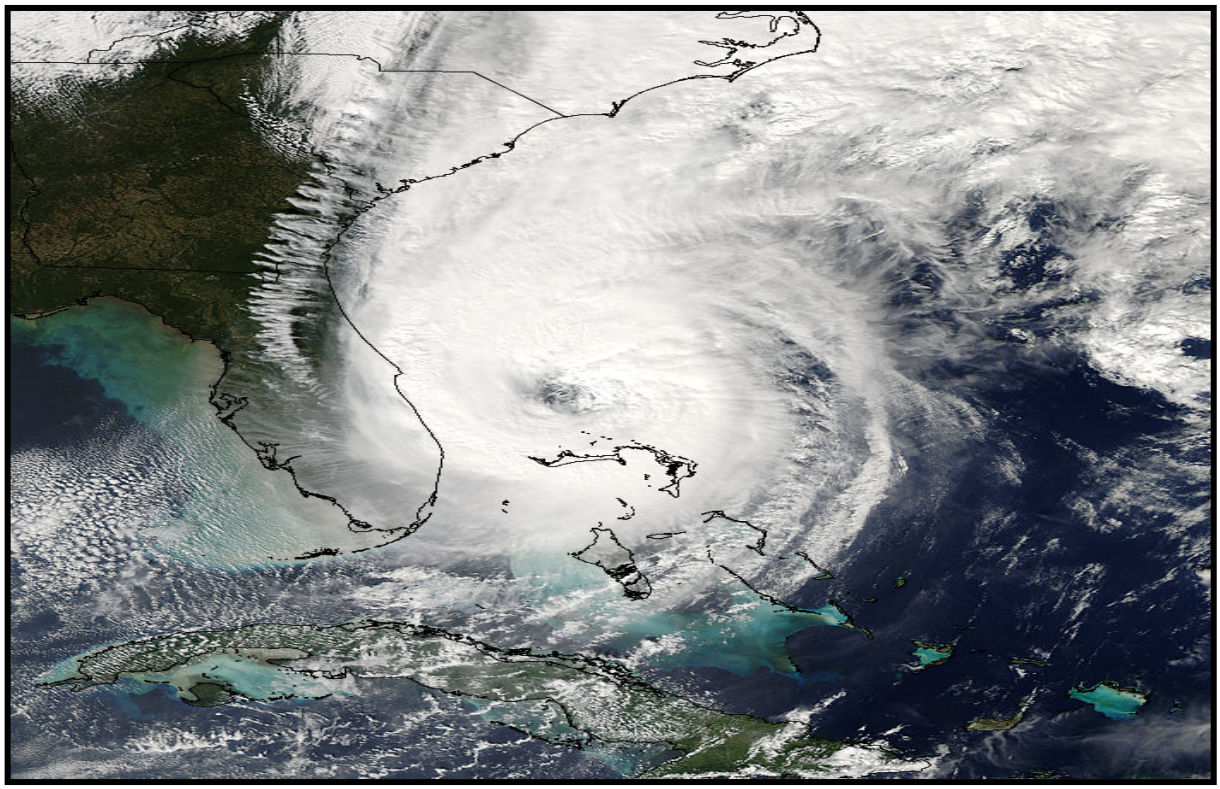

**Figure 2-2.** This image was captured by the MODIS instrument on the Aqua spacecraft on October 24, 2005. It shows Hurricane Wilma departing Florida after crashing into the western side of Florida early that morning. Credit: NASA

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

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

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

### 2.3.1 Federal Emergency Management Agency, Department of Homeland Security

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

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

### 2.3.2 Department of Health and Human Services

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

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

### 2.3.3 Department of Housing and Urban Development

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

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

### 2.3.4 National Institute of Standards and Technology, Department of Commerce

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

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

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

A number of Federal entities have responsibilities for coordinating R&D or formulating and overseeing policy initiatives and priorities of either direct or indirect relevance to some part of the end-to-end system for tropical cyclone forecasts and warnings. These policy and coordination roles are increasingly important to understanding the flow of requirements and the transfer of

knowledge and information among the sectors of the tropical cyclone community of practice. The principal entities engaged in interagency coordination are described here.

### 2.4.1 OFCM

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

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

### 2.4.2 Office of Science and Technology Policy

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

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

### 2.4.3 National Science and Technology Council

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

#### Committee on Environment and Natural Resources

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

#### Subcommittee on Disaster Reduction

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

#### United States Group on Earth Observations

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

### 2.4.4 NSF National Science Board

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

### 2.4.5 Joint Hurricane Testbed

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

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

### 2.4.6 Joint Center for Satellite Data Assimilation

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

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

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

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

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

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

## 2.5 Role of Academia in Tropical Cyclone Research

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

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

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

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

on tropical cyclone observations and data interpretation is funded by ONR, NRL-Monterey, and NOAA/NESDIS.

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

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

## 2.6 International Contributions to Tropical Cyclone Research

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

### 2.6.1 Principal Tropical Cyclone R&D Centers around the World

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

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

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

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

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

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

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

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

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

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

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

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

## 2.7 External Advisory and Advocacy Groups

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

### 2.7.1 National Academy of Sciences and National Research Council

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

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

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

### 2.7.2 American Meteorological Society Policy Program

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

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

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

## 2.8 Prior Documentation of Tropical Cyclone Operational and Research Needs

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

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

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

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

### 2.8.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers

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

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

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

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

### 2.8.2 Interdepartmental Hurricane Conferences

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

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

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

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

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

During the 59th IHC in 2005, the JAG/TCR conducted a strategic planning session to begin developing a framework for this strategic research plan. Additionally, the OFCM planned a workshop during the 60th IHC on "Tropical Cyclone Research: Priorities for the Next Decade,"

which included a review of a draft version of this document. The workshop is discussed further in section 2.8.8.

### 2.8.3 USWRP Implementation Plan for Hurricane Landfall

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

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

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

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

Other areas of research identified for attention include the following:

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

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

### 2.8.4 HWRF Model Workshop

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

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

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

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

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

### 2.8.5 NOAA/OAR Science and Technology Infusion Plan

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

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

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

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

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

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

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

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

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

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

### 2.8.6 Workshop on Air-Sea Interactions in Tropical Cyclones

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

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

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

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

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

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

### 2.8.7 Previous Efforts in Social Sciences

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

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

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

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

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

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

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

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

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

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

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

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

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

### 2.8.8 Concurrent Hurricane Projects/Studies

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

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

### 2.8.9 Results of the 60$^{th}$ IHC

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

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

## Tropical Cyclone Research

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

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

## Proposed New Model for Tropical Cyclone Forecast and Warning Communications

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

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

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

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

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

### 2.8.10 Summary on Prior Documentation of Operational and Research Needs

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