6
KEY FINDINGS AND RECOMMENDATIONS: THE WAY AHEAD

6.1 Introduction

To improve the predictability of tropical cyclones will require a concentrated, collaborative, all-inclusive community effort. Accurate forecasts of tropical cyclone behavior are a critical need for many segments of society. Obtaining a better understanding of the complex interactions of tropical cyclone intensity, structure, track, and environmental forcing is too large a problem for any single research entity or Federal agency to address alone.

As shown in chapters 1 and 2, numerous organizations and entities in the public and private sector, including the academic community, contribute to tropical cyclone research. It is imperative that this community of practice (see section 1.5) work together to further improve the forecast skill of all tropical cyclone–related components (e.g., intensity and structure [wind radii], track, sea state and storm surge, and precipitation). Table 6-1 illustrates the community of practice. Additionally, social sciences research needs to be enhanced and integrated with the research of other disciplines, and those results must be incorporated into operational procedures. The key findings and recommendations that are summarized later in this chapter involve all of these organizations/entities. This all-inclusive plan provides a collaborative "way ahead" for the Nation's tropical cyclone program.

To review, chapter 1 illustrated the fundamental rationale for continuing efforts to further advance the Nation's tropical cyclone forecasts and warnings. It introduced the operational centers for the Nation's tropical cyclone warning service, serving both civilian and military needs, and the community of practice that supports these operational centers. Chapter 2 described in more detail the community of practice and also reviewed recent and concurrent planning activities that were taken into account in formulating the research priorities. The results of the planned R&D will need to be transitioned to operational NWP models to reap real benefits for the Nation.

Chapter 3 assessed the current capabilities and limitations of the Nation's tropical cyclone warning service. These capabilities constitute a classic end-to-end meteorological warning and forecasting system, from data collection through data assimilation and NWP modeling to dissemination of warnings and forecasts, including end-user education, training, and outreach. Chapter 4 used the same end-to-end system structure to present the JAG/TCR's perspective on future capabilities planned to meet the operational needs identified by the operational centers.

Chapter 5 presented the tropical cyclone research priorities to aid in meeting the future operational needs of the tropical cyclone forecast and warning centers and enhancing all aspects of the end-to-end forecast system. The priorities were divided into three categories: atmospheric/oceanic, seasonal forecasts (climatological), and social sciences.

Table 6-1. Illustration of the Tropical Cyclone Community of Practice

Entity/Organization	Contribution
NASA	Remote sensing/satellites – New instrument development Field experiments/tropical cyclone research JHT JCSDA (GMAO)
NSF	Field experiments/tropical cyclone research – Includes social sciences Sponsor – University/academia research grants – NCAR
U. S. Navy	Field experiments (ONR)/tropical cyclone research NWP modeling (NRL/FNMOC) JHT JCSDA
U.S. Air Force	53rd Weather Reconnaissance Squadron SFMR Air Force Weather Agency JCSDA
USACE - ERDC	Field research facility—continuous coastal field data collection Typhoon field data collection—Pacific Islands Numerical model development (WaveWatch III, ADCIRC, STWAVE, ESMF)
NOAA	Field experiments/tropical cyclone research – OAR laboratories (e.g., AOML HRD) – NESDIS – NOS – Aircraft Operations Center – JHT NWP ,modeling (NCEP/EMC) – Operations and research JCSDA
Academia	Field experiments/tropical cyclone research (numerous universities) – Includes social sciences – Focused education programs
International Organizations	Tropical cyclone research NWP modeling
JTWC (U.S. Navy, U.S. Air Force)	Operational tropical cyclone forecasting Tropical cyclone research, development, and testing
TPC/NHC and CPHC (NOAA)	Operational tropical cyclone forecasting Tropical cyclone techniques development and testing

This chapter presents the JAG/TCR summary of key observations/findings and recommendations for a roadmap of activities to improve tropical cyclone forecasting and warnings. The ultimate goal of these activities is to enable precise, high-confidence decisions that save lives and reduce property damage in storm-threatened areas.

6.2 Summary of Key Findings

This plan highlights several key findings, which are summarized below. For a detailed discussion of a finding, refer to the referenced section within this plan.

6.2.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers

1. Table 4-1 lists the operational needs, in the priority order given in the 2006 AFFO, along with related needs statements emphasized by the DOD participants at the 59th IHC. This listing thus represents the best available compilation and prioritization of operational needs across the three U.S. centers: TPC/NHC, CPHC, and JTWC **(section 4.1)**.
2. To continue to advance operational tropical cyclone forecasting capability and to meet the operational needs summarized in table 4-1, the Nation must be committed to supporting—through research, development, and transition to operations—the following key areas vital to the tropical cyclone forecast and warning program **(chapter 4, introduction)**.
    - Advanced observations
    - Advanced data assimilation technologies
    - Advanced NWP models
    - Investment in human and infrastructure resources

6.2.2 Data Collection/Observations

1. Continuing to advance observational capabilities for tropical cyclone analysis and numerical weather prediction is a vital component of the Nation's tropical cyclone program. With numerous new observational platforms and sensors potentially available in the next several years, a coordinated approach is needed to improving tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.) **(section 4.2)**.
2. Observations of the tropical cyclone inner core are essential for tropical cyclone analysis and the initialization of the tropical cyclone vortex in operational, high-resolution, next generation NWP models. The initialization is critical to improving tropical cyclone intensity and structure forecasts. Given the current limitations in satellite observations, the only inner-core wind data routinely available are collected by aircraft reconnaissance (**section 3.1.6**).
3. The new and improved observation systems that are under development or being planned (sections 4.2.2 through 4.2.12) hold substantial promise for improving tropical cyclone analysis; NWP modeling; and our fundamental understanding of the tropical cyclone atmosphere and ocean environment, the tropical cyclone inner and outer cores, and the interactions among these components. These systems include in situ measurements of

winds over oceans in areas with tropical cyclones, as well as remote-sensing methods to measure temperatures, humidity, winds, sea surface heights, ocean wave heights and swell motion, and precipitation. The remote-sensing data will be provided from a combination of sensors located on aircraft, on polar-orbiting and geostationary satellites, and on land (e.g., weather surveillance radar). However, as discussed in s**ections 4.2.2 and 4.2.12**, there are significant gaps in meeting the observation requirements for altimetry and ocean surface vector winds that must be addressed. Researchers and system developers must work together to seek viable solutions to meet these requirements (**section 4.2.13**). The development and evaluation of new observational technologies and observing strategies are research priorities identified in chapter 5 of this report.

a. Tropospheric Winds

   i. Due to the importance of ocean surface vector winds (OSVW) data—for use by tropical cyclone forecasters and in tropical cyclone NWP systems—the JAG/TCR strongly endorses the development and acquisition of a capability to meet the OSVW observation requirements. This capability is absolutely critical to meeting the operational needs of the tropical cyclone forecast and warning centers summarized in table 4-1 **(section 4.2.12).**

   ii. The JAG/TCR also strongly endorses the development of a capability to accurately measure the three-dimensional global wind field to optimally specify global initial conditions for numerical weather forecasts and much improved tropical cyclone track forecasts **(section 4.2.12)**.

b. Since satellite altimetry is vital to addressing the needs of the tropical cyclone forecast and warning centers summarized in table 4-1, the JAG/TCR strongly endorses the acquisition of an altimeter instrument for NPOESS as an alternative to the cancelled NPOESS ALT instrument (**section 4.2.2**).

6.2.3 NWP Modeling and Data Assimilation

1. While global and regional-scale NWP models have proven highly successful at forecasting tropical cyclone tracks, coupled models with much higher resolution will be necessary to make further strides in forecasting tropical cyclone intensity, structure (wind radii), sea state and storm surge, and precipitation***. Increased skill in forecasting intensity and structure, sea state and storm surge, and precipitation is now on the horizon, much as improving track forecast skill was two decades or so ago*** **(sections 3.3, 4.4.2, and 4.4.3).**

2. The development of new techniques for assimilating high-resolution data sets is a fundamental activity required for advancing numerical prediction of hurricane intensity and structure, both of which are important to improved forecasts of intensity, structure, sea state, storm surge, and precipitation. New data sources are critical to initializing the forecast system in two key domains: (1) the large-scale environment, and (2) the vortex core. One of the most significant challenges to be met by NCEP and other operational NWP modeling centers over the next two decades is the assimilation of data from new satellite instruments that are scheduled to be launched. As described in **sections 2.4.6** and **3.6.5**, this challenge is being addressed through the JCSDA **(section 4.4.2)**.

Improving tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state and storm surge, and precipitation is the overall goal guiding the ongoing development of next generation hurricane forecast systems. The work led by NOAA/EMC to develop the HWRF Air-Sea-Land Hurricane Prediction System is described in **section 4.4.2**. The parallel and complementary effort led by NRL-Monterey and FNMOC to continue improving the COAMPS Tropical Cyclone System is described in **section 4.4.3**. These complementary development efforts should be a national priority. They should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies. **(section 4.4)**.

a. Additional human and infrastructure resources (e.g., items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems) will be necessary to support development, operations, and maintenance of advanced data assimilation and NWP modeling systems **(section 4.4)**.

b. The HWRF Air-Sea-Land Hurricane Prediction System is NOAA's next generation, high-resolution hurricane prediction system scheduled for operational implementation at NCEP in 2007. The HWRF system will use advanced data assimilation capabilities and incorporate sophisticated physics suitable for high-resolution and coupled air-sea-wave-land modeling processes. The Nonhydrostatic Mesoscale Model (NMM) will be the core model of the HWRF system. The system will make use of moving nests with two-way feedback in the atmospheric, ocean, and wave models. By coupling the HWRF system with advanced wave and storm-surge models, the HWRF system will provide improved predictions of coastal inundation. To address the inland flooding problem, the land-surface component of the HWRF system will be coupled to a hydrology model for improved precipitation guidance for landfalling tropical cyclones **(section 4.4.2)**.

c. For the U. S. Navy, regional, high-resolution model development is based on COAMPS. NRL has developed a prototype advanced data assimilation system which is targeted for operational implementation at FNMOC in 2008. NRL will collaborate with NASA/GMAO and NCEP/EMC during the future development of this data assimilation system. The future COAMPS Tropical Cyclone System will couple an ocean and wave model to the COAMPS nonhydrostatic atmospheric dynamical core. The system will make use of moving nests with two-way feedback in the atmospheric model and will eventually include nested grids in the ocean models. In order to model the fluxes more accurately, the atmospheric and ocean wave models will interact with a sea spray submodel to represent the air-sea exchanges in the wave boundary layer **(section 4.4.3)**.

d. Development of the COAMPS Tropical Cyclone System will occur in parallel with development of the HWRF Air-Sea-Land Hurricane Prediction System. Statistics on tropical cyclone track guidance clearly demonstrate that superior track guidance is produced using a multi-model consensus. For the future, it is vital to have such a multi-model capability for intensity forecasting as well **(section 4.4.3)**.

3. A parallel operational NWP research capability for testing and implementing changes to the operational NWP configuration is absolutely essential. To maximize improvements to the operational NWP model, it is also critically important to have a steady flow of relevant research focused on improvements to the operational NWP system (i.e., focused on the NWP research priorities outlined in chapter 5). The current infrastructure at NRL/FNMOC and NCEP/EMC is inadequate to conduct extensive parallel testing **(sections 3.6.1 and 4.5)**.
4. Funding for the transition of research to operations remains deficient. Within an era of constant or diminishing dollars, R&D and transition needs will likely be competing with each other. A mechanism is needed to enhance development and transition of research to operations activities throughout the tropical cyclone operations and research community to further improve operational, high-resolution tropical cyclone NWP models, thereby maximizing benefits for the Nation **(section 4.5.3)**.

6.2.4 Forecasting and Warning

1. Probabilistic guidance based on advanced high-resolution regional models (e.g., HWRF and COAMPS ensembles) is necessary to estimate adequately the forecast uncertainties in critical storm attributes and in related impacts such as damaging winds, precipitation, and storm surges that arise from the combined uncertainties in track, structure, and intensity. However, the capability to run HWRF and COAMPS ensembles and multi-model ensembles within operational forecasting time constraints depends directly on the available computing power **(section 4.4.2)**.
2. An action that stemmed from the 60th IHC was that the Nation's hurricane warning program warranted a review, which should include NOAA working with user groups to develop and test warning message format modifications to optimize desired outcomes. Both technical and actionable messages should be reviewed and optimized, and product timing cycles should be coordinated with end users, especially for media news cycles. Additionally, the OFCM will organize meetings to bring together the appropriate Federal agencies to begin the process of reviewing and improving the National hurricane warning system **(section 2.8.9)**.

6.2.5 Tropical Cyclone Research and Research Coordination

1. **Research**
    a. **Section 5.1** provides the consensus views of the Federal agencies on specific atmospheric- and oceanic-related tropical cyclone research priorities. **Section 5.2** details the climate research priorities regarding intraseasonal, interannual, and longer-term variability of tropical cyclones. **Section 5.3** and **appendix P** discuss social science research areas important for the hurricane forecast and warning system.
        (1) In addition to physical sciences research that must continue to meet forecast challenges, greater emphasis is needed on social sciences research **(section 1.3).**

(2) While there is a growing recognition of the potential contributions of social sciences research, to date it remains underfunded and underutilized **(section 5.3.5)**.

b. Sufficient funding to sustain the analyses of the data sets from field experiments should be a priority. **(section 3.5.5)**.

2. **Coordination**

Another element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to conduct the following activities **(section 5.4)**:

- Monitor and update a listing of the operational needs of the tropical cyclone forecast and warning centers
- Monitor and update a listing of the research priorities required to meet the needs of the operational tropical cyclone forecast and warning centers
- Develop a succinct 10-year, multiagency research implementation plan that outlines specific strategies to address research priorities
- Update the implementation plan (above bullet) as required (e.g., at least annually)

6.2.6 Education, Outreach, and Workforce Development

1. The agencies and organizations—public and private—involved with education, training, and outreach concerning the public's knowledge and appreciation of tropical cyclone impacts and the appropriate public responses to reduce those risks must never assume their task is done. These efforts must continue, and they must be accorded the priority they deserve **(section 3.7.3)**.
2. An area of extreme importance for improving tropical cyclone forecasts is advancing data assimilation and tropical cyclone NWP modeling systems. An important example of a deficiency in workforce development is that the United States is not producing enough new personnel with the education and training required for improving tropical cyclone forecasts via advanced data assimilation and numerical modeling systems. Resolving this deficiency will require strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities **(section 3.7.3)**.

6.3 Recommendations

The JAG/TCR developed recommendations that follow logically from some of the key findings identified above. The recommendations are listed in table 6-2.

Figure 6-1, which is associated with recommendations 1 and 2, illustrates the focused research, collaborations, and increased resources that are required and envisioned to lead to essential tropical cyclone prediction improvements over the next decade. Every component represented in

Table 6-2. JAG/TCR Recommendations

No.	Category	Recommendation	Section 6.2 Reference
1	**Tropical cyclone NWP modeling**	The continued development and implementation of the next-generation tropical cyclone forecast systems, such as the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, to improve tropical cyclone forecast guidance for TPC/NHC, CPHC, and JTWC forecasters regarding intensity, structure, track, sea state/storm surge, and precipitation should be a high priority for the Nation. a. Development and transition of research to operations: (1) The development efforts of the next-generation hurricane forecast systems should form the basis for projects supporting hurricane research and collaboration among experts from the university community, international researchers, the private sector, and other Federal agencies. (2) Sufficient human and infrastructure[a] resources should be provided to support development of advanced data assimilation and NWP modeling systems (see figure 6-1). (3) An interagency working group, under the auspices of the OFCM, should be formed to develop a plan to support the tropical cyclone NWP program. The plan should: (a) include procedures to enhance the flow of relevant research focused on improvements to the operational NWP systems; (b) improve the conduit by which the academic community could be involved in the next-generation hurricane model development and testing (e.g., through the JHT and DTC) and (c) account for having sufficient human and infrastructure[a] resources for development work and transition of research to operations activities, including sufficient resources to support collaborative ventures (see figure 6-1). b. Operations: Sufficient human and infrastructure[a] resources, including the capability to run ensembles with the HWRF Air-Sea-Land Hurricane Prediction System and the COAMPS Tropical Cyclone System, should be provided to NCEP/EMC and FNMOC for their operational NWP tropical cyclone model programs.	6.2.3: 1,2 6.2.3: 2 6.2.3: 2a 6.2.3 6.2.4: 1
2	**Tropical cyclone research and research coordination**	a. **Research** (1) The JAG/TCR recommends strong support for activities focused on the tropical cyclone research priorities identified in chapter 5. (2) Results of social science research need to be an integral part of the hurricane forecast and warning program. With increased funding, a possible venue to pursue social science research questions is through the Joint Hurricane Testbed (without compromising current projects). (3) Sufficient and sustained funding is needed for analyses of field experiment data sets. b. **Research Coordination.** An element that is vital to the tropical cyclone R&D program is a formal, multiagency, coordination entity to perform the tasks described in section 6.2.1, paragraph #2. The JAG/TCR recommends that this coordination requirement and development of a research implementation plan be satisfied through the OFCM infrastructure.	6.2.5: 1a 6.2.5: 1a 6.2.5: 1b 6.2.5: 2

3	**Strategic plan for tropical cyclone observations**	Through the OFCM infrastructure, a strategic plan for improved tropical cyclone reconnaissance and surveillance systems (manned, unmanned, spaced-based, etc.) needs to be developed. The plan should consider observations and observing strategies for tropical cyclone forecaster needs, data assimilation for NWP models, and NWP model diagnostics and verification.	6.2.2: 1
4	**Tropical cyclone warning program review**	NOAA (including OFCM), along with Federal agencies, should continue to review and improve the Nation's hurricane warning program.	6.2.4: 2
5	**Education, out-reach, and work-force development**	a. Education, training, and outreach efforts concerning the public's knowledge and appreciation of tropical cyclone impacts must continue, and they must be accorded the priority they deserve. b. To resolve the deficiency within this Nation in producing enough qualified (educated) personnel with the requisite NWP modeling education and training, there needs to be strong backing (advocacy) by professional organizations (e.g., American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science), as well as long-term commitment from Federal agencies (e.g., NSF, NOAA, NASA) and from the academic institutions that are the principal providers of degreed personnel employed by agencies that conduct the Nation's sophisticated NWP activities.	6.2.6: 1 6.2.6: 2

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

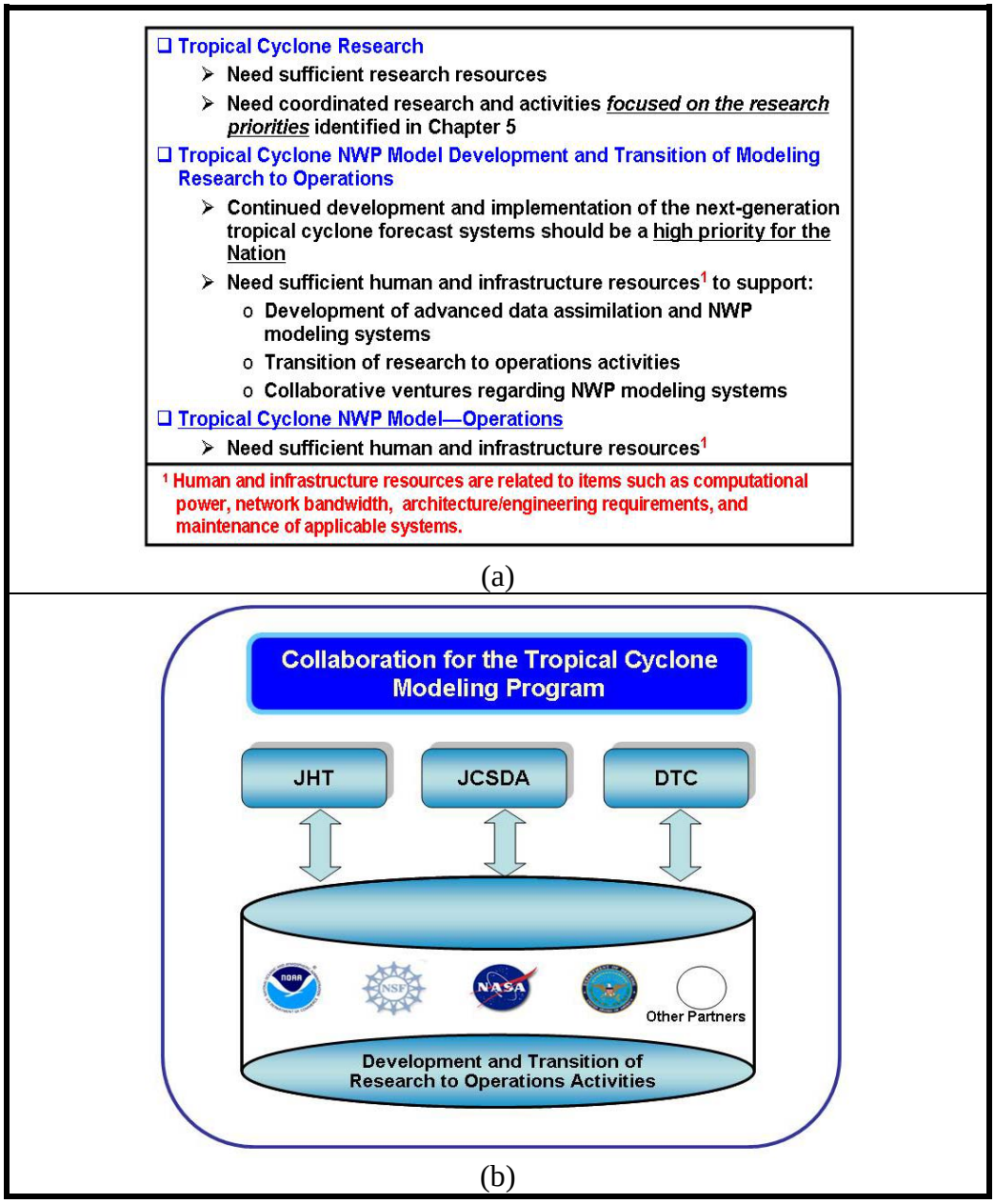

Figure 6-1. Illustration of recommendations 1 and 2.

figure 6-1a is absolutely essential to ***maximize the benefits for the Nation***. The activities for tropical cyclone model development and for transition to operations ***will be the keystone for successful R&D.*** These R&D and operational transition activities are the proving ground and implementation process for all of the tropical cyclone research categories and topics. Results from a broad spectrum of government and academic initiatives will require significant planning, scientific and technical evaluations, coordination and testing, and implementation activities. The envisioned tropical cyclone modeling program will therefore need significant infrastructure with major testing resources and substantial workforce to achieve the savings in life and property expected from the research results. Each collaboration entity represented in figure 6-1b

contributes to the overall improvement in modeling capability. For example, the JCSDA serves a key role in expediting the assimilation of data from new satellite-based observing systems and instruments into operational models used to prepare forecasts and warnings.

6.4 Resource Estimates Associated with Recommendations

Table 6-3 summarizes new investments (funding increases above currently projected levels) that are associated with the JAG/TCR recommendations and are required to continue advancing tropical cyclone science and operational capabilities. These investments are the best estimates of the JAG members, based on their combined experience with current and past budgets for tropical cyclone research and development

- The ***development*** of advanced data assimilation ***and*** NWP modeling systems is vital to further improving the Nation's tropical cyclone forecasting capability. The tasks associated with the development of these systems will require additional resources to tackle the myriad of complex, manpower-intensive work that needs to be accomplished. Funding to significantly enhance tropical cyclone ***transition of research to operations*** activities and capabilities will be the keystone for successful R&D. As mentioned in section 6.3, these functions are the proving ground and implementation process for all of the tropical cyclone research categories and topics **(table 6-2, recommendation 1a)**.
- Sufficient human and infrastructure resources need to be provided to the tropical cyclone ***operational*** NWP modeling centers (i.e., NCEP/EMC and FNMOC), including sufficient computing power to sustain and enhance the tropical cyclone forecast and warning program. Obviously, moving to higher resolution, coupled NWP models will require increased computing power. As an example, NOAA's high performance computing experts estimate that increasing hurricane model resolution to 1 km would be 14,580 times more computationally expensive. This enhancement would take over 28 years to achieve at current budget levels/strategies.[1] This underscores the vital need to significantly enhance current funding levels of the Nation's operational tropical cyclone NWP models. As mentioned above, the human and infrastructure resource investments must account for the two U.S. NWP centers providing operational guidance for informed critical decisions (i.e., the two centers, NCEP/EMC and FNMOC, that plan to run advanced, coupled models and apply consensus and ensemble techniques for operational tropical cyclone guidance) **(table 6-2, recommendation 1b)**.
- The atmosphere/ocean research priorities are described in Section 5.1. The investments included in this category are expected to provide results for transitioning into operations through the hurricane testbed process (e.g., JHT, JCSDA, DTC, NCEP/EMC, NRL/FNMOC) and later in the education and outreach category. Therefore, the investments are shown increasing/decreasing in the associated categories as results mature and feed into the transition and operations activities **(table 6-2, recommendation 2)**.

[1] Personal communication from Frederick Toepfer, NOAA Environmental Modeling Program Manager, to Mark Welshinger, OFCM.

Table 6-3. Additional Resource Estimates ($ millions above Current Plan) Associated with the JAG/TCR Recommendations[a]

Rec. No.	Recommendation Summary	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17
1a	Development of advanced data assimilation *and* NWP modeling systems; Transition of research to operations	30	30	30	30	30	30	30	25	25	25
2a	Atmospheric- and ocean-related research, including analyses of field experiment data sets	15	15	15	15	15	10	10	10	10	10
	SUBTOTAL ***Research, Model Development, and Transition to Operations***	45	45	45	45	45	40	40	35	35	35
1b	Operational NWP computing (NCEP *and* FNMOC)	30	30	30	30	30	30	30	30	30	30
	SUBTOTAL ***Previous Subtotal Plus Operational NWP Computing***	75	75	75	75	75	70	70	65	65	65
2a	Social science research	10	10	10	10	10	5	5	5	5	5
	TOTAL	**85**	**85**	**85**	**85**	**85**	**75**	**75**	**70**	**70**	**70**

[a]The estimates do not include some significant *operational* acquisition costs (e.g., to plan, build, launch, and support an ocean surface vector wind satellite system).

- Analyses of field experiment data sets will require consistent funding throughout the next decade. Initially, a large effort will be needed to harvest and analyze the information from past, current, and continuing field experiments. When new observing platforms and sensors are available, their data sets will require analyses and integration with the results from heritage systems **(table 6-2, recommendation 2)**.
- Social sciences will require strong research emphasis in the early funding years to help bring multidisciplinary talents to bear on these important aspects of research described in section 5.3. As this research matures, its results will feed into the testbed process and will require greater emphasis in the education and outreach category **(table 6-2, recommendation 2)**.

The following general factors for research investments are relevant to all of the resource estimates presented in table 6-3:

- Investments in each of the research categories are not mutually exclusive. Research in any of the areas is expected to help leverage investments in other areas, to the overall benefit of tropical cyclone prediction accuracy, and in the application of the predictions by decisionmakers.
- Each of the research categories includes some research that may also be supported by studies or experiments in other research areas or in transition into operational activities where the research results are applied.
- Proposed budget figures are increased or decreased with time, based on expected increases in knowledge and understanding and subsequent improvements in operational applications that implement the results of the new knowledge and understanding.
- The proposed research funds may be distributed among all agencies that conduct tropical cyclone research or research on the impacts of tropical cyclones on the U. S. population and resources at risk.

6.5 Summary

Coastal population growth and land development have resulted in a dramatic rise in the assets at stake that could be affected by tropical cyclones. Approximately fifty percent of Americans now live within 50 miles of a coastline (NRC 1999) and are thus potentially exposed to the wrath of a landfalling hurricane. Annual U.S. hurricane losses average about $10 billion (Pielke et al. 2007). In a recent analysis of hurricane damages from 1900 to 2005, Pielke et al. (2007) noted that their normalization method agrees with insurance industry data in projecting a doubling of economic losses from landfalling hurricanes every ten years.

One important contribution to avoiding loss of lives and reducing risk and vulnerability to hurricane landfall and tropical cyclone movement is highly accurate meteorological forecasts that can be used to ensure that credible warnings are issued in a timely manner. In addition, the public and military operations being threatened must have confidence in those warnings, understand them, and take the appropriate actions to protect property and evacuate when necessary. Further improvements to the Nation’s tropical cyclone forecast and warning service

are feasible, within reach, and ***valuable investments for our safety, security, and economic well-being***.

This comprehensive plan: (1) reviewed the tropical cyclone R&D community; (2) examined the current capabilities and limitations of the Nation's tropical cyclone forecast and warning system; (3) summarized the operational needs of the tropical cyclone forecast and warning centers—TPC/NHC, CPHC, and the JTWC—and the planned capabilities to meet the needs; (4) identified tropical cyclone research priorities to aid in meeting the operational needs; and (5) presented a comprehensive roadmap of activities to further improve the effectiveness of the Nation's tropical cyclone forecast and warning service during the next decade and beyond.

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