817 AN OPERATIONAL ASSESSMENT OF THE JOINT HURRICANE TESTBED'S FIRST DECADE

Edward N. Rappaport[1]*, Jiann-Gwo Jiing[1], Christopher W. Landsea[1] and Shirley T. Murillo[2]

[1]National Weather Service, National Centers for Environmental Prediction, National Hurricane Center, Miami, FL

[2]Office of Oceanic and Atmospheric Research, Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, Miami, FL

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA), in conjunction with the United States Weather Research Program (USWRP), established the Joint Hurricane Testbed (JHT) in 2001 to expedite the transfer of tropical cyclone research into forecast operations (Rappaport et al. 2009, Knabb et al. 2005). The testbed's *Terms of Reference* (TOR) (**http://www.nhc.noaa.gov/jht/JHTTOR. 13Sep2002.pdf**), applied by the JHT administrative staff, Steering Committee (SC), and NOAA National Hurricane Center (NHC) staff, helps guide the JHT through a proposal selection, testing, and potential implementation process spanning a period of about two years.

Beginning with the second JHT round, from 2003-2005, prospective investigators have responded to a Federal Register Notice of an Announcement of Federal Funding Opportunity that indicates priority areas for research identified by the NHC and Environmental Modeling Center (EMC) (e.g., see Appendix). The proposal process includes a review of around 40 "Letters of Intent" from researchers, followed by a formal review of about half that number of full proposals. Depending on the amount of funds available, the 10-15 highest rated proposals are then funded. Most projects run two years, with a few one-year projects having been approved. Mid-term reviews of the two-year projects have approved second-year funding for all but three of the 62 JHT projects from rounds 1-5.

The JHT concluded its first decade in 2010. The period coincided with several significant advances at the NHC (Rappaport et al., 2009; Franklin, 2010). NHC extended its forecast horizon from three to five days, and its track forecast errors decreased significantly in large part due to improvements in operational computer model forecast guidance and tools available to forecasters.

* *Corresponding author address: Edward N. Rappaport, National Hurricane Center, 11691 SW 17th Street, Miami, FL 33165-2149; e-mail: edward.n.rappaport@noaa.gov*

The NHC Hurricane Specialists (forecasters) during that period were asked in June-July 2010 to rate the overall operational impact of the JHT program, as well as the contribution from each of the 50 JHT projects during the first four rounds whose funding concluded by 2009. While some of the JHT projects also have led to operational implementation and improvements at the Central Pacific Hurricane Center and the Joint Typhoon Warning Center (JTWC), the main focus of the JHT projects has been on addressing priorities established by the NHC and the EMC, with testing conducted at those Centers and at the facilities of the funded organizations. This assessment of the operational impacts of the JHT is based on input obtained from the NHC Hurricane Specialists. The paper presents the survey results, identifies and describes the highest-scoring projects, and discusses the most significant obstacles encountered during the JHT's first ten years.

2. EVALUATION OF THE JHT PROGRAM AND INDIVIDUAL PROJECTS

Hurricane Specialists were asked to apply a rating system where a score of 3 indicates a transformational advance, 2 represents a significant operational advance, 1 stands for a minor benefit to operations, and 0 means the project was not accepted by management for operations or it was implemented but did not have a net positive impact. Respondents could alternately indicate they had no opinion, signifying they were not sure of impact during their time as a Hurricane Specialist, or that they were not a Hurricane Specialist when the project became operational. For this review, "operational" means that managers in the National Centers for Environmental Prediction (NCEP), NHC's and EMC's parent organization, decided to accept a completed JHT project into regular operational use, and the steps of technical implementation were completed at those Centers. Most projects implemented operationally at the NHC are real-time applications, whereas at EMC they are enhancements to operational numerical weather prediction (NWP) models whose output is used as guidance by NHC forecasters. For projects with multiple components, the Hurricane Specialists were instructed to enter the highest rating for any of the component accomplishments.

Twelve current and former NHC Hurricane Specialists participated in the survey.

2.1 *Overall JHT program assessment*

The forecasters gave an average score of 2.2 to the JHT program as a whole. This translates to a contribution between significant and transformational, closer to the former.

The survey revealed a few other interesting ratings. The average score for the 50 individual projects (average of the 50 averages) was 0.9. A total of 15 projects were not accepted at their conclusion by NHC or EMC management for Operations. The average score for the remaining 35 projects that were implemented was 1.3. Highest score for a project implemented by EMC or NHC into their operational systems was 2.2. Lowest score for an implemented project was 0.3.

2.2 *Projects having the greatest positive impact on operations*

This section describes in brief the highest-scoring projects and provides a flavor of the JHT contributions said by NHC forecasters to be most successful. Detailed information on all past projects including project reports is available at http://www.nhc.noaa.gov/jht/past_projects.shtml.

1) Improvements in deterministic and probabilistic tropical cyclone surface wind predictions (Investigators: Knaff and DeMaria; 2003-5; score=2.2)

This project had two distinct components, as implied by the proposal title. The goal of improving the "deterministic" Statistical Hurricane Intensity Prediction Scheme (SHIPS) forecast intensity model guidance (DeMaria et al. 2005) by adding satellite and aircraft data, and/or by taking a neural network approach, was not achieved during the course of the project (though satellite data later became part of the SHIPS formulation). The work to develop probabilistic forecast wind speeds, in contrast, made this the highest ranked project. A request to the NHC from marine forecasters at the NOAA Ocean Prediction Center for additional guidance on storms at sea initiated the work on forecast probabilities. The Insurance Friends of the National Hurricane Center, a consortium established (but no longer active) to accelerate improvements in forecasting in response to damage incurred during Hurricane Andrew (1992), provided seed money for the work before the JHT got off the ground.

The investigators applied a Monte Carlo approach to generate probabilistic point and field forecasts of tropical cyclone wind speeds (DeMaria et al. 2009). For each NHC forecast, their program generates 1000 realizations by sampling NHC's track and intensity forecast error distribution over the most recent five years, and a forecast model of climatological wind radius.

The JHT has funded follow-on projects to this work to improve the technique and develop additional applications. The products, example of which are shown in Figures 1 and 2, are consulted internally by the NHC forecasters and have become the only new NHC public products derived from JHT work to date. Figure 1 shows an example of the graphical wind speed probability products. Figure 2 shows a portion of an NHC text product based on the probability computations.

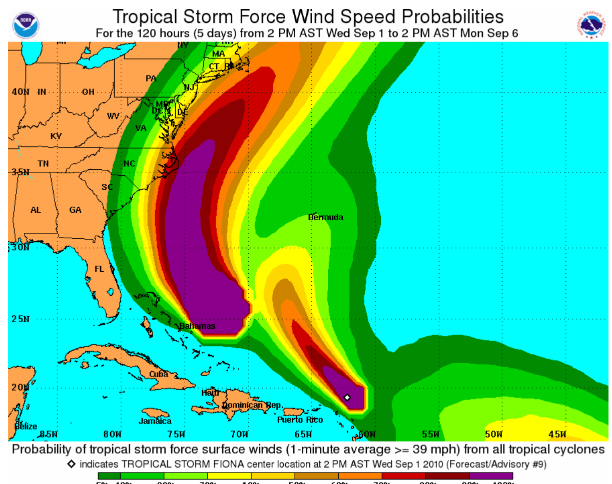

Figure 1. Wind speed probabilities for 1 min tropical storm force winds (at least 39 mph/63 kph) issued by NHC on 2100 UTC 1 September 2010 for the combined forecasts of Hurricane Earl (centered initially just east of the Bahamas), Tropical Storm Fiona (centered initially northeast of Puerto Rico), and Tropical Storm Gaston (centered initially off the edge of the figure between Africa and the Caribbean).

2a) (tie) Quantifying tropical cyclone track forecast uncertainty and improving extended-range tropical cyclone track forecasts using an ensemble of dynamical models (Investigator: Goerss; 2003-5; score=2.0)

The tropical cyclone forecast track found by combining predictions from the normally best performing individual NWP models has been the most accurate guidance, on average, in most years. The arithmetic

CHANCES OF SUSTAINED (1-MINUTE AVERAGE) WIND SPEEDS OF AT LEAST

...34 KT (39 MPH... 63 KPH)...
...50 KT (58 MPH... 93 KPH)...
...64 KT (74 MPH...119 KPH)...
FOR LOCATIONS AND TIME PERIODS DURING THE NEXT 5 DAYS
PROBABILITIES FOR LOCATIONS ARE GIVEN AS IP(CP) WHERE
IP IS THE PROBABILITY OF THE EVENT BEGINNING DURING AN INDIVIDUAL TIME PERIOD (INDIVIDUAL PROBABILITY)
(CP) IS THE PROBABILITY OF THE EVENT OCCURRING BETWEEN 18Z WED AND THE FORECAST HOUR (CUMULATIVE PROBABILITY)
PROBABILITIES ARE GIVEN IN PERCENT
X INDICATES PROBABILITIES LESS THAN 1 PERCENT
PROBABILITIES FOR 34 KT AND 50 KT ARE SHOWN AT A GIVEN LOCATION WHEN THE 5-DAY CUMULATIVE PROBABILITY IS AT LEAST 3 PERCENT.
PROBABILITIES FOR 64 KT ARE SHOWN WHEN THE 5-DAY CUMULATIVE PROBABILITY IS AT LEAST 1 PERCENT.

- - - - WIND SPEED PROBABILITIES FOR SELECTED LOCATIONS - - - -

TIME PERIODS			FROM 18Z WED TO 06Z THU	FROM 06Z THU TO 18Z THU	FROM 18Z THU TO 06Z FRI	FROM 06Z FRI TO 18Z FRI	FROM 18Z FRI TO 18Z SAT	FROM 18Z SAT TO 18Z SUN	FROM 18Z SUN TO 18Z MON
FORECAST HOUR			(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT								
NANTUCKET MA	34	X	X(X)	X(X)	23(23)	51(74)	X(74)	X(74)	
NANTUCKET MA	50	X	X(X)	X(X)	2(2)	39(41)	X(41)	X(41)	
NANTUCKET MA	64	X	X(X)	X(X)	1(1)	17(18)	X(18)	X(18)	
PROVIDENCE RI	34	X	X(X)	X(X)	18(18)	31(49)	X(49)	X(49)	
PROVIDENCE RI	50	X	X(X)	X(X)	1(1)	17(18)	X(18)	X(18)	
PROVIDENCE RI	64	X	X(X)	X(X)	X(X)	6(6)	X(6)	X(6)	
MONTAUK POINT	34	X	X(X)	X(X)	29(29)	24(53)	X(53)	X(53)	
MONTAUK POINT	50	X	X(X)	X(X)	4(4)	18(22)	X(22)	X(22)	
MONTAUK POINT	64	X	X(X)	X(X)	1(1)	6(7)	X(7)	X(7)	
NEW YORK CITY	34	X	X(X)	1(1)	25(26)	6(32)	X(32)	X(32)	
NEW YORK CITY	50	X	X(X)	X(X)	3(3)	3(6)	X(6)	X(6)	
BALTIMORE MD	34	X	X(X)	5(5)	10(15)	X(15)	X(15)	X(15)	
WASHINGTON DC	34	X	X(X)	6(6)	8(14)	X(14)	X(14)	X(14)	
OCEAN CITY MD	34	X	X(X)	21(21)	30(51)	1(52)	X(52)	X(52)	
OCEAN CITY MD	50	X	X(X)	1(1)	16(17)	X(17)	X(17)	X(17)	
OCEAN CITY MD	64	X	X(X)	X(X)	5(5)	X(5)	X(5)	X(5)	
NORFOLK VA	34	X	2(2)	42(44)	11(55)	X(55)	X(55)	X(55)	
NORFOLK VA	50	X	X(X)	8(8)	7(15)	X(15)	X(15)	X(15)	
NORFOLK VA	64	X	X(X)	1(1)	2(3)	X(3)	X(3)	X(3)	
CAPE HATTERAS	34	X	17(17)	71(88)	2(90)	X(90)	X(90)	X(90)	
CAPE HATTERAS	50	X	X(X)	60(60)	4(64)	X(64)	X(64)	X(64)	
CAPE HATTERAS	64	X	X(X)	30(30)	6(36)	X(36)	X(36)	X(36)	
WILMINGTON NC	34	X	16(16)	21(37)	1(38)	X(38)	X(38)	X(38)	
WILMINGTON NC	50	X	1(1)	4(5)	X(5)	X(5)	X(5)	X(5)	
COLUMBIA SC	34	X	1(1)	2(3)	X(3)	X(3)	X(3)	X(3)	

Figure 2. Wind Speed Probability Table for a subset of locations showing data from the NHC's 2100 UTC September 1, 2010 advisory for Hurricane Earl.

mean of the forecast positions from the U.S. Global Forecast System (GFS), U.S. Geophysical Fluid Dynamics Laboratory (GFDL), U.S. Navy Operational Global Atmospheric Prediction System (NGP) and the United Kingdom Meteorological Office (UKM) was known as GUNA. This scheme was the NHC standard for "consensus" guidance for several years. Some models, however, did not contain a proper initialization of the tropical cyclone or lost the vortex prematurely in their forecast fields. In such cases, at least one of the component model outputs and the associated GUNA forecast were not available to the NHC.

This project introduced a new consensus scheme known as "CONU". CONU provided the track from the averages of the available models noted above and the Navy's version of the GFDL model run from the NGP global fields (GFDN)—as long as at least two of the five models are present. CONU supplanted GUNA as the forecasters' choice because of its comparable performance quality (Fig. 3) and superior availability. For 24 h forecasts during the test period, for example, GUNA and CONU data came to the forecasters 72% and 91% of the time, respectively. At 120 h, the availability became 50% and 85% at those times*.

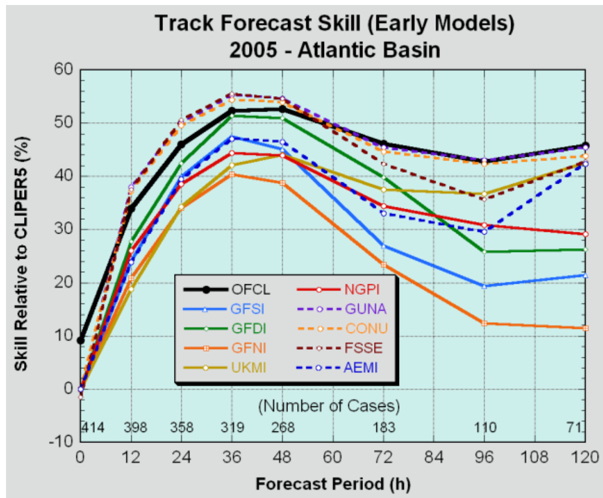

Figure 3. Homogeneous track model comparison for NHC official forecasts (OFCL) and selected models available in operations. Skill is measured here relative to the simple climatology and persistence (CLIPER) benchmark. Individual models adjusted (or "interpolated" – the "I" suffix) to the initial forecast time include: the U.S. Global Forecast System (GFSI), the U.S. Geophysical Fluid Dynamics Laboratory (GFDI) run from the GFS model, the U.S. Navy's Operational Global Atmospheric Prediction System (NGPI), the Geophysical Fluid Dynamics Laboratory (GFNI) run from the NGP model, and the United Kingdom's Meteorological Office (UKMI). Simple consensus models include GUNA (average of GFDI, UKMI, NGPI, and GFSI – all members must be present), CONU (average of GFDI, UKMI, NGPI, GFSI, and GFNI – at least two members must be present), and AEMI (average of the GFS ensemble members). FSSE – the Florida State Super Ensemble – is a weighted, bias-corrected averaging system for selected models.

A second part of the study found that the CONU track error was a strong function of the spread of the component models and the initial and forecast

* CONU is now known as TVCN. Its membership is determined annually before the start of the hurricane season.

intensity (Goerss 2007). From the forecast error distributions the researcher developed Goerss Prediction of Consensus Error (GPCE) "confidence circles" centered on the CONU forecast point that would be expected to contain the actual position at the forecast time about 75% of the time (Fig. 4). This provides information about forecast uncertainty to the hurricane specialist.

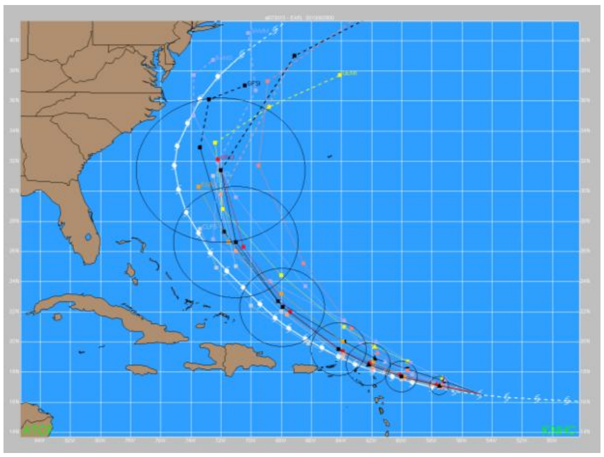

Figure 4. Example of GPCE (black circles) providing 75% confidence guidance to forecasters for the Hurricane Earl track forecast from 00 UTC 29 August 2010, when Earl's center was located near the tropical storm symbol at ~16N 55W. Lines emanating from there are model and NHC forecasts. Symbols along the white line provide subsequent six-hourly center location and intensity information for Earl determined by NHC forecasters from their post-storm analyses.

*2b) (tie) Improved statistical intensity forecast models (*Investigators: Knaff, DeMaria Kaplan; 2005-7; score: 2.0)

This project made two important improvements to SHIPS. SHIPS and its successor that accounts for decay over land (DSHIPS) have provided the most accurate intensity guidance, on average, during the past several years. Figure 5 (top) shows a 3-7 percentage improvement in DSHIPS resulting from the project's advances in accounting for the impact of small islands near to, or encountered by, storms (DeMaria et al. 2006). Figure 5 (bottom) shows the positive impact on DSHIPS obtained from an improved way the system handles wind shear.

4) Continued development of tropical cyclone wind probability products (Investigators: Knaff and DeMaria; 2005-7; score=1.9)

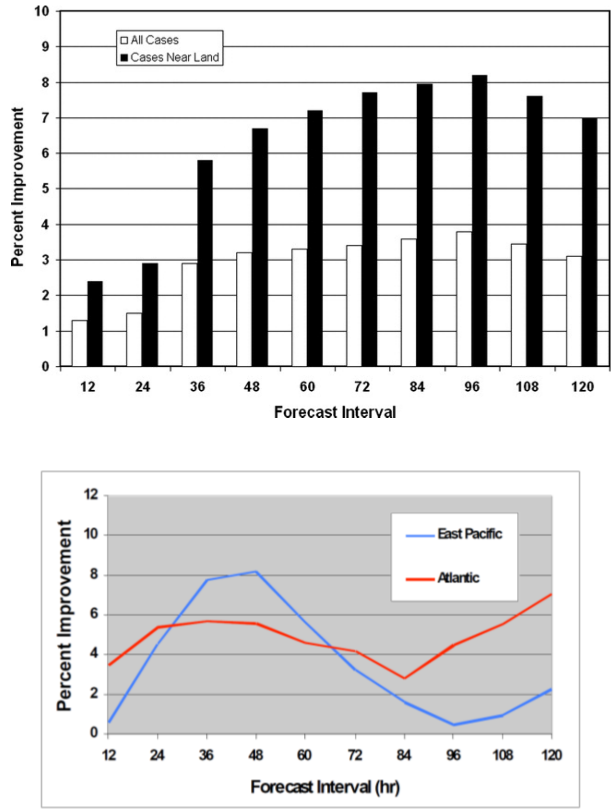

Figure 5. Improvements in SHIPS forecasts due to (top) the inclusion of a new inland decay model, for total sample period and the Atlantic sample where the best track position was within 500 km of land, and (bottom) a modified shear and new GFS vortex variable.

This follow-on work to the top-rated project above helped develop outreach materials used by the NHC for training forecasters at NWS Weather Forecast Offices and others on how to interpret and use the wind speed probability products, including how the probabilities could be used by the NWS in its decision process for issuing tropical storm and hurricane warnings and watches. The third part of the project consisted of a verification of the probability forecasts in the form of reliability diagrams and a comparison between the probabilistic forecasts and the corresponding single, "deterministic" forecast of the NHC and the JTWC.

5) *Hurricane* [model] *transition to operations at NCEP/EMC* (Investigators: Surgi, Tuleya, Shen; 2001-3; score 1.8)

Forecasters gave good marks to several projects that improved operational NWP model guidance. This project, coordinated with the EMC, earned the highest score among them. Its investigators, working in cooperation with researchers at the GFDL, made several upgrades to the GFDL hurricane model. They implemented both the Simplified Arakawa-Schubert convective parameterization scheme and the planetary boundary layer scheme (Hong and Pan, 1996) that was then contained in the parent Aviation global model (AVN). Among the other enhancements, the number of vertical levels in the GFDL model was increased to 42, to be the same as the AVN.

6) Development and implementation of NHC/JHT products in ATCF (Investigator: Sampson; 2005-7; score=1.7)

The NHC forecasters put a high priority on potential improvements to their operating environment (e.g., Appendix, element N-6). A key part of their local information technology infrastructure for the past twenty years has been the Automated Tropical Cyclone Forecast System (ATCF) (Miller et al. 1990; Rappaport et al. 2009).

About 50 upgrades to the ATCF system environment came from this project. The operational display of the confidence circles developed in item 2b above and shown in Fig. 4 was one of them. Other examples included expanded model display capabilities, new visualization options, revised verification process for "Special" advisory forecasts, and technical improvements to handle error checking, changes to the operating system, software bug fixes, etc.

3. PROGRAM CHALLENGES

The JHT's successes came while overcoming some difficulties. Table 1 lists the issues considered to be the most significant by the 15 people who responded to an invitation to comment, including members of the SC, JHT administration, NHC forecasters, NOAA and NHC administration and researchers. The authors, each with significant roles in the JHT, have folded in their observations to the discussion below.

Respondents identified issues falling into one of five program areas: oversight and administration; funding; staff participation; researcher and operational organization collaboration; proposal process. We now discuss some of the most significant issues.

The USWRP established the JHT in the spring of 2001. The mid-fiscal year start led to an expedited and in some ways awkward initial program governance and project selection and funding process for the JHT's first year. During that first two-year cycle, program leaders developed and implemented the TOR and other supporting documents (e.g., a description of NHC's information technology infrastructure) that have remained in force with no important changes since their inception. These documents have smoothed the JHT proposal process in subsequent cycles and likely prevented the number of issues from being larger. We recommend that future testbeds put program documents in place before beginning associated activities to minimize the chances of a rough start.

The JHT staff and SC expend considerable time and effort ensuring the program complies with administrative and legal guidance governing proposals and funding activities. The types of issues on which they work were partly determined when JHT leaders decided early on that the program would fit better within the federal grant's program than in the contract world. The funding process for grants, for example, is complex. For the JHT, it takes about 15 months to complete all the steps to execute funding, from crafting a Federal Register Notice call for proposals which contains input from the operational customers, through completing a legal review of the Notice, obtaining and evaluating documents submitted by prospective investigators, to dispensing the last of the first-year funds to successful candidates. The funding distribution phase itself can take up to about six months due to the protracted nature of awarding grants to organizations using differing processes within NOAA, other federal agencies, universities, cooperative institutes, and private sector companies.

Respondents dislike the protracted nature of the above process. They also indicated several other concerns with funding processes and decisions. The viability of the entire JHT, like other government programs, is subject to the federal budget process. During its first 10 years, the USWRP provided $13.46M to the JHT. The program has been funded every year since its inception, though not without concerns in some years that the testbed would be suspended or terminated for lack of support. In some years, the JHT has operated at levels of funding that were less than required for optimal execution. In those instances the JHT director decided how best to distribute the available funds across the selected projects.

The policy to allow organizational subunits of the host and sponsoring agency, in this case NOAA, to compete against external applicants for resources represented one of the most contentious issues. Figure 6 shows in the aggregate how funds have been distributed across organizational categories from 2001-10 (includes fifth round projects).

Table 1. Potential challenges for new testbeds. Issues grouped under five functional headings. Bold indicates relatively important. Italics identify JHT elements substantially unresolved.

A. Oversight and Administration

- **Having an effective and enduring Terms of Reference and/or Concept of Operations document(s) to guide testbed activities before the first proposal/funding cycle begins**
- **Complexity and length of the federal proposal, grant and legal review process**
- **deciding whether to use grants or contracts**
- ***Portion of funds going to organizations within the sponsoring agency***
- NHC staff support for administrative activities (e.g., JHT Director and administrative position; JHT Steering Committee co-chair)
- "Recusal" and confidentiality requirements for proposal/project reviewers
- *Defining and potentially altering who is the end user organization(s)*; limited attention given to NWS Weather Forecast Office interests
- *Few subject matter experts in community from which to draw researchers, scientific administrators, and steering committee/reviewers who do not wish to submit testbed proposals (prohibited).*
- Adequate testbed visibility in research community during initial years

B. Funding

- ***Relatively small amount of funds per project compared to other sources***
- ***Annual funding uncertainty***
- ***(Lack of) testbed funds provided by "partner" (i.e., non-NOAA) organizations***
- **Establishing and retaining funding to employ sufficient administrative staffing**
- ***Delays in dispersing funds due to long proposal/grant review process can preclude testing during climatologically preferred time of year***
- Funding negotiations between JHT and principal investigators of accepted proposals

C. Staff Participation

- **Insufficient staff interest during early stages of Testbed**
- *Limited staff time for testbed work during busy operational periods*
- NHC staff support for technical activities, including project implementation

D. Researcher and Operational Organization collaboration

- ***Limited number and scope of pre-proposals (Letters of Intent)***
- **Researcher understanding of differences between conventional research projects and time-limited transition-to-operations projects**
- **Limitations on ability of Operations to accommodate new NWP model systems**
- Compatibility of researcher's and operational Information Technology (IT) environments—make available to researchers an IT description of operational organization's infrastructure, including security, software requirements, hardware platforms, etc
- *Researcher program code that meets operational quality requirements*
- Rules of engagement (restrictions) on contact between testbed and operational staff with potential and actual proposers during proposal invitation and review periods
- Physical proximity of testbed work (infrastructure and people) to Operations (can be too near or far)
- Researcher reporting requirements (frequency and content) and communications with user "Points of Contact"

E. Proposal Processes

- Agreement on project milestones and timelines
- Proposals for duplicative work and/or funds for covered employees and organizations
- *Adherence by prospective principal investigators (PIs) to proposal development requirements; employing standards consistently to help ensure an even playing field.*
- *Content of feedback from testbed to scientists on why proposal was not accepted*
- Defining public operational acceptance criteria
- Provide PIs a mid-cycle project review and continuation decision
- Attracting interest from outside the mainstream tropical meteorology community

The money provided per project has averaged around $100K a year. No project has received more than about $200K in a year. These levels are lower than available through other options (e.g., National Science Foundation (NSF)) and may explain why the number of Letters of Intent to the JHT in its six cycles has never exceeded about 40 per cycle. The relatively low funding levels can be also explained in part by noting that to date only NOAA has contributed to the funds for projects (though the original JHT plan was to have at least two additional non-NOAA funding partners, to make it truly a "joint" hurricane testbed.) The diversity of *recipients* of the funds and in the membership of the SC, nevertheless, make the JHT a "joint" activity in at least in these regards. Another reason for the small interest level is that the JHT has remained true to the program's intended special niche—supporting advances in science or technology that are relatively mature for operational needs; that is, those that are ready to cross the "Valley of Death" between research and operations as it was termed by the National Research Council (NAS 2000).

The relatively small size of the tropical meteorology community is another reason for the modest interest noted. The small size also has an impact on the SC. With SC rules prohibiting its members from receiving financial support for JHT project work during their tenure on the committee, the JHT has been fortunate to have had so many experts volunteer their time to serve on the SC when they and their charges could have instead potentially been funded investigators. Section 4.1 recognizes these scientists by name.

The NHC, as the host site and primary beneficiary of the JHT, contributes to the program in several ways. It dedicates a portion of its forecast operations room and office space to the JHT. It also contributes staff time. Its Technical Support Branch chief serves as the JHT director. Two administrative assistants—one of whom is the NHC Science and Operations Officer—help him. The NHC Deputy Director is the operational co-chair of the JHT SC. NHC's Hurricane Specialists and some other staff serve as "Points of Contact" representing operational interests in their collaboration on projects with JHT investigators. In addition, NHC's IT staff is heavily involved in project testing and evaluation, and also during the operational implementation of applications at NHC. These activities amount to about 1.5 people per year and represent a considerable, mostly "out-of-hide" additional activity for the staff of an operational forecast office of about 45 government employees. The successes of the JHT have largely overcome the initial skepticism and reticence of staff associated with these new staff responsibilities. Still, operations come first and there are times when the NHC must turn its attention from testbed work to forecast duties, even when it might seem to be the best opportunity to conduct real-time testbed activities. The EMC and NCEP's Central Operations have also contributed resources, mainly through testing and implementing NWP projects.

JHT funds also cover administrative and other support tasks at a level usually near $250K per year (see, "Infrastructure" in Fig. 6). About half of that amount covers the salary and associated overhead for a JHT Information Technology facilitator (programmer). This scientist-programmer works with the JHT investigators and NHC staff. The JHT applies the remainder of the infrastructure funds, about 5-10% of the total JHT budget, to JHT-related IT purchases, travel, supplies and other administrative needs of the program.

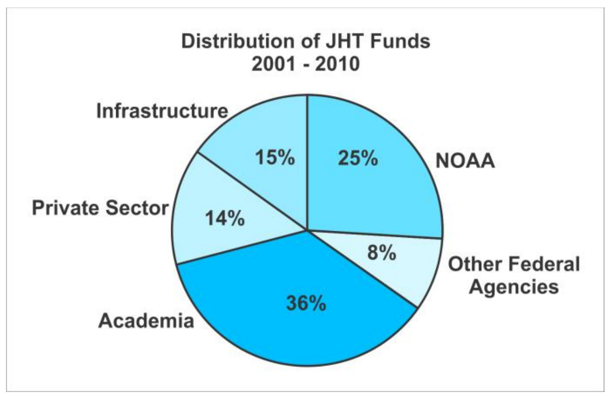

Figure 6. Distribution of JHT funds, 2001-2010.

Testbeds are intended to bridge the work and work environments of researchers and operational personnel. For the JHT, these material and cultural differences include information technology (e.g., computer capabilities, security, communication and software protocols); test standards; product reliability and timeliness, as well as expectations about the processes to be employed and documentation. The JHT has been successful because of the willingness of researchers and operational staff to work closely to develop and employ collaborative procedures.

4. TESTBED CONTRIBUTORS

4.1 *Individuals*

Many scientists, technology specialists, and administrators contribute their expertise to the JHT. This section recognizes some of them, in part for their due credit and in part to indicate the number of people and institutions, and the breadth of capabilities required, to start and sustain a testbed like the JHT.

Russell Elsberry (U.S. Naval Postgraduate School) developed the initial JHT concept and was a member of an *ad hoc* coordinating team that helped establish the testbed.

NOAA, through the USWRP, has been the JHT's sole funding agency. USWRP leaders during the time the JHT was under development, especially Louis Uccellini, Bill Hooke and Rit Carbone, provided backing and critical guidance.

Jiann-Gwo Jiing has served as the JHT's only Director. Richard Knabb, Christopher Landsea and Shirley Murillo have been JHT Administrative Assistants helping him. Alison Krautkramer and Jose Salazar facilitated IT interactions between the investigators and NHC staff.

Mark DeMaria (NOAA) and Ed Rappaport (NOAA) were the other members of the initial, informal coordinating team noted above that preceded the JHT's Steering Committee (SC). John Molinari (State University of New York—Albany), Bill Frank (Penn State University), John Gamache (NOAA) and Ed Rappaport have held SC co-chair positions. Others who have served, or are serving, as SC members are Kerry Emanuel (Massachusetts Institute of Technology), Frank Marks (NOAA), Naomi Surgi (NOAA), Ed Fukada (JTWC), Hugh Willoughby (Florida International University), Jeff Hawkins (Naval Research Laboratory), Christopher Landsea (NOAA), Elizabeth Ritchie (University of Arizona), and Vijay Tallapragada (NOAA).

Additional administrative support from NOAA came primarily from Ward Seguin, John Gaynor, and staff from the NOAA Office of Weather and Air Quality.

4.2 *Investigator organizations*

The JHT provided funds for projects originating from organizations in several sectors of the community, distributed as follows. The organizations participating in Round 5 projects are shown in bold lettering.

Federal

Cooperative Institute for Mesoscale Meteorological Studies
Cooperative Institute for Research in the Atmosphere
NASA Goddard Space Flight Center
Naval Research Laboratory
NOAA/NESDIS Office of Research and Applications
NOAA/NWS Environmental Modeling Center
NOAA/NWS Hydrometeorological Prediction Center
NOAA/NWS National Hurricane Center
NOAA/OAR Earth System Research Laboratory
NOAA/OAR Geophysical Fluid Dynamics Laboratory
NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory
NOAA/OMAO/Aircraft Operations Center
United States Air Force Reserves

Academia

Naval Postgraduate School
Old Dominion University
UCAR/NCAR Earth Observing Laboratory
UCAR/NCAR Visiting Scientist Program
United States Air Force Academy
University of Alabama
University of Central Florida
University of Hawaii
University of Maryland
University of Miami
University of Rhode Island
University of Western Ontario
University of Wisconsin

Private Sector

Computer Science Corporation
ProSensing Inc.
Remote Sensing Solutions, Inc.
Remote Sensing Systems
Science Applications International Corporation

5. SUMMARY AND PROSPECTS FOR THE JHT

A survey of the JHT's primary customers—the NHC hurricane forecasters—reveals a largely favorable view of the testbed. The forecasters rated the JHT's contribution to NHC operations as significant. They indicate the most successful projects include improvements to operational NWP models, applications for forecasters and other end users, and more efficient forecast support processes.

The JHT's current focus includes projects for its fifth cycle that began in 2009 (http://www.nhc.noaa.gov/jht/09-11_proj.shtml), with eleven of twelve of those now advanced to second-year activities. Decisions on their possible operational implementation will occur in early 2012. The JHT has also begun its sixth two-year cycle. It received more than 30 Letters of Intent, later narrowed to 23 qualifying full proposals for that cycle. These numbers, which are comparable to previous rounds, suggest that the testbed retains steady if not full interest within the small community of tropical meteorology.

The JHT's retains its niche of facilitating the transfer of promising research into tropical cyclone forecast operations within a period of about two years. Its focus complements the NOAA's new Hurricane Forecast Improvement Project (HFIP), a 10-year project designed to accelerate improvements in one to seven day forecasts for hurricane track, intensity, and storm surge, and to reduce forecast uncertainty. HFIP has very ambitious goals for model guidance (e.g., http://www.hfip.org) it intends to achieve, and a commensurate budget that is about an order of magnitude larger than the JHT's. While the structures and time lines of the two programs also differ, it is to the JHT's credit that HFIP is adopting some of JHT's administrative processes as best practices.

The future of both programs will depend on the availability of funds during an era of expected increased federal budget austerity. To date, NOAA has provided an average of about $1.3 million per year to the JHT. Compared to the annual ~$10 billion in damage (Pielke et al. 2008) plus loss of life associated with tropical cyclones in the United States alone, the JHT budget, intended to expedite improvements in hurricane forecasts, seems modest given the significant successes realized by the testbed during its first decade.

6. REFERENCES

DeMaria, M., J. A. Knaff, and J. Kaplan, 2006: On the decay of tropical cyclone winds crossing narrow landmasses. *J. Appl. Meteor. Climatol*. **45**, 491-499.

DeMaria, M., J. A. Knaff, R. Knabb, C. Lauer, C. R. Sampson and R. T. DeMaria, 2009: A new method for estimating tropical cyclone wind speed probabilities. *Wea. Forecasting*, **24**, 1573-1591.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

Franklin, J. F., cited 2010: 2009 National Hurricane Center forecast verification report. [Available on line at http://www.nhc.noaa.gov/verification.]

Goerss, J. S., 2007: Prediction of consensus tropical cyclone track forecast error. *Mon. Wea. Rev.,* **135**, 1985-1993.

Hong, S.-Y. and H.-L. Pan, 1996: Nonlocal Boundary Layer Vertical Diffusion in a Medium-Range Forecast Model. *Mon. Wea. Rev.*, **124**, 2322-2339.

Knabb, R. D., J-G. Jiing, C. W. Landsea, and W. R. Seguin, 2005: The Joint Hurricane Testbed (JHT): Progress and Future Plans. American Meteorological Society, Ninth Symposium on Integrated Observing and Assimilation Systems for The Atmosphere, Ocean, and Land Surface (IOAS-AOLS), San Diego, CA, 3 pp.

Miller, R. J., and A. J. Schrader, C. R. Sampson, and T. L. Tsui, 1990: The Automated Tropical Cyclone Forecasting System (ATCF). *Wea. Forecasting*, **5**, 653-660.

NAS, cited 2000: From research to operations in weather satellites and numerical weather prediction: Crossing the Valley of Death. The National Academies Board on Atmospheric Sciences and Climate. [Available online at http://dels.nas.edu/Report/From-Research-Operations-Weather/9948]

Pielke, R. A., Jr., J. Gratz, C. W. Landsea, D. Collins, M. A. Saunders, and R. Muslin, 2008: Normalized hurricane damage in the United States: 1900-2005. *Natural Hazard Review*, **9**, 29-42.

Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24**, 395-419.

7. APPENDIX

JHT priorities for the 6th two-year funding cycle as identified by the National Hurricane Center and Central Pacific Hurricane Center (N), Joint Typhoon Warning Center (J) and Environmental Modeling Center (E):

N-1, J-1 Guidance for tropical cyclone intensity change, especially for the onset, duration, and magnitude of rapid intensification events, as well as for over-water rapid weakening events

N-2, J-2, Improved capability to observe the tropical cyclone and its environment to support forecaster analysis and model initialization

N-3, J-5, Statistically based real-time guidance on guidance to assist in the determination of official track and intensity forecasts; this could include multi-model consensus approaches, provided in probabilistic and other formats

N-4, J-10, Advanced coastal inundation modeling and/or applications, visualization, or dissemination technology that enhances operational storm surge forecast accuracy or delivery

N-5, J-6, Improved and extended track guidance. Identification, and then reduction of, the occurrence of guidance and official track outliers, focusing on both large speed errors (e.g., accelerating recurvers and stalling storms) and large direction errors (e.g., loops), and on specific forecast problems, including interactions between upper-level troughs and tropical cyclones, track forecasts near/over land or elevated terrain, and extratropical transition

N-6, J-4, Enhancements to the operational environment (e.g., ATCF, AWIPS-II) to increase forecaster efficiency, by expediting analysis, forecast, coordination, and/or communication activities

N-7, J-3, Guidance for tropical cyclone genesis that exhibits a high probability of detection and a low false alarm rate, and/or provides probability of genesis

N-8, J-15, An extended (seven-day or longer) climatology-persistence skill baseline model for tropical cyclone track and intensity

N-9, J-9, Operational analysis of the surface wind field in tropical cyclones, including the analysis of the maximum sustained winds, and winds affecting elevated terrain and high-rise buildings

N-10, J-8, Guidance for changes in tropical cyclone size/wind structure and related parameters, including combined sea heights

N-11, J-11, Single-model track or intensity ensembles that have skill comparable to multi-model consensus techniques

N-12, J-7, Techniques to improve the utility of microwave satellite and radar data for tropical cyclone analysis

N-13, J-12, Guidance for precipitation amount and distribution associated with tropical cyclones and tropical disturbances

N-14, J-13, Improved techniques for estimating the intensity of tropical cyclones passing over and north of sea-surface temperature gradients (e.g., in the eastern North Pacific Ocean and the Atlantic Gulf Stream)

N-15, J-14, Quantitative guidance tools for seasonal tropical cyclone forecasts for the Atlantic and eastern North Pacific basins, using statistical and/or dynamical methodologies

E1, General model improvements to advance hurricane track in the NCEP global model. Model improvements should address extending useful track skill for NHC from five day to seven-day forecasts

E-2, Diagnostic techniques to further increase the utility of global models (e.g., NCEP, UKMO, NOGAPS) in forecasting tropical cyclone genesis

E-3, Improvements specific to operational HWRF modeling system:

E-4, Development of new methods or improving existing GSI techniques to assimilate satellite data and airborne Doppler radar, SFMR, flight-level winds and dropsonde observations in the hurricane core region for initialization of the hurricane vortex. Initialization of the vortex with satellite data is of the highest priority

E-5 Develop diagnostic capabilities to compare model output to satellite derived datasets (including NASA A-Train, CloudSat, AIRS, AMSU, AQUA MODIS etc.) and evaluate their potential use in vortex initialization

E-6, Diagnose and improve HWRF wind-pressure relationship in comparison to NHC best track estimates

E-7, Improvements to physics suitable for high resolution (~3 km or less) including air-sea transfer physics in high wind conditions, representation of convection, moist cloud physics, and radiation

E-8, Diagnostics on HWRF analyses and forecasts for evolution of both large-scale hurricane environment and evolving storm scale structure throughout tropical storm life cycle