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1. INTRODUCTION

The skill of operational hurricane forecasting has advanced significantly during recent decades. Numerous forecast challenges remain, however, in order to address the emergency management needs of growing coastal populations that are extremely vulnerable to loss of life, property damage, and economic hardship due to hurricanes. While track forecasting has improved markedly, intensity forecasting remains only minimally skillful. Further, forecasts of tropical cyclone genesis, size (wind radii), storm surge, rainfall, and other parameters are comparatively in their infancy. Basic and applied science and technology research are currently being carried out in these areas. However, to impact operational analyses and forecasts, a more streamlined approach is needed to transfer the most promising and mature research to operations. In particular, an infrastructure and a procedural framework are needed for testing and evaluating new techniques. In order to develop and accelerate this approach for hurricane forecasting, the Joint Hurricane Testbed (JHT) has been established at the National Oceanic and Atmospheric Administration's (NOAA's) Tropical Prediction Center/National Hurricane Center (TPC/NHC), under the auspices of the United States Weather Research Program (USWRP).

The purpose of this paper is to expand awareness of the JHT and its collaborative activities, challenges, and impacts to encourage the ongoing participation of the research community and to serve as a prototype for other similar initiatives within the USWRP and other programs.

2. JHT OVERVIEW

2.1 JHT Formation and Mission

The mission of the JHT, formed in 2001, is to facilitate the transfer of new technology, research results, and observational advances of the USWRP, its sponsoring agencies, the academic community, and the private sector for improved operational tropical cyclone analysis and prediction. This mission is accomplished

by identifying promising and mature research and technology, providing the infrastructure to test and evaluate the selected techniques in an operational setting, and presenting the results to the operational center(s) to consider for operational implementation. Institutions and their principal investigators are funded via grants, each with a nominal duration of two years, to prepare their own techniques for the operational center(s) to test and evaluate in the JHT quasi-operational environment. Researchers work collaboratively with the operational center(s) with facilitation provided by the JHT.

The JHT has been initially established at NOAA's TPC/NHC, a part of the National Centers for Environmental Prediction (NCEP) within the National Weather Service (NWS). Such a facility could have been, and may soon be, established at the Joint Typhoon Warning Center (JTWC) operated by the U. S. Navy and Air Force and/or NOAA's Central Pacific Hurricane Center (CPHC), or any other operational forecasting or numerical modeling center with responsibility for tropical cyclones. While support for the JHT grants and infrastructure comes from NOAA USWRP resources, all operational centers are expected to benefit from the JHT. The governing document of the JHT, the *JHT Terms of Reference* approved by the USWRP, provides additional details on the organization of the JHT and is available via the JHT website (<http://www.aoml.noaa.gov/hrd/Landsea/jht>).

2.2 JHT Infrastructure

The infrastructure of the JHT includes the personnel and information technology (IT) resources that are necessary to select and conduct each JHT project. This ambitious effort, involving many individuals at widely spaced locations, demands effective planning and collaboration. JHT projects require that frequent communications and interactions take place between the funding agency (NOAA) and the funded researchers to carry out the proposed tasks.

Administration of the JHT is provided by the JHT staff, which includes a quarter-time Director, two quarter-time administrative assistants, and one full-time information technology (IT) facilitator. The JHT Steering Committee (SC) advises the JHT Director on all JHT activities, and its primary responsibility is to review proposals submitted to the JHT by the research community. The SC is composed of seven members,

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including one representative from NOAA tropical cyclone operations, one from NOAA tropical cyclone research, one from NOAA numerical model development, one from Department of Defense (DoD) tropical cyclone operations, one from DoD tropical cyclone research, and two from academia with expertise in tropical cyclones.

A JHT IT infrastructure, separate from but similar to an operational center's IT environment, is required for robust testing and evaluation of each technique without imposing unnecessary distractions, risk, and expense upon the operational center. Further, IT security concerns and operational resources dictate that the JHT systems be separate from operations to allow access and use by externally-funded researchers. The JHT IT environment closely mimics the basic TPC/NHC IT environment (data flow and formats, communications, hardware platforms, software applications, etc.) in order to test and to best prepare each technique for possible operational implementation at the conclusion of the project. TPC/NHC provides real-time access to the operational data stream to the JHT environment. Characteristics of the TPC/NHC and JHT IT environments are communicated to the research community in JHT announcements of opportunity so that needs for modifying new techniques can be established at the proposal stage and be properly addressed during the course of a project.

2.3 JHT Concept of Operations

Real-time testing of JHT projects takes place on the hurricane operations floor of TPC/NHC during active tropical cyclones in the Atlantic and eastern North Pacific basins. This approach encourages forecasters to utilize experimental JHT techniques during the course of their actual operational shifts as time permits, and it allows them to provide immediate feedback to the JHT staff and the funded researchers so that modifications can be made, often during that same season. Forecasters also provide important post-season feedback, based largely on their real-time experiences, when JHT project results are being verified and evaluated. While experimental JHT techniques can, and sometimes do, undergo testing in a case study or simulation mode, real-time testing of the techniques has proven, for many projects, to be an invaluable method for obtaining reliable results on which to later base decisions on operational implementation.

3. JHT PROJECT LIFE CYCLE

Fulfilling the mission of the JHT requires successfully identifying, selecting, testing, evaluating, and then possibly implementing new science and technology, including observational advances, for operational tropical cyclone analysis and prediction. JHT projects proceed through a life cycle that includes identification via an announcement of opportunity, selection via a proposal review and grants award process, testing and evaluation at the operational center(s), and decisions for operational implementation

by the operational center(s).

3.1 Proposal Review Process

Availability of JHT funds for the research community is advertised via the periodic publication of a JHT Announcement of Federal Funding Opportunity (AFFO). The AFFO includes essential information regarding the program objectives and priorities and the submission requirements. Most researchers worldwide, both within and outside of the Federal government, are eligible to submit proposals, which are all competed against one another. The JHT testing and evaluation of existing, mature, and promising science and technology in an operational setting is funded by NOAA grants. The funding instrument for non-Federal applicants is a cooperative agreement (a type of grant), due to the substantial amount of interaction between the funded researchers and NOAA scientists during the course of a JHT project. While projects follow an accelerated schedule with mutually agreeable timetables, no contract is involved and no requirements are dictated to the funded researchers.

A JHT AFFO has thus far been published approximately every other year in step with a nominal two-year project cycle. While the first round of JHT projects (2001-03) arose from an announcement in 2001 with comparatively limited distribution, the first announcement inviting worldwide applicants was published in January 2003 to advertise availability of fiscal year 2003 funding. Fifteen one- to two-year projects in this second round were funded in summer 2003 as a result. Approximately 36% of the fiscal year 2003 funds were awarded to organizations outside of the Federal government, primarily state and private universities but also including a small amount to private companies. No announcement was published in fiscal year 2004 when JHT funds were used to renew the twelve current two-year projects through summer 2005. Details of the first and second round of JHT projects are provided on the JHT website (<http://www.aoml.noaa.gov/hrd/Landsea/jht>). A new AFFO was published on 30 June 2004 to again invite applicants worldwide to compete for fiscal year 2005 funding (also refer to JHT website to obtain AFFO). Submissions in response to this AFFO have been under review during summer and fall 2004, and the process is expected to result in the funding of 8 to 15 new one- to two-year projects in 2005, in time for testing and evaluation during the 2005 and possibly 2006 hurricane seasons.

The AFFO conveys a myriad of specific information to prospective applicants. The publication of this information initiates, early in the process, the communication between operational centers and research institutions that is needed to begin the process of transferring research to operations. For example, the AFFO contains a list of TPC/NHC and NCEP Environmental Modeling Center (EMC) forecast improvement needs that have been identified and prioritized by these centers. Applicants are directed to

identify clearly in their proposals which of these areas are addressed by their technique. Further, the AFFO provides the detailed criteria by which each submitted proposal is reviewed. In particular, the criteria address not only the scientific merit of the technique, but also its readiness for real-time testing based on factors such as the maturity of the research and its technical compatibility with operational systems.

3.2 Project Testing and Evaluation

Each JHT project demands its own tailored approach to real-time testing, since projects may involve new software applications, observations, assimilation techniques, dynamical model components, guidance products, and/or other forecast and analysis techniques. Additionally, the operational center(s) designate a forecaster and/or technical point of contact for each JHT project at its inception. The points of contact interact directly with their project's principal investigator(s) during testing and evaluation in order to accelerate the flow of information between research and operations and to help keep the project on schedule. In the process, funded researchers prepare scientific and technical documentation, train operational personnel on the use of new techniques, convert techniques to run in operational environments, and perform actual testing and evaluation. In some cases, new techniques are modified during the project to make them more forecaster-friendly and time-efficient. Output must be formatted to suit the particular technique, in order to provide substantive information in a concise manner to be digested quickly during the forecast process. The amount of time asked of the forecaster for testing each technique also varies widely. Some projects may even be nearly transparent to the forecaster; for example, upgrades to existing operational dynamical models may only require that forecasters note and assess any changes in model behavior and performance as compared to previous versions.

Transferring research results and new technology into operations is not a trivial task. This endeavor requires sufficient funding, facilities, and other resources, including systems and personnel to prepare, test, and evaluate new approaches. However, the potential stumbling blocks for a new technique are not limited to these factors. Research results are often manifested as new software originally configured to run in an environment significantly different from that of an operational center. The techniques may also involve input data or supporting software that are not routinely available to the center. Forecasters and technical support staff may require extensive training, even after the JHT project ends, in order to utilize and maintain a new algorithm. Finally, generating output from a new technique may not fit into current operational time constraints, and substantial work may be required to make the output available in the proper format to be easily utilized by forecasters. The testing and evaluation process addresses all of these issues prior to an operational center deciding whether or not to commit resources to the implementation of a new technique.

3.3 Decisions on Operational Implementation

The conclusion of a JHT project is followed by the submission of a final JHT report to the TPC/NHC Director (and/or other operational center(s) if applicable). This report comes from the JHT staff and is based not only on their own evaluations but also on input from the project's funded researcher(s) and operational center point(s) of contact. The operational center Director makes the decision on whether or not to operationally implement the techniques resulting from the project. These decisions are at the sole discretion of the operational center(s). The TPC/NHC Director's decisions, for example, are based on an analysis of the following four factors:

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

It is important to note that these factors are not used in the evaluation of the original proposals to the JHT (although they are closely related), but are applied by TPC/NHC to the results of the project following the conclusion of its JHT-funded activity. Therefore, even if a JHT project's testing and evaluation activities are completed as planned at the project's inception, there is no guarantee of acceptance for implementation by the operational center. The goal of each JHT project is to give the new technique the best chance for operational implementation, while ensuring that the operational center has sufficient information about the technique for making an informed decision on committing its resources.

The JHT has been in existence since 2001, and during the first two years nine projects were completed. Late in 2003, the Director of TPC/NHC reviewed the results of two years of testing and evaluation and made the decision to accept four of these JHT projects for operational implementation. The Director of NCEP, also in 2003, accepted two (of the nine) additional projects that produced upgrades to the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model run operationally by NCEP. The JHT website (<http://www.aoml.noaa.gov/hrd/Landsea/jht>) provides a brief description of those techniques accepted for operational implementation. Decisions regarding JHT projects concluding during 2004 and 2005 will be made late in those calendar years, respectively. In the longer term, projects expected to begin during spring 2005 will have durations of one to two years, resulting in operational implementation decisions in 2006 and/or 2007.