FY22 NOAA/OAR Weather Program Office

Forecaster Support Products for Analysis of Tropical Cyclone Intensity and Structure from Aircraft Reconnaissance Observations

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Research to Operations Transition Plan

Office of Oceanic and Atmospheric Research
and
National Weather Service

Date Submitted

Approval Page

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Research to Operations Transition Plan

The parties listed below, by providing signatures, are satisfied with and approve of the transition plan outlined in this document, which may be reviewed on an annual basis and updated as needed. This document does not constitute a formal commitment of funds or other resources, but instead demonstrates a general agreement on the path forward for the future transition which may eventually require additional resources.

It is acknowledged herein that operational implementation of these new capabilities is subject to successful completion of the described research, development, and/or demonstration, review and approval through appropriate end user NOAA Line Office governance procedures, and availability of funding.

[Name] Date
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National Weather Service Point of Contact

1. Transition Summary

The purpose of this Research to Operations Transition Plan is to outline a concept for transitioning research outputs, from the project entitled "Forecaster Support Products for Analysis of Tropical Cyclone Intensity and Structure from Aircraft Reconnaissance Observations", to a long-term sustained operational capability within the NOAA National Weather Service.

This project focuses on operationally implementing integrated aircraft reconnaissance analysis products that improve the spatial and temporal analysis of the surface wind field in TCs. TC forecasters at the National Hurricane Center (NHC) are often faced with a time crunch as they seek to synthesize incoming aircraft reconnaissance and radar information. This project is developing products to help forecasters better interpret conflicting radar and reconnaissance data in order to more quickly assess the tropical cyclone intensity and structure in real-time. The project team has assembled a strong portfolio of codes and analysis techniques to ease this process. The goal of this project is to implement and transition these capabilities to the point where they are ready for acceptance into operations.

1.1 Transition Products

- A real-time suite of observational analysis products will provide high quality spatial gridded analysis of the TC wind field from the surface up to ~3 km height.
- Objective state estimation techniques will then be applied to provide temporal analysis of the storm's intensity, radius of maximum winds, and wind radii..
- Graphical and tabular outputs of the analyzed intensity and structure information, along with estimated uncertainty, will allow forecasters to analyze TC intensity and structure more quickly and with greater confidence.

1.2 Transition Adopter

The R&D output will be transitioned to NHC, the primary intended recipient of this project. The managing office is the NWS. The capabilities are designed to run on a Linux/Unix system that supports Python v3.8+, NCL v6.6.2, and Julia v1.6.

1.3 Transition Benefits

This project seeks to operationally implement integrated aircraft reconnaissance analysis products that improve the spatial and temporal analysis of the surface wind field in TCs. The project will add the project's analysis products into NHC's data visualization architecture (i.e., Advanced Weather Interactive Processing System-2, AWIPS2, and the NHC Display). We anticipate that the automated observational analysis products will substantially simplify and speed-up the forecasters' task of analyzing trends in the VMAX, RMW, and wind radii while also providing information about the uncertainty associated with such estimates. We expect that this will result in a measurable decrease in forecaster workload and improve forecaster's confidence in analyzing TC parameters when observations seem to conflict.

The unified parameterization will be of substantial scientific value to researchers and will also be of considerable practical use beyond operations. We anticipate that an improved analysis of the surface wind field will be particularly beneficial to improving forecasts of storm surge, and this will also benefit researchers and industry studies of damage impacts. Finally, improving the real-time TC analysis for VMAX, RMW, and wind radii has the potential to improve the predictions made by operational TC models that depend on accurate initial conditions and verification, and thereby, improve intensity and size forecasts. This will potentially save lives, reduce TC-induced property damage, increase the public's awareness, and enhance confidence in NOAA's official forecasts and warnings.

2. Research Overview

The National Center for Atmospheric Research (NCAR), Colorado State University (CSU), and University of Miami (UM) PIs have developed a comprehensive suite of observational processing and analysis capabilities that will be extensively leveraged and extended in this project. Four observational processing and analysis techniques will be integrated during this project:

- Spline Analysis at Mesoscale Utilizing Radar and Aircraft Instrumentation (SAMURAI), a 3-d variational data assimilation method which has been used extensively in field campaigns to develop research-grade analyses and has recently become optimized to run in real-time (Bell et al. 2012, Boehm and Bell 2021);
- Enhanced Vortex Data Message Dataset (VDM+): which processes Vortex Data Messages into a structured machine-readable format with over 100 parameters (Vigh et al. 2015; Vigh 2015);
- Extended Flight Level Dataset for Tropical Cyclones Dataset (FLIGHT+): a research-grade dataset which includes earth-relative aircraft observations processed into storm-relative radial legs at the highest temporal resolution available (e.g., 30-s, 10-s, or 1-s) using automatic leg parsing and quality control, then interpolates the data to a standardized radial grid (Vigh et al. 2021);
- TC-OBS (Vigh et al. 2016, 2018), which uses objective criteria-weighted analysis algorithms to analyze input observations to provide detailed temporal analysis of TC intensity, wind structure, and size, as well as the time- and observations-dependent uncertainty bounds for track, intensity, RMW, and wind radii;

The desired outcomes are the transition products listed in section 1.1.

3. Capabilities and Functions

3.1 Current Capability

3.1.1 Current status of capabilities

Each major technique (SAMURAI, VDM+, FLIGHT+, and TC-OBS) has been demonstrated or used in a research capacity, with most capabilities resulting in significant published work in peer-reviewed journals. The unified parameterization will necessarily involve new research in order to take advantage of the great wealth of high quality observations that have accumulated since legacy studies were done a decade or more ago.

Substantial adaptation of codes for operational implementation will be undertaken. A significant portion of the project will involve integration of these capabilities together in order to develop the specific products required to meet the project's objectives of reducing forecaster workload. While the envisioned linkages are fairly simple, the challenge will be to get a system that can rapidly and robustly process the voluminous raw data feeds.

The project plan follows a staged approach which plans to bring new capabilities online for testing in each hurricane season in an increasingly operational-like environment.

3.1.2 Current Readiness Level (RL) and the expected RL upon project completion

The core capabilities of the techniques being used in this project are at RL-5. At the project completion, all capabilities are planned to be RL-8.

3.2 Anticipated Operational Capability

The operational end state of the project will see the integrated capabilities set up with complete automation and documentation to run on the preferred operational system (whether this be a dedicated machine at NHC or NCO's operational system). The concept of operations will be automated, in which all data ingest, processing, and product generation occur without the need for human intervention or input. Text and gridded products will be supplied to NHC through NOAA's preferred dissemination system(s). Graphical products can be generated by the integrated system capabilities, or through the NHC Display and/or AWIPS2 workstation.

3.3 Impacts on Operations

3.3.1 Does this transition change or replace an existing operational capability?

No. The transition will add new operational capabilities.

3.3.2 Does the capability have an established upgrade schedule?

During the project, there will be regular updates as the capabilities are refined. Four versions of the system are anticipated:
- v0.3: Capabilities demonstrated Jul-Nov 2023
- v0.5: Capabilities demonstrated Jun-Nov 2024
- v0.9: Capabilities demonstrated from Jul 2025 onward
- v1.0: The operational system (if accepted)

After the project ends, no additional updates are planned because the capabilities are planned to be fully mature. Improvements for reliability could be made with small supplemental funding, as needed.

Given the complex nature of the analysis systems and their reliance on improved research and scientific understanding, any major upgrades would take place through new research as a follow-on project.

3.3.3 Does the capability require new or expanded computing/storage resources?

The project capabilities will be capable of running on a multi-core Linux project workstation. The computation and storage resources are modest (10-50 GB of storage per season).

3.3.4 Is there an internal and/or external data delivery requirement?

The capabilities will deliver text and gridded data for external delivery.

4. Transition Activities, Checkpoints, and Acceptance

4.1 Milestones and Checkpoints

Milestone/Checkpoint (Goal completion date)	**Transition Activities (if any)**	**Date (MM/YY)**
9A: First NHC visit to gather requirements and establish evaluation protocols (Oct 2022)		
1A: FLIGHT+/VDM+ modified to run in real-time using operational data (Oct 2022)		
3A: Complete organization of post-processed data (Nov 2022)		
2A: Willoughby-Chelmow technique running in real-time using operational data (Dec 2022)		
3B: Complete preliminary version of surface wind reduction parameterization (May 2023)		
5A: TC-OBS implemented in real-time to provide temporal analysis of VMAX / RMW / size (May 2023)		
4A: SAMURAI implemented in real-time to provide 3-d and 2-d analyses (Jun 2023)		
7A: Outputs available to NHC forecasters via TCGP (Jun 2023)		
7B: First demo period begins (Jul 2023)		

9B: Second NHC visit to gather feedback and observe and train forecasters (Aug 2023)	Forecaster training	
7C: First demo period ends (Nov 2023)		
8A: Evaluation completed for first demo period with report to NHC (Feb 2024)		
3C: Single unified parameterization for the vertical profile of wind completed (Mar 2024)		
2B: Implement improved center-finding for weak storms (Apr 2024)		
5B: TC-OBS optimal parameter estimation techniques improved (Apr 2024)		
4B: SAMURAI updated to use unified parameterization (May 2024)		
7D: Outputs provided in formats for testing in AWIPS-2 and the NHC HFIP Display (May 2024)		
7E: Second demo period begins (Jun 2024)	Capabilities running in NHC sandbox	
7F: Second demo period ends (Nov 2024)		
2C: Center-finding improved to handle simultaneous recon flights (Jan 2025)		
6A: Uncertainty quantified in TDR / SFMR / Dropsondes (Jan 2025)		
8B: Evaluation completed for second demo period with report to NHC (Feb 2025)		
1B: Update FLIGHT+ for simultaneous recon flights (Feb 2025)		
5C: TC-OBS updated with quantified uncertainty and multiple flight capability (Feb 2025)		
9C: Complete automation to run on operational systems (Mar 2025)	Testing in a functionally-similar operational	

	environment	
8C: Two manuscripts submitted for publication (Mar 2025)		
9D: Documentation and training materials completed (May 2025)	Documentation made available through online or internal resources	
7G: Demonstration begins of all capabilities at NHC on testbed resources (Jun 2025)	Demonstration in the operational environment	
9E: Third NHC visit to train forecasters on use of tools (Jun 2025)	In-person training, evaluation, and feedback	
9F: Codes available for operational transition (Jul 2025)	Codes begin running in operational environment (subject to acceptance)	
8D: Final report submitted (Aug 2025)		

4.2 Evaluation Criteria for Transition

To be considered ready for transition, the project's output must meet the following criteria:
- The analysis products of this project will be evaluated for the attributes of robustness, accuracy, improved representation of rapid variations, observed improvements in models, rated usefulness by forecasters, evidence of use by forecasters, and resulting time-savings to forecasters.
- The full evaluation protocols will be established early in the project through close coordination with NHC and HOT and revised throughout the project, as expressed in the Testing Plan.

4.3 Data Management

Data products generated by this project will be made accessible to the public free of charge as soon as they have been processed. The data will be hosted at NCAR on TCGP (http://hurricanes.ral.ucar.edu) and archived on the Tropical Cyclone Data Project (TCDP, http://verif.ral.ucar.edu/tcdata/) website. Long term storage, archiving, and provisions for access of all key datasets will be ensured through submission of the data products to the NOAA National Centers for Environmental Information

(NCEI) or another similar institutional repository. Project data will be preserved and made publicly available for no less than five years after the end of this project. The project datasets and research data products will be made discoverable through the use of NCAR's Digital Asset Search (DASH) service (https://data.ucar.edu/), which supports metadata archiving and data discovery for a wide range of digital assets. Data will normally be available in NetCDF format, a fully self-describing machine readable format, and will also be accompanied by machine-readable documentation (metadata), based on the NetCDF Climate and Forecast Metadata Conventions (CF conventions; http://cfconventions.org/), or a similar widely used international standard appropriate for each specific type of data. Images will be provided in PNG format. Project documents will use Portable Document Format (PDF). The total expected volume of data to be collected is 60 GB. The following table describes the types of data that are expected to be created by this project.

Description of data / *Tentative date when data will be made available*	**Prior Experience in making such data available**
Real-time VDM+ data products / *Within 1 minute of receipt of a new VDM*	VDM+ Dataset, v1.100 (Vigh et al. 2015, http://doi.org/10.5065/D61Z42GH); VDMs for current and past TCs are on the TCGP web site: http://hurricanes.ral.ucar.edu/structure/vortex/
Real-time FLIGHT+ data products / *Within 5-10 min of receipt of data*	FLIGHT+ Dataset, v1.3 (Vigh et al. 2021; http://doi.org/10.5065/D6WS8R93)
Real-time TC-OBS analyses) / *As soon as generated, every 15 minutes or sooner*	TC-OBS Database (Vigh et al. 2016, 2018; http://doi.org/10.5065/D6BC3X95)
SAMURAI analyses / *As soon as generated after receipt of input data are received/processed*	An example research dataset from SAMURAI analyses of Hurricane Michael (2018) is available at https://doi.org/10.5281/zenodo.5146325
Visualizations of the real-time observational data products / *As soon as generated as per processing above*	TCGP hosts a large number of forecast guidance plots; TCDP hosts many plots used for quality control/quality of the FLIGHT+, VDM+, and TC-OBS data products
Reports, papers, meeting minutes, and other relevant notes / *Within two weeks of being generated or published*	The project website for a previous HFIP-funded project is: https://ncar.github.io/tcprediction/

The proposal budget includes the costs of data preparation, accessibility, or archiving. The final pre-publication manuscripts of scholarly articles produced by this project will be submitted to the NOAA Institutional Repository after acceptance, and no later than upon publication. Access to this project's products will follow UCAR/NCAR privacy policy, terms of use and copyright/disclaimer, and will either be open access with registration, or will be released into the public domain under the

UCAR/NCAR terms of use policy (https://www.ucar.edu/terms-of-use/data). Appropriate citation and acknowledgement will be outlined and recommended.

5. Roles and Responsibilities

Entity/Office	Roles/Responsibilities	Team Members
OAR	Subject to availability of funds, the OAR Weather Program Office (WPO), will fund this project under NOAA cooperative agreement No. NA22OAR4590527, which describes the terms and conditions of this project, for a period of three years starting August 1, 2022. WPO will provide management oversight of the grant project. WPO will also provide infrastructure funds to support the testing and demonstration of this project's capabilities at the Hurricanes and Oceans Testbed (HOT).	
NWS	NHC will participate in the demonstration and evaluation of the diagnostics through the HOT and transition the analysis capabilities into their forecaster workflows where relevant. NHC HOT and Technology and Science Branch (TSB) staff will provide the PIs with technical standards to ensure that the resulting code is ready for operational transition at the end of the project. The NHC and HOT points of contact will provide invaluable critical feedback from NHC forecasters and guide the project to be fully responsive to NHC's operational priorities and the HOT program goals. They will assist in implementing the evaluation protocols at NHC. Pending NHC agreement to transition this project's results into operations, NHC support and/or assistance from the HOT Testbed will be needed to incorporate results into forecaster systems such as AWIPS-2 and the NHC HFIP Display, as well as to	Wallace Hogsett (NHC SOO) John Cangialosi (NHC HSU Senior Forecaster) Stephanie Stevenson (NHC TSB) Alan Brammer (HOT Facilitator)

	guide the transition of codes to full operations.	
Other	Principal Investigators and researchers at NCAR, CSU, and UM will perform the project tasks outlined above, with NCAR focusing on the transition of the FLIGHT+, VDM+, and TC-OBS capabilities and overall integration of project products. CSU will develop the unified parameterization and implement an operationally-tuned version of SAMURAI to produce the 2-d and 3-d gridded analyses. UM will contribute to the dropsonde and radar data processing and assist with the development of uncertainty estimates on the analyzed products. The PIs will also coordinate with the HOT facilitator as directed by NHC for demonstration and evaluation of the analysis products.	Jonathan Vigh (NCAR) Michael Bell (CSU) Jun Zhang (UM) Eric Hendricks (NCAR) Christopher Rozoff (NCAR) Jennifer DeHart (CSU) Alex DesRosiers (CSU)

6. Estimated Costs

The costs provided in this section are subject to the availability of appropriated funds. All transition costs are contingent upon the NWS decision regarding operational implementation. This is not a commitment of resources, but rather a documentation of the potential need for resources.

6.1 Cost of R&D

Subject to availability of appropriated funds, the final development and demonstration part of this project is funded by the Weather Program Office at a cost of $748,584 over 3 years from 08/01/2022 to 07/31/2025.

6.2 Cost of Transition

The transition cost provided in this section is subject to the availability of appropriated funds.

The integrated analysis system will be transitioned pending acceptance. If accepted, the system will be installed on suitable operational infrastructure, as determined by NWS staff . If NHC chooses to accept the system with Python, C++, NCL, and Julia codes, the total ROM transition cost estimate is negligible. If it is desired to port all NCL codes to Python, there could be a considerable transition cost on the order of $100,000 for additional software engineering. This estimate will be refined as the project progresses.

6.3 Cost of Operational System Maintenance

The cost provided in this section is contingent upon NWS's decision regarding operational implementation of this project, and subject to availability of appropriated funds.

Once the system is transitioned, no significant upgrades are planned. If any changes or bug fixes are made, however, any updates can be installed by NWS staff. Annually averaged ROM costs for NWS staff will be determined at a later stage in the project, at which time this document will be updated.

7. Risks and Mitigation

Risk 1 (20%): PI Vigh's portions of the work continue to be impacted by his fire recovery.

Mitigation 1: Monthly coordination between NCAR, CSU, and UM PIs will track progress through shared GitHub development repositories, issues, and Project Boards will help each project participant track progress to maintain the schedule and keep everyone informed of larger timeline concerns. If Vigh's fire recovery continues to impact the project timeline, additional time can be allocated to Co-PIs Hendricks and Rozoff to assist with some of Vigh's tasks.

Risk 2 (20%): Continuing COVID restrictions impacting in-person forecaster evaluation at NHC.

Mitigation 2: NHC forecasters will undertake virtual evaluation should in-person evaluation be limited or unavailable during the testing period.

Risk 3 (14%): A key personnel is lost or out of commission due to pandemic-related (or other) health issues.

Mitigation 3: Project effort can be reapportioned amongst the project personnel or other staff at the relevant institution.

Risk 4 (16%): A nuclear Electromagnetic Pulse (EMP) is detonated over the U.S. by its adversaries or there is a full-scale nuclear exchange.

Mitigation 4: Project codes will be stored on a computer or storage device protected from EMP and updated monthly as the project progresses. In the event of wide scale societal disruption from an EMP attack or nuclear exchange, surviving project staff may need to relocate outside of the U.S. and continue work as they are able. Delays of 5-10 years may occur as physical and human infrastructure is rebuilt. If project staff survive, transition activities can be continued once NOAA operations resume.

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