2023 NOAA/AOML/HRD Hurricane Field Program - APHEX

INTRODUCTION

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1. Description of the Advancing the Prediction of Hurricanes Experiment (APHEX)

One of the key aspects of NOAA's Mission is, "To understand and predict changes in the climate, weather, oceans, and coasts..." with a long-term goal of achieving a, "Weather-ready Nation," in which society is able to prepare for and respond to weather-related events. This objective specifies the need to improve the understanding and prediction of tropical cyclones (TCs). The NOAA/National Weather Service/National Hurricane Center (NHC) is responsible for forecasting TCs in the Atlantic and East Pacific basins, while NOAA/National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC) provides numerical weather prediction (NWP) forecast guidance for the forecasters. Together they have made great strides in improving forecasts of TC track. With support from the research community, forecast errors of TC track have decreased by about 50% over the past 30 years. However, there has been much less improvement in forecasts of TC intensity, structure, and rainfall. This lack of improvement is largely the result of deficiencies in routinely collecting inner-core data and assimilating it into the modeling system, limitations in the numerical models themselves, and gaps in understanding of the physics of TCs and their interaction with the environment. Accurate forecasts will rely heavily on the use of improved numerical modeling systems, which in turn will rely on accurate observational datasets for assimilation and validation.

The operational Hurricane Weather Research and Forecasting (HWRF) model uses an assortment of physical parameterizations intended to represent subgrid-scale processes important in TC evolution. Such a modeling system holds the potential of improving understanding and forecasting of TC track, intensity, structure, and rainfall. In order to realize such improvements, however, new data assimilation techniques must be developed and refined, physical parameterizations must be improved and adapted for TC environments, and the models must be reliably evaluated against detailed observations from a variety of TCs and their surrounding environments.

To conduct the research necessary to address the issues raised above, between 2005 and 2020 NOAA conducted an experiment designed to improve operational forecasts of TC intensity, called the Intensity Forecasting EXperiment (IFEX; Rogers et al., BAMS, 2006, 2013; Zawislak et al., BAMS 2022). Beginning in 2021, the NOAA Hurricane Field Program (HFP) was flown as the Advancing the Prediction of Hurricanes EXperiment (APHEX; Zawislak et al. 2022). APHEX broadens IFEX goals by incorporating current, 5-year Hurricane Forecast Improvement Program (HFIP) priorities around better forecasting and communicating for all storm hazards (wind, rain, surge, and tornadoes). These goals, developed through a partnership involving the NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML)'s Hurricane Research Division (HRD), NHC, and EMC, aim to improve operational forecasts of TC intensity, structure, and hazards by providing data to improve operational (e.g., the Hurricane Analysis and Forecast System (HAFS)) numerical modeling systems and by improving understanding of the relevant physical processes. These goals will be accomplished by satisfying a set of requirements and recommendations guiding the collection of the data:

- <u>GOAL 1:</u> Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation
- <u>GOAL 2:</u> Develop and refine measurement strategies and technologies that provide improved real-time analysis of TC intensity, structure, environment, and hazard assessment

- GOAL 3: Improve the understanding of physical processes that affect TC formation, intensity change, structure, and associated hazards

A unique, and critical, aspect of APHEX is the focus on providing measurements of TCs at all stages of their life cycle. While the focus of hurricane research flights during the past 40 years has been predominantly on mature storms, leading to a dataset biased toward these types of systems, APHEX continues a recent focus on the genesis and early stages of storms. This emphasis will not only provide critical observations during a period in the storm life cycle when there is perhaps the greatest uncertainty in the track and intensity forecasts, but also fills an observing gap during the early stages of a storm's development where case and composite studies have lacked.

2. Experiments Overview

HFP-APHEX includes experiments and modules for each stage of the TC life cycle: "Genesis", "Early", "Mature", and "End" of life cycle. Many of these experiments and modules are cross-cutting in terms of the APHEX goals (listed above) that they address.

The *"**Genesis Stage Experiment**"* consists of objectives that require observations during the pre-Tropical Depression (TD), or "Invest" (designated by NHC) period of a developing (or non-developing) storm. This overarching experiment includes 2 sub-experiments with goals that focus on progressively larger-scale aspects of a tropical disturbance:

1. **Favorable Air Mass (FAM) Experiment**: to collect observations of mid-level humidity and winds to assess the favorability of the disturbance's environment for tropical cyclogenesis. These aircraft observations may also provide helpful guidance for the expanded use of satellite observations in the absence of aircraft observations.
2. **Precipitation during Formation and Observing its Response across Multiple Scales (PREFORM)**: to use aircraft observations to investigate how precipitation (rainfall) within a tropical disturbance (such as an African easterly wave) is involved in the development and intensification of an incipient tropical storm circulation by sampling the characteristics of the precipitation, as well as the thermodynamic and wind structure of the circulation.

The *"**Early Stage Experiment**"* consists of objectives that require observations in TCs at TD, Tropical Storm (TS), or Category 1 hurricane intensity. This overarching experiment includes 6 sub-experiments and modules with goals that focus on early stage TCs:

1. **Analysis of Intensity Change Processes Experiment (AIPEX):** to understand the physical processes and structures that govern whether storms will intensify in conditions where there is a lack of rainfall coverage all around the center of the storm and there are prominent dry air masses in the environment that can be transported into the inner circulation.
2. **Convective Burst Structure and Evolution Module (CBM):** to sample the vertical motion and reflectivity structure of strong thunderstorm complexes at a high frequency (e.g., every 15–20 minutes, over a 1–2 h period) to observe how the structure of these systems change over time and as they move around the TC center, along with observing how those changes affect the structure and intensity of TCs.

3. **Flight-Level Assessment of Intensification in Moderate Shear (FLAIMS):** repeatedly sample the wind and precipitation structure of the region where the maximum wind speed is found). This begins similarly to a conventional figure-4 pattern, but after the center is fixed on the first pass, the outbound radial leg is along the same azimuth as the inbound leg. This pattern is then repeated throughout the flight (with full radial legs), thereby maximizing the temporal sampling of the region of maximum winds during a period that may lead up to and include the onset of RI.
4. **Impact of Targeted Observations on Forecasts (ITOFS) Experiment:** to use advanced guidance from multiple sets of forecast models to determine locations where aircraft observations could potentially improve forecasts of tropical cyclone track, intensity, and structure.
5. **Stratiform Spiral Module (SSM):** to sample the distribution of cloud and rain droplets and ice and snow particles and how those distributions vary with altitude across the freezing level in broad regions of relatively weak precipitation and upward motion.
6. **Vortex Alignment Module (VAM):** to acquire high-frequency temperature, moisture, and wind observations of the TC inner-core structure during the alignment process to identify how the TC structure and local environment evolves during alignment as well as potential precursors to vortex alignment and intensification.

The *"**Mature Stage Experiment**"* will consist of objectives that require observations in stronger hurricanes (Category 2 intensity or greater). Science objectives during this stage are separated into those that will evaluate internal processes to the TC and those that will investigate the interaction of a TC with its environment. This overarching experiment includes 11 sub-experiments and modules with goals that focus on mature stage TCs:

1. **Eye-Eyewall Mixing Module**: to observe the temperature, and humidity, and structure of small features in the eyewalls of very intense tropical cyclones have been hypothesized to increase the amount of energy available for hurricane intensification, or to be responsible for damaging surface wind at landfall or intense turbulence features impacting flight operations.
2. **Gravity Wave Module:** to collect data to quantify the characteristics of gravity waves in hurricanes and explore their potential relationship with storm intensity.
3. **NESDIS Ocean Winds, Waves, and Precipitation Experiment:** to collect fine resolution remote sensing of the atmosphere (winds and precipitation) and ocean surface (winds and waves) to support satellite calibration/validation and product improvement, to provide real-time data to NHC to support their decision making, and to improve the understanding of the interactions at air-sea interface in the TC environment.
4. **Research In Coordination with Operations Small Unmanned Aircraft Vehicle Experiment (RICO SUAVE):** to leverage NOAA's P-3 aircraft to deploy uncrewed assets into regions of the TC environment that are unsafe for crewed operations. The experimental goals are to improve physical understanding, situational awareness, and ultimately, TC operational forecasts of TC intensity change and short term track.

5. **Surface Wind Speed and Wave Validation Module:** to collect data in mature hurricanes to continue improving surface wind speed and rain rate estimates from the Stepped-Frequency Microwave Radiometer (SFMR). It will also verify surface wave observations and identify the extent of 8 ft significant wave height waves. The final module will collect data over buoys to simulate a time series of observations that can be used to understand the time-averaging inherent in the various surface wind speed observation types.
6. **TDR Analysis Evaluation Module:** Two P-3 aircraft will fly repeated orthogonal flight patterns through the eyewall region, staggered so that coincident TDR measurement of peak winds near flight level (close to the radar of one aircraft and at substantial distance from the radar of the other aircraft) may be accomplished. In addition to permitting evaluation of peak wind representation in TDR analyses, the overall robustness of HRD's 3-D wind analysis to flight track orientation will be assessed through direct comparison of overlapping, near-simultaneous analyses from the two aircraft.
7. **TC Diurnal Cycle Module:** to collect observations that improve the understanding of how day-night fluctuations in radiation affect the intensity and structure of hurricanes. One component of these oscillations is a phenomenon called the tropical cyclone diurnal cycle where the cloud fields of storms are seen to expand and contract each day. These daily expansions are associated with a pulse of thunderstorms and rain that travel hundreds of kilometers away from the storm center that affects the flow of air into the storm at the lowest levels above the ocean.
8. **TDR Dual-PRF Technique in Hurricanes Module:** A P-3 aircraft will fly a short pass through the eyewall of a mature hurricane while the TDR is running in dual-PRF (Pulse Repetition Frequency) mode. A dual-PRF technique permits extension of the Nyquist range of the TDR, reducing (or perhaps eliminating altogether) the need for dealiasing Doppler radial velocity in the hurricane core. Running in dual-PRF mode, however, introduces new errors. The developmental dataset collected from this module will be used to test a new method for correcting those errors and may ultimately lead to implementation of a new approach to NOAA TDR quality control that allows near real-time streaming of Doppler radials from the aircraft.
9. **Boundary Layer Wind Asymmetry and Distribution Examination Module:** to refine the accepted understanding of wind profiles within the boundary layer of TCs in both the inner and outer core by sampling the cyclone relative to its surface wind asymmetry. Data collected will be used to re-evaluate reduction assumptions asymmetrically, investigate wind distribution asymmetries in the boundary layer as they relate to wind hazards, and expose potential boundary layer biases in HAFS.
10. **Secondary Eyewall Formation (SEF) Module (to replace Rainband Complex Module):** to sample the structure of long, spiral bands of rainfall (rainbands) that often extend outward from the eyewall of strong hurricanes out to very large distances from the center. These rainbands, often containing mixtures of strong thunderstorms and lighter rainfall that can cover huge areas, are thought to affect the structure and intensity of the hurricane within which they are embedded, sometimes leading to the development of an outer eyewall where the surface wind field broadens. The data from this module will seek

to explore these structures and their potential relationship with hurricane structure and evolution.

11. **Hurricane Boundary Layer Module:** to improve our understanding of physical processes in the boundary layer that control the TC intensity change. These data can be used to evaluate and improve the performance of TC forecast models.

The ***"End Stage Experiment"*** consists of objectives that require observations in TCs making landfall, approaching the coastline, undergoing rapid weakening, or extratropical transition. This overarching experiment includes 2 sub-experiments and modules with goals that focus on end stage TCs:

1. **Extratropical Transition Experiment:** The changes to the thermodynamic structures of tropical cyclones as they encounter high-shear environments and/or cold surface water are not well understood or forecast, leading to large forecast errors when this occurs. The goal of this experiment is to sample tropical cyclones as they undergo this extratropical transition.
2. **Tropical Cyclones at Landfall Experiment:** Collect observations to validate near-shore surface TC wind speed estimates and to improve our understanding of the factors that modulate TC sustained and gust wind speed magnitude and tornado generation both prior to and after the time of landfall.

There are also several experiments/modules that cross-cut the TC life cycle stages with goals of satellite validation and understanding the response of hurricanes to changes in underlying ocean conditions. These additional experiments/modules in the 2023 HFP Plan (HFPP) include:

Ocean Observing Experiments

1. **Ocean Survey Experiment**: to collect observations targeted at better understanding the response of hurricanes to changes in underlying ocean conditions. New (or improved) technologies will be tested to fill gaps in the existing suite of airborne measurements of air-sea interaction processes.
2. **CHAOS (Coordinated Hurricane Atmosphere-Ocean Sampling):** CHAOS focuses on the coordination of diverse new observing platforms (i.e., autonomous, uncrewed, expendable) and conventional ones (e.g., aircraft) to support:
    - Sustained monitoring of the essential ocean features of the Gulf of Mexico and/or the Caribbean Sea – e.g., Loop Current Extension, eddy production, and freshwater barrier layers from the Mississippi & Amazon-Orinoco River Plumes
    - Targeted observing of the air-sea transition zone to improve the understanding of air-sea interactions for improved prediction of TC intensification, and/or
    - A combination of sustained and targeted observing approaches.

Satellite Validation Experiment

1. **Evaluation of the Tropical Transition Environment Using Satellite Soundings Experiment:** collocate GPS dropsondes with real-time satellite sounding products to

understand the near and surrounding environment of pre-Tropical Cyclones and/or Tropical Cyclones. The focus of this year's flights is extratropical transition, tropical transitions, and invests, if useful cases arise. This module will also explore the value of satellite soundings for Tropical Cyclone monitoring and forecasting using newly developed web-based and software tools.

2. **TROPICS Satellite Validation Module:** to calibrate and validate temperature, moisture, and precipitation measurements obtained from the new TROPICS satellites. These profiles will be compared to NOAA P-3 and G-IV aircraft observations, whose flight patterns will be coordinated in space and time with overpasses from the satellite.

3. HFP Plan Organization

The HFP-APHEX experiment and modules documents discussed in Sec. 2 are available at: https://www.aoml.noaa.gov/2023-hurricane-field-program/

Each experiment/module includes 2 elements that provide the information needed for the PIs, HRD HFP FIELD PROGRAM DIRECTOR (**Jason Dunion**), DEPUTY DIRECTOR (**Heather Holbach**), SCIENCE DIRECTOR (**Rob Rogers**), and AOC aircraft crew to effectively plan and execute a mission associated with an experiment.

Science Description

- This element provides an overview of the experiment/module science, including plain language description, links to NOAA APHEX, motivation, background, goals, scientific hypotheses, objectives, high-level overviews of proposed aircraft flight patterns, links to other APHEX experiments/modules, and data analysis strategies.

Flight Pattern Descriptions

- This element provides comprehensive descriptions of the mission execution, including details of what and when to target, flight pattern designs, and requirements for expendables and aircraft instruments.
- “Patterns” refers to missions that require an entire dedicated mission (i.e., generally greater than 3 h of flight time). “Modules” refer to break-away (e.g., from the “standard” patterns described APPENDIX A), shorter flight segments that generally require less than 3 h or less of flight time for completion.
- Multiple “Patterns” and “Modules” are possible for each experiment/module and are numbered sequentially. In most cases (unless otherwise noted), “Patterns” will be identified as one of the “standard” patterns, illustrated in APPENDIX A (e.g., Lawnmower, Square-spiral, Figure-4, Rotated Figure-4, Butterfly). Many of the “Patterns” outlined in the experiments are “standard” patterns that are subsequently modified to meet the sampling needs of the science objective(s).

References:

Rogers, R., and co-authors, 2006: The Intensity Forecast Experiment: A NOAA multiyear field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc.*, **87**, 1523–1537.

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Zawislak, J., and co-authors, 2022: Accomplishments of NOAA's Airborne Hurricane Field Program and a Broader Future Approach to Forecast Improvement, *Bulletin of the American Meteorological Society*, ***103*****(2)**, E311-E338. Retrieved Jun 1, 2022, from https://journals.ametsoc.org/view/journals/bams/103/2/BAMS-D-20-0174.1.xml