INTRODUCTION

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 Analysis and Forecast System (HAFS) 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**: proposes 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. Efforts will also include collaborations with the 2024 ONR MAGPIE and ORCESTRA field campaigns.
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 (i.e., a pre-TC, 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 within which the precipitation occurs.

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. **Flight-Level Assessment of Intensification in Moderate Shear (FLAIMS):** repeatedly samples the region of maximum wind speed for weak, but intensifying tropical cyclones (TCs), in order to assess the temporal evolution of both the wind and precipitation fields. Such TCs are often asymmetric, and substantial intensification can occur on short time scales (1-2 hours or less). By focusing on the part of the storm where the strong winds and

rain exist, we can be able to capture these changes, which is important for understanding how intensification begins.

2. **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.
3. **Stratiform Spiral Module (SSM):** samples 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.
4. **TDR Dual-PRF Technique in Hurricanes Module:** to collect P3 radar data from a tropical cyclone while running the system in dual-PRF (Pulse Repetition Frequency) mode. Operating radars in this way is done to mitigate the occurrence of velocity ambiguities. The dataset will be used to test a method for correcting data errors introduced when operating in dual-PRF mode. A successful test may ultimately lead to implementation of a new approach to NOAA radar quality control that allows near real-time streaming of radar data from the aircraft rather than transmission only after a complete transect through the storm, as is presently done.
5. **Vortex Alignment Module (VAM):** improve our understanding of the alignment process through the collection of relatively-high frequency observations of the three-dimensional TC structure.

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. **Distribution of Hazardous Winds:** to refine assumptions asymmetrically, estimate the uncertainty in quadrant wind radii, investigate asymmetries in the boundary layer as they relate to wind and wave hazards, and expose potential boundary layer biases in numerical weather and climate models.
2. **Eye-Eyewall Mixing Module**: to observe the temperature, and humidity, and structure of small features in the eyewalls of very intense tropical cyclones that could increase the amount of energy available for hurricane intensification or cause damaging surface wind at landfall or intense turbulence features impacting flight operations.
3. **Gravity Wave Module:** to collect data to quantify the characteristics of the gravity waves in mature-stage hurricanes and their relationship with storm intensity and intensity change.
4. **NESDIS Ocean Winds, Waves, and Precipitation Experiment:** to improve our understanding of microwave retrievals of the ocean surface and atmospheric wind fields, to evaluate new remote sensing techniques/technologies, to help validate satellite-based sensors of the ocean surface in extreme conditions and reduce risk for future satellite

mission, and to provide forecasters with near-real-time hurricane boundary layer profiles, where possible.

5. **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 operational forecasts of TC track and intensity.
6. **Surface Wind and Wave Validation Module**: This module will collect data in mature hurricanes to continue improving surface wind speed and rain rate estimates from the Stepped-Frequency Microwave Radiometer (SFMR) and understand how the wind speed observations from the SFMR, flight-level winds, dropsondes, tail-Doppler radar (TDR) and, Imaging Wind and Rain Airborne Profiler (IWRAP) should be averaged and adjusted to statistically consistent 1-minute mean (or sustained) winds. Additionally, surface wave observations will be verified and the extent of 8 ft significant wave height waves will be identified. Improved measurements from the SFMR and understanding how the various aircraft-based wind observations should be averaged and adjusted to statistically consistent 1-minute mean winds along with improving our knowledge of the surface wave field have numerous implications for forecasting and research efforts, such as providing more accurate observations to estimate tropical cyclone (TC) intensity and size along with improved estimates of marine hazards and comparisons for satellite observations. These improvements allow for better watches and warnings for a TC's potential impacts to be provided to emergency managers and the general public and leads to more accurate research results.
7. **TDR Analysis Evaluation Module:** to provide three-dimensional wind analyses derived from two P-3 aircraft equipped with tail-Doppler radar (TDR) and flying simultaneous, perpendicular transects through the hurricane eyewall are compared in an evaluation of the Doppler-radar wind analysis method.
8. **Ventilation Module:** to collect observational data to study ventilation pathways, validate model simulations of ventilation in TCs, and assess the link between ventilation and intensity changes.

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:** to sample tropical cyclones as they undergo this extratropical transition, aiming to improve forecasts of these systems. The mechanisms by which tropical cyclones become extratropical is not well forecast by numerical models leading to large errors, especially in impacts downstream of the actual transitioning cyclone. The changes to the thermodynamic structures of tropical cyclones as they encounter high-shear environments and/or cold surface water are also not well understood.

2. **Tropical Cyclones at Landfall Experiment:** seeks to utilize P-3 aircraft, land-based mobile research team instrumentation, and ocean-based uncrewed surface vehicles to collect data in landfalling TCs to improve both our understanding and capability to predict the dangerous phenomena often associated with these landfalling systems.

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. **CHAOS (Coordinated Hurricane Atmosphere-Ocean Sampling):** CHAOS focuses on the coordination of a diverse suite of innovative observing platforms (i.e., autonomous, uncrewed, expendable) and conventional ones (e.g., aircraft) to support:
    - Targeted coordinated observations of the air-sea transition zone to improve the understanding of air-sea interactions, including the ocean's response and recovery to tropical cyclone (TC) forcing, and for improved prediction and modeling of TC intensification changes.
    - Coordinated atmospheric and oceanic observations with sustained monitoring of key ocean features of the Gulf of Mexico, tropical Atlantic, and/or the Caribbean Sea – e.g., Loop Current, Gulf Stream, eddies and rings, and freshwater barrier layers from the Mississippi & Amazon-Orinoco River Plumes.
2. **Ocean Survey Experiment**: to provide a unique opportunity to evaluate how well coupled forecast models represent these lowest regions of storms. The new type of observations that are collected should help improve the model initialization and inform how coupled forecast models represent interactions between the ocean and atmosphere in hurricanes.
3. **Tropical Cyclone Boundary Layer Module:** to collect observational data to improve our understanding of physical processes in the boundary layer that control the TC intensity change. This data can be used to evaluate and improve the performance of TC forecast models such as the Hurricane Analysis and Forecast System (HAFS).

Satellite Validation Experiment

1. **SARWIND:** seeks to use aircraft observations to better validate high-resolution surface wind speed measurements becoming more frequently available with Synthetic Aperture Radar (SAR) polar orbiting passes. This will be accomplished by coordinating NOAA P-3 flights to occur simultaneously with an orbiting SAR pass near a TC or other ocean environments deemed research relevant to sample the wind and wave interface near the surface.
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/2024-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 (**Gus Alaka**), SCIENCE DIRECTOR (**Jason Sippel**), 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:

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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