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 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 2021). Beginning in 2021, the NOAA hurricane field program 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 were developed through a partnership involving the NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML)'s Hurricane Research Division (HRD), NHC, and EMC, are to improve operational forecasts of TC intensity, structure, and rainfall by providing data to improve the operational numerical modeling system (i.e., HWRF) 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

- GOAL 2: 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.

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 4 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 the storm circulation is tilted in the vertical with 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. **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.
4. **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.

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 10 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 quantify the characteristics of gravity waves emanating from mature-stage hurricanes and their relationship with storm intensity and intensity change. These data could also provide valuable information for model evaluation and physics improvement.
3. **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.
4. **NESDIS Ocean Winds Experiment:** to improve our understanding of microwave retrievals of the ocean surface and atmospheric wind fields, and 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 missions. To provide forecasters with near-real-time hurricane boundary layer profiles, where possible.
5. **Rainband Complex Module RCM):** to explore spiral bands of rainfall (rainbands) in hurricanes and their potential relationship with storm structure and evolution.

6. **Research In Coordination with Operations Small Unmanned Aircraft Vehicle Experiment (RICO SUAVE):** to use small drones, instead of crewed aircraft, to sample the lowest and most dangerous regions of the TC. It is believed that observations from these unique platforms will improve basic understanding and enhance forecaster situational awareness. Detailed analyses of data collected from these small drones also have the potential to improve the physics of computer models that predict changes in storm intensity.
7. **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 SFMR and understand how the wind speed observations from the SFMR, flight-level winds, dropsondes, tail-Doppler radar and, Imaging Wind and Rain Airborne Profiler (IWRAP) relate to each other and to a 1-minute mean (or sustained) wind. It will also aid the development of surface wind products from synthetic aperture radar (SAR) satellites. 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.
8. **TDR Analysis Evaluation Module:** 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. Through this evaluation, we seek to gain a better understanding of how to relate radar-derived peak wind speed and other aspects of hurricane wind structure to similar estimates using conventional observations.
9. **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.
10. **Ventilation Module:** Ventilation occurs when drier and/or cooler environmental air intrudes into a vertically sheared tropical cyclone (TC). Ventilation pathways include lateral intrusion (radial ventilation) and downward intrusion (downdraft ventilation) of dry and/or cool air. Both pathways may weaken a TC or delay its intensification. This module aims to collect observational data to study ventilation pathways, validate model simulations of ventilation in sheared 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:** tropical cyclones can either decay (spin down) or transform into powerful extratropical cyclones when they encounter cold water below or high wind shear in the atmosphere. 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. This experiment aims to improve forecasts of these systems.
2. **Tropical Cyclones at Landfall Experiment:** landfalling TCs often produce a variety of high impact weather over land including tornadoes and damaging winds (particularly gusts) for which there exists limited objective forecast guidance. Thus, our experiment seeks to utilize P-3 aircraft and land-based mobile research team instruments 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 2022 HFP Plan (HFPP) include:

Ocean Observing Experiments

1. **Ocean Survey Experiment**: to evaluate how well forecast models represent the lowest region of the atmosphere just above the ocean surface in hurricanes. The observations that are collected should help improve how forecast models represent interactions between the ocean and atmosphere in hurricanes.
2. **Sustained and Targeted Ocean Observations Module:** to provide ocean observations that will serve for analysis to improve the ocean representation in hurricane forecast coupled models, improve our understanding of the air-sea transition zone (the upper ocean, air-sea interface, and marine atmospheric boundary layer), and to increase situational awareness about the types of ocean observations available. Sustained and targeted ocean observations will be directed to monitor essential ocean features (e.g., ocean currents, eddies, warm pools, freshwater barrier layers, and subsurface cool pools) known to be linked to TC changes for use in analysis and to improve the ocean representation in coupled models to forecast TC intensity. Sustained (year-round) and seasonal observations will be mainly conducted from underwater gliders, saildrones, Argo floats, drifters, and XBTs, while targeted observations may also come from these observing platforms plus from air-deployed assets (ALAMO floats, drifters, AXBTs) and airborne remote sensing instruments, some of which are described in other modules, and from specifically designed operations to help better assess the ocean impact on TCs (e.g., co-located saildrones-glider pairs).

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/2022-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 (Jonathan Zawislak), 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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