INTRODUCTION

1. Description of Intensity Forecasting Experiment (IFEX)

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, since 2005 NOAA has been conducting an experiment designed to improve operational forecasts of TC intensity, called the Intensity Forecasting EXperiment (IFEX; Rogers et al., BAMS, 2006, 2013). The IFEX goals, 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
- <u>GOAL 2:</u> Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment
- <u>GOAL 3:</u> Improve understanding of the physical processes important in intensity change for a TC at all stages of its life cycle

A unique, and critical, aspect of IFEX 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 30 years has been predominantly on mature storms, leading to a dataset biased toward these types of systems, IFEX now also places a 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-IFEX 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 investigate the favorability in both dynamics (e.g., vertical wind shear) and thermodynamics (e.g., moisture) for tropical cyclogenesis in the environment near a pre-tropical depression, especially the downstream environment.
2. **Precipitation during Formation and Observing its Response across Multiple Scales (PREFORM)**: to investigate the mesoscale distributions of various precipitation modes that are prevalent during the genesis stage, the evolution of their key characteristics (e.g., areal coverage and intensity), and how they are involved in the development and intensification of an incipient tropical storm circulation by also understanding the link between precipitation properties and the local pouch and environmental characteristics (e.g., vertical wind shear, moisture, and relative humidity).

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 5 sub-experiments and modules with goals that focus on early stage TCs:

1. **Analysis of Intensity Change Processes Experiment (AIPEX):** to collect aircraft observations that will allow us to characterize the precipitation and vortex-scale kinematic and thermodynamic structures of TCs experiencing moderate vertical shear. Understanding the reasons behind these structures, particularly greater azimuthal coverage of precipitation, vortex alignment, and boundary layer ventilation and recovery, will contribute toward a greater understanding of the physical processes that govern whether TCs will intensify, (especially those that undergo RI) in this type of environment.
2. **Boundary Layer Module:** To better understand details of boundary layer structure and evolution before and during TC intensification.
3. **Convective Burst Structure and Evolution Module (CBM):** to obtain a quantitative description of the kinematic and thermodynamic structure and evolution of intense

convective systems (convective bursts) and the nearby environment to examine their role in TC intensity change.

4. **Gravity Wave Module:** to collect observations for improving our understanding of the characteristics of gravity waves in early-stage hurricanes. Quantify how the characteristics of these waves are related to hurricane intensity and intensity change.
5. **Surface Wind Speed and Significant Wave Height Validation Module:** to improve the wind speed and rain rate estimates obtained by the P-3 SFMRs. Improve NHC/TAFB's High Seas analyses and forecasts and NOAA's Wavewatch III ocean model by collecting WSRA significant wave height data in the environment of TCs.

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 8 sub-experiments and modules with goals that focus on mature stage TCs:

1. **Eye-Eyewall Mixing Module**: to measure the kinematic and thermodynamic structures of miso- and meso-vortices in the eye with dropsondes, and in the eyewall with flight-level data. The long-term goal is to test whether these features are important for intensity change.
2. **Gravity Wave Module:** to collect observations for improving our understanding of the characteristics of gravity waves in mature-stage hurricanes. Quantify how the characteristics of these waves are related to hurricane intensity and intensity change.
3. **NESDIS Ocean Winds Experiment:** to improve our understanding of microwave scatterometer retrievals of the ocean surface wind field and to evaluate new remote sensing techniques/technologies.
4. **Rainband Complex Module:** to improve understanding of the dynamic and microphysical processes of the mature rainband complex and role in storm evolution.
5. **Research In Coordination with Operations Small Unmanned Aircraft Vehicle Experiment (RICO SUAVE):** to collect PTHU observations within the high wind eyewall and boundary layer inflow regions of mature hurricanes and provide real-time data of winds to improve operational situation awareness (RMW, VMax). A longer-term goal is to improve basic understanding of a sparsely-sampled, yet critically important region of the storm where turbulent exchanges of heat, moisture, and momentum with the ocean and eye-eyewall interfaces regularly occur. These observational data will also be used to evaluate operational model performance as it relates to boundary layer thermodynamic and kinematic structure and SST ocean response.
6. **Surface Wind Speed and Significant Wave Height Validation Module:** to improve the wind speed and rain rate estimates obtained by the P-3 SFMRs. Improve NHC/TAFB's High Seas analyses and forecasts and NOAA's Wavewatch III ocean model by collecting WSRA significant wave height data in the environment of TCs.
7. **TC Diurnal Cycle Experiment:** to collect observations targeted at better understanding how radiative processes, particularly the TCDC, affect hurricane intensity and structure

and the environment surrounding the storm. This experiment will also investigate how the TCDC impacts day-night oscillations of the full 3-D circulation of these storms, particularly winds in the lower and middle levels (inflow and outflow) and the upper-level cirrus canopy (outflow).

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. **Tropical Cyclones at Landfall Experiment:** to employ the P-3 aircraft to collect thermodynamic and kinematic observations in landfalling TCS to better understand the mechanisms that modulate a TC's potential for producing tornadoes, to investigate the factors that control both the magnitude of the wind gusts and rate of decay of the sustained wind both at and after landfall, and to reduce the uncertainty in SFMR wind speed estimates in coastal regions.

There are also several experiments/modules that cross-cut the TC life cycle stages with goals of satellite validation, understanding the response of hurricanes to changes in underlying ocean conditions, and developing new sampling strategies for optimizing the use of aircraft observations to improve model forecasts. These additional experiments/modules in the 2020 HFP Plan (HFPP) include:

- **Satellite Validation Experiments**
  - ***ADM-Aeolus Satellite Validation Module:*** to coordinate P-3 Orion and G-IV under-flights of the ADM-Aeolus satellite that will provide opportunities to calibrate and validate the satellite-based wind observations against the remote sensing and in situ observations that will be collected by the NOAA aircraft.
  - ***NESDIS JPSS Satellite Validation Experiment:*** to use GPS dropsondes launched from the NOAA G-IV jet to validate NUCAPS 3- dimensional temperature and moisture profiles produced from the NOAA-20 and Suomi-NPP polar orbiting satellites. Use GPS dropsonde data to assess the skill of NUCAPS soundings and evaluate analyses from the GFS and FV3-GFS models.
- **Ocean Survey Experiment:** to collect observations targeted at better understanding the response of hurricanes to changes in underlying ocean conditions. Evaluate and improve TC model physics related to air-sea interaction.
- **Synoptic Flow Experiment:** to investigate new sampling strategies for optimizing the use of aircraft observations to improve model forecasts of TC track, intensity, and structure.

3. HFP Plan Organization

The HFP-IFEX experiment and modules documents discussed in Sec. 2 are available at: https://www.aoml.noaa.gov/2020-hurricane-field-program/

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

i. Science Description

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

ii. 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.

Rogers, R., and co-authors, 2013: NOAA's Hurricane Intensity Forecasting Experiment: A Progress Report. *Bull. Amer. Meteor. Soc.*, **94**, 859–882.