INTRODUCTION

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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:

- GOAL 1: Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation
- GOAL 2: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment
- GOAL 3: 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 storms development where case and composite studies have lacked.

2. Experiments Overview

This season, HFP-IFEX includes experiments 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 3 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. **Pouch Evolution during Genesis (Pouch) Experiment:** to investigate the importance of the pouch, including the shear sheath, which tends to indicate a tropical storm, and its relationship to a low-level circulation and organized deep convection within the pouch
3. **Precipitation Mode (PMODE) Experiment:** to investigate the precipitation modes (e.g., stratiform or convective precipitation) that are prevalent during the genesis stage, the evolution of key characteristics (e.g., areal coverage and intensity of precipitation), and the response of the potentially developing vortex to the observed precipitation organization

INTRODUCTION

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 collect aircraft observations (i.e., tail Doppler radar, lower fuselage radar, dropsonde, flight-level data, Doppler Wind Lidar, and stepped-frequency microwave radiometer) 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 and vortex alignment, will contribute toward a greater understanding of the physical processes that govern whether TCs will intensify in this type of environment.
2. **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.
3. **Airborne Doppler Wind Lidar (DWL) Module:** to create a more comprehensive 3-D analysis of the wind field within a TC through the addition of DWL observations to existing wind observing platforms.
4. **Gravity Wave Module:** to collect observations for improving our understanding of the characteristics of gravity waves in early-stage hurricanes and to quantify how the characteristics of these waves are related to hurricane intensity and intensity change. The observational data collected in this module will also be used to evaluate the hurricane structure in hurricane model simulations.
5. **Stepped-Frequency Microwave Radiometer (SFMR) Module:** to improve the wind speed and rain rate estimates obtained by the P-3 and G-IV Stepped-Frequency Microwave Radiometers (SFMR). For the P-3 SFMR, we aim to be able to obtain wind speed and rain rate estimates when the aircraft is not flying straight and level. For the G-IV SFMR, we aim to develop algorithm corrections to retrieve wind speed and rain rates from a higher altitude.
6. **Tail Doppler Radar (TDR) Experiment:** to provide real-time quality-controlled airborne Doppler-radar radial velocities, as well as Doppler wind fields in the form of three-dimensional Cartesian analyses, and vertical cross-sections of analyzed wind along the inbound and outbound radial flight tracks, to EMC, NHC, and CPHC. A new goal is determining whether the three-dimensional analyses can provide better information for assimilation than the more raw Doppler radial velocities. Another goal is to begin to test assimilation of TDR radar reflectivity.

INTRODUCTION

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. **Environment Interaction (TC in Shear) Experiment:** collect observations targeted at better understanding the response of mature hurricanes to changes in vertical wind shear, the variation in speed and direction with height of the winds surrounding a storm.
2. **Eye-Eyewall Mixing Module:** to gain greater understanding of the structure of eyewall miso- and meso-scale vortices and their ultimate impact on intensity changes.
3. **Gravity Wave Module:** to collect observations to improve our understanding of the characteristics of gravity waves in hurricanes, that radiate outward from the hurricane core. The goal is to quantify how the characteristics of these waves are related to hurricane intensity and intensity change. The observational data collected in this module will also be used to evaluate the hurricane structure in hurricane model simulations.
4. **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.
5. **Secondary Eyewall Formation Module:** to sample the TC inner core convection and environment when secondary eyewall formation (SEF) appears likely to occur or has already occurred within the storm. The module will provide critical observations for improving the understanding of the dynamic and physical processes of SEFs and eyewall replacement cycles, which have impacts on storm intensity and structure.
6. **Stepped-Frequency Microwave Radiometer Module:** to improve the wind speed and rain rate estimates obtained by the P-3 and G-IV Stepped-Frequency Microwave Radiometers (SFMR). For the P-3 SFMR, we aim to improve the high wind speed retrievals and to be able to obtain wind speed and rain rate estimates when the aircraft is not flying straight and level. For the G-IV SFMR, we aim to develop algorithm corrections to retrieve wind speed and rain rates from a higher altitude.
7. **Tail Doppler Radar (TDR) Experiment:** to provide real-time quality-controlled airborne Doppler-radar radial velocities, as well as Doppler wind fields in the form of three-dimensional Cartesian analyses, and vertical cross-sections of analyzed wind along the inbound and outbound radial flight tracks, to EMC, NHC, and CPHC. A new goal is determining whether the three-dimensional analyses can provide better information for assimilation than the more raw Doppler radial velocities. Another goal is to begin to test assimilation of TDR radar reflectivity.
8. **TC Diurnal Cycle Experiment:** collect observations targeted at better understanding how the tropical cyclone (TC) diurnal cycle affects hurricane intensity and structure and the environment surrounding the storm. This experiment will also investigate how the TC

diurnal cycle impacts day-night oscillations of winds in the lower and middle levels (inflow and outflow) and the upper-level cirrus canopy (outflow) of these storms.

The *"End Stage Experiment"* consists of objectives that require observations in TCs making landfall, 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 gain greater understanding of the extratropical-transition process with the ultimate goal of improving forecasts of these potentially high-impact events.
2. **Tropical Cyclones at Landfall Experiment:** to better understand the mechanisms that modulate a TCs potential for producing tornadoes, 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 reduce the uncertainty in SFMR wind speed estimates in coastal regions.

Additional experiments/modules in the 2019 HFP Plan (HFPP) include:

- **Satellite Validation Experiment**
  - ***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 and aerosol 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 3-dimensional temperature and moisture profiles produced from the NOAA-20 and Suomi-NPP polar orbiting satellites. The skill of these atmospheric profiles, created using the NOAA Unique Combined Atmospheric Processing System (NUCAPS) algorithm will be assessed using GPS dropsonde data and will also be used to 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. The observational data collected in this experiment will be used to evaluate and improve hurricane 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 tropical cyclone 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/hrd/HFP2019/index.html

Each experiment/module includes 3 elements that provide the information needed for the PIs, HRD HFP FIELD PROGRAM DIRECTOR (Jonathan Zawislak), DEPUTY DIRECTOR (Lisa Bucci), SCIENCE DIRECTOR (Jason Dunion), and AOC aircraft crew to effectively plan and execute a mission associated with an experiment.

i. **Science Goals & Observational Applications**
   - This element includes a high-level description of the experiment/module goal(s) and the IFEX goal(s) that it links to (see Sec. 1). It also links the observations that will be collected in the field back to IFEX numerical modeling efforts, including initialization and evaluation, optimizing targeting strategies, and data impact studies (e.g., OSSEs and OSEs).

ii. **Science Description**
   - This element provides an overview of the experiment/module science, including objectives, motivation, background, scientific hypotheses, high-level overviews of proposed aircraft flight patterns, links to other HRD experiments/modules, and data analysis strategies.

iii. **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.