GENESIS STAGE EXPERIMENT
Science Description

Experiment/Module: Favorable Air Mass (FAM)

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Requirements: Pre-genesis disturbances (pre-tropical cyclones; pre-TCs), including NHC-designated "Invests"

Plain Language Description: Although the ingredients for tropical cyclone formation have been well-documented for decades, it is still difficult to predict which disturbances will develop and which ones will not. A big factor in this uncertainty is the favorability of the air mass ahead of, and interacting with, the disturbance. This 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.

Genesis Stage Science Objective(s) Addressed:

The overarching objective is to investigate the physical processes that determine if a pre-genesis disturbance will mature into a tropical cyclone (TC), including the organization of convection and the development of a closed low-level circulation.

1) To investigate the favorability in both dynamics (e.g., vertical wind shear) and thermodynamics (e.g., moisture, stability) for tropical cyclogenesis in the environment near a pre-TC, especially the downstream environment [*APHEX Goal 3*].

Motivation: The environment near a pre-TC is critical to the favorability for tropical cyclogenesis to occur. The probability of cyclogenesis for a given pre-TC, such as an African easterly wave, is dependent upon thermodynamics (e.g., moisture, relative humidity) and dynamics (e.g., vertical wind shear) in the adjacent air mass(es). Increased observations of lower- and mid-tropospheric humidity in the near-disturbance environment would shed light upon critical moisture thresholds important (or necessary) for tropical cyclogenesis and would help correct moisture biases in numerical weather prediction models. The downstream environment is most important for cyclogenesis predictions because that is the environment that a pre-TC moves into.

Background: As early as the 1930s, westward propagating disturbances in the lower troposphere were identified as seed circulations for most TCs in the North Atlantic Ocean (Dunn 1940). The origins of these pre-genesis disturbances, or pre-tropical cyclones (pre-TCs), were traced back to North Africa and are now known as African easterly waves (AEWs; Riehl 1945). About 70% of all TCs and, more impressively, 85% of major hurricanes in the North Atlantic Ocean have been found to initiate from AEWs (Landsea 1993). On average, sixty AEWs exit the West African coast each year. However, determining which of these AEWs will develop into TCs has proven to be a forecasting challenge. For example, over 50% of TC genesis events in the Atlantic main development region predicted by the Global Forecast System (GFS) from 2004–2011 were false alarms (Halperin et al. 2013).

Recent research has shed some light on the relationship between AEWs and TC genesis in the North Atlantic Ocean. The AEW-relative flow around an incipient disturbance has been hypothesized to be an important factor in protecting the disturbance from environmental intrusions, and thus creating or maintaining a favorable environment for TC genesis to occur (Dunkerton et al. 2009). Brammer and Thorncroft (2015) have shown that, as AEWs leave West Africa, the troughs are sensitive to the low-level environment to their west and northwest. Although the vortex at 700 hPa typically has a closed circulation in the wave-relative reference frame, the AEW troughs are still cold-core in the lower troposphere and, therefore, there is relative westerly flow under the vortex and through the lower levels of the trough. In a composite analysis, significant differences in the moisture of the low-level environment to the northwest of the troughs were found between developing and non-developing waves. Favorable developing waves had significantly higher moisture content in the lower troposphere to the northwest of the trough as they exited the West African coast compared to favorable non-developing waves. Trajectory analysis for all the waves revealed that as the AEWs transition over the West African coast the troughs are typically open to the environment ahead and to the northwest of the trough. For developing waves this means that moist air (e.g., moist tropical sounding, Dunion 2011) is ingested into the lower levels of the system, while for non-developing waves dry air (e.g., SAL or mid-latitude dry air intrusion soundings) is ingested. At this stage in the AEW life cycle, moisture differences may be fundamental in determining whether a favorable wave will develop or not.

The depth and the integrity of the closed circulation around the pre-genesis disturbance is an important consideration for providing a convectively favorable environment for TC genesis. Freismuth et al. (2016) argue that the vortex of ex-Gaston (2010) was susceptible to dry air above the vortex maxima, which hindered deep convection and led to a weakening of the vortex. In addition, non-developing disturbance AL90 (2014) encountered lower tropospheric dry air to its west and northwest, which was ingested by the disturbance and was likely a major contributor in the failed genesis. Brammer and Thorncroft (2017) showed that as AEWs leave the West African coast there is an increase in air parcel trajectories reaching the AEW circulation from low-levels to northwest of the trough circulation. Although the AEW troughs typically possess closed circulations at 700–600 hPa as they leave the West African coast, the circulation can remain open to the environment both above and below the 700–600-hPa layer. As AEWs propagate across the North Atlantic, the troughs are more likely to exhibit closed circulations at low-levels due to either increased vorticity within the trough or the changing background shear profile over the central Atlantic. It was therefore hypothesized that AEWs are especially sensitive to the low-level environment to the west and northwest of the trough during the first three days after leaving the West African coast. Since AEWs typically propagate at 7.5 m s^{-1} over the Atlantic (Kiladis et al. 2006), these waves are typically located near 35°W after three days.

Goal(s): To investigate the favorability in both dynamics (e.g., vertical wind shear) and thermodynamics (e.g., moisture, relative humidity) for tropical cyclogenesis in the environment near a pre-tropical depression, especially the downstream environment.

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Hypotheses:

1. Environmental air downstream from a pre-TC (or AEW trough axis) is ingested before the low-level circulation is closed.
2. High environmental relative humidity to the West or Northwest and low environmental vertical wind shear in the vicinity of a pre-TC are critical for a disturbance to develop into a tropical cyclone.
3. Dry air, often associated with but not limited to the Saharan Air Layer (SAL), inhibits or delays genesis of pre-TCs.

Objectives:

1. Collect aircraft observations of thermodynamics and dynamics in the air mass surrounding and ahead of a pre-TC.
2. Consecutive missions are recommended to observe the evolution of the observations over time and how that pertains to the (non-)development of a pre-TC.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information):

G-IV Pattern #1: Sample the environment to the west of a pre-tropical cyclone (pre-TC), especially if dry air is detected in that region. Sample when the pre-TC is forecast to develop in reliable computer models or is showing signs of development in observations. Standard Lawnmower pattern should be used to set up a grid of observations and dropsondes, with drops every 150 n mi (280 km). The most likely orientation of the lawnmower pattern will be to the West or Northwest of the pre-TC. To maximize the usefulness of the data, a minimum of two lawnmower legs should be flown. In some situations, the same box could be flown twice to maximize data coverage in a more specific region.

P-3 Pattern #1: G-IV Pattern #1 (described above) can be modified to accommodate the P-3. Flight level should be 20-25 kft to maximize the altitude of dropsonde data. P-3 missions will likely start later than G-IV missions due to the greater range of the G-IV, especially if the disturbance is in the Atlantic Main Development Region.

Links to Other Genesis Stage Experiments/Modules: This experiment is ideally suited to include sampling of the disturbance itself, including the vorticity maximum and precipitation properties identified from the TDR, and thus the PREFORM experiment (also part of the Genesis Stage). Of course, special consideration must be given to the length of the flight and the distance of the disturbance from the takeoff/landing airport(s). It may be especially fruitful to evaluate the relative humidity in the environment ahead of a disturbance and consequently investigate the precipitation properties within the disturbance itself. The FAM observing strategy is ideally flown in support of the Impact of Targeted Observations on Forecasts, especially the 2022 ITOFS – East

Atlantic (ITOFS-East) experiment (description below) that will be flown from the Cabo Verde Islands.

ITOFS-East: The overarching objective of ITOFS-East is to fly the NOAA G-IV to collect rare measurements of tropical disturbances and tropical cyclones in their very early stages of development, farther east than any NOAA hurricane reconnaissance aircraft has ever flown. Operating from Cabo Verde, G-IV research missions will provide an opportunity to sample an African easterly wave (AEW) as it emerges from the West African coast. AEWs (as a pre-cursor to a TC) accounts for about 60% of the tropical storms and non-major hurricanes and 85% of the major hurricanes in the Atlantic, and is therefore a high priority target for ITOFS-East. The three goals of ITOFS-East are:

1. Examining the operational impact of in-situ observations in the normally data sparse eastern and central North Atlantic through real-time monitoring of AEWs and the early stages of TCs, and assessing how those observations may improve model and National Hurricane Center (NHC) short- and long-term forecasts of TC formation;
2. Understanding the structural aspects of AEWs, such as the SAL and African easterly jet (AEJ), that make them favorable or unfavorable for possible development in the western North Atlantic;
3. Evaluating the accuracy of experimental (e.g., NASA TROPICS) and operational (e.g., from GOES, NOAA-20, Suomi-NPP) satellite product guidance in the region against collected G-IV observations (collaboration with the 2022 HFP Experiments: *Evaluation of Tropical Cyclone Environment Using Satellite Soundings Experiment* and *TROPICS Satellite Validation Module*).

In addition to the research opportunities ITOFS-East offers, NOAA NHC is interested in:

- Accessing GPS dropwindsonde and tail Doppler radar observations in the central and eastern North Atlantic to capture the early lifecycle stages of tropical disturbances and tropical cyclones, especially those that pose a threat to land areas in the central and western part of the Atlantic basin, including the CONUS, Puerto Rico, and the U.S. Virgin Islands.
- Testing strategies for sampling tropical disturbances and tropical cyclones farther east and earlier in their lifecycles. These efforts will help address strategies for future requirements and capabilities, including NOAA NHC 7-day tropical cyclone forecasts and the enhanced range capabilities of the anticipated G550 aircraft.

Link to ONR's Moisture and Aerosol Gradients / Physics of Inversion Evolution (MAGPIE): In addition to ITOFS-East, FAM could be flown in coordination with MAGPIE and the ONR Twin Otter aircraft. The Twin Otter will be stationed in Barbados for about six weeks in July through early August 2023, sampling the marine boundary layer in the vicinity of Barbados. In partnership with MAGPIE, we propose to investigate the marine boundary layer structure, evolution and its interaction with the mesoscale thermodynamic and kinematic environments associated with pre-genesis disturbances, differentiating between developing and non-developing systems. To accomplish this we will target the structure of African easterly waves (AEWs), including moist tropical environments and embedded mesoscale convective systems (MCSs), the environments with which they are interacting with such as, e.g., Saharan Air Layer (SAL) outbreaks (Dunion et al. 2004; Hopsch et al. 2010; Brammer and Thorncroft 2015), and the boundaries between AEWs and the SAL.

Emphasis will be placed on TC genesis in the Atlantic main development region (Goldenberg and Shapiro 1996) and the physical processes controlling genesis:

- Marine boundary layer (MBL) processes (e.g., air-sea interaction and turbulent mixing) and evolution in environments of AEWs, the SAL, and AEW-SAL boundaries
- Static stability, saturation fraction, and relationships with cloud structure and evolution in AEWs, the SAL, and AEW-SAL boundaries

Many of the efforts described above are similar to the objectives outlined in FAM. In addition to conducting these process studies, we will also be testing new technologies for sampling the MBL in these unique environments, such as Altius 600 and Dragoon sUASs. Flight-level measurements from the ONR Twin Otter aircraft will provide measurements of the structure of the marine boundary layer, providing information on cold pool structure and evolution, static stability for perturbations originating from the boundary layer, and their relationship with larger-scale features such as the SAL and passage of an AEW.

Analysis Strategy: Dropsonde profiles will be evaluated to determine the horizontal gradients and advection of environmental relative humidity. Characteristics of the dry air mass will be scrutinized, including the minimum relative humidity, the height/depth of the dry air, and the horizontal extent of the dry air. Wind analyses from dropsondes and TDR will be evaluated to determine the impact of environmental vertical wind shear on the pre-genesis disturbance. This analysis will go beyond the traditional deep layer vertical wind shear metric, taking into account the hodograph to evaluate vertical wind shear through a number of different levels. The observations collected in this experiment will be crucial to evaluation of dynamics/thermodynamics and the diagnosis of genesis false alarms in numerical weather prediction models (e.g., GFS, HAFS, HWRF). In particular, moisture biases in numerical weather prediction models have long been hypothesized to play a crucial role in false alarm genesis forecasts and, therefore, will be evaluated using observations collected by this module.

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