2024 NOAA/AOML/HRD Hurricane Field Program - APHEX

GENESIS STAGE EXPERIMENT
Science Description

Experiment/Module: Precipitation during Formation and Observing its Response across Multiple Scales (PREFORM)

Investigator(s): Rob Rogers, Ghassan Alaka, Trey Alvey, Jason Dunion, Michael Fischer, Paul Reasor, Jun Zhang, Philippe Papin (NOAA/NHC), Xiaomin Chen (Univ. Alabama - Huntsville), Dave Raymond (New Mexico Tech), Zeljka Stone (New Mexico Tech), Stipo Sentic (New Mexico Tech)

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

Plain Language Description: An accurate prediction of hurricane formation requires an improved knowledge of the precipitation (rainfall) structure and organization and the developing storm circulation response, in the context of environmental characteristics, during the formation process. The overall goal of this experiment is 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.

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 TC, including the organization of convection and the development of a closed low-level circulation.

1) To investigate the precipitation modes that are prevalent during the genesis stage and the response of the vortex to that precipitation organization [*APHEX Goal 3*].
2) 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*].
3) Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in tropical disturbances that are in the pre-genesis or genesis stage. These measurements include improved three-dimensional representation of the tropical disturbance/TC wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*APHEX Goal 2*]

Motivation: A longstanding challenge for hurricane forecasters, theoreticians, and numerical weather forecast systems is to distinguish tropical waves that will develop into hurricanes from tropical waves that will not develop. One of the fundamental requirements to achieve a more accurate understanding and prediction of tropical cyclogenesis events is an improved knowledge of the precipitation organization and the developing vortex response, in the context of environmental (i.e., kinematic and thermodynamic) conditions, during the formation process.

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While true that the favorable environmental conditions for tropical cyclogenesis have been well accepted for decades, those conditions also frequently exist in non-developing disturbances. An understanding of the sequence of events, and thus more informed prediction, of tropical cyclogenesis is still very much constrained by our inability to describe the relative contributions of precipitation organization (e.g., deep convection vs. stratiform rain), in the context of the environmental properties, to the evolution of the developing incipient vortex. Numerical models are a convenient platform to study tropical cyclogenesis events, and are often able to reproduce them, but the processes — particularly the relative roles of various precipitation modes involved — that contribute to genesis have generally been unobserved. Satellites are also a key tool for identifying precipitation properties, particularly with the availability of the Dual-frequency Precipitation Radar (DPR) on the core satellite of the Global Precipitation Measuring Mission (GPM) and multiple higher resolution passive microwave sensors (AMSR2, GMI, SSMIS), but the vortex itself (particularly the kinematic structure) is not well observed; thus, the co-evolution of precipitation and vortex cannot be described using satellites alone. Dedicated aircraft missions (outside of the GRIP-PREDICT-IFEX, tri-agency field program effort in 2010 and the TCS-08 experiment) have historically been too few, but provide much-needed data for analysis of processes critical for TC genesis, as well as an opportunity to compare our much-used numerical models with reality.

Background: Results from previous observational case studies of genesis suggest that convergence (spin-up) is initially maximized in the middle troposphere, and as genesis nears the troposphere moistens (humidity increases to saturation) and stabilizes (warming at upper levels and cooling near the surface) (Raymond and Sessions 2007; Davis and Ahijevych 2012; Komaromi 2013; Zawislak and Zipser 2014a). The stabilization apparently coincides with a lowering of the peak in the vertical mass flux, and thus a more bottom-heavy mass flux profile whereby convergence and spin-up is maximized at low levels (Raymond and López Carillo 2011; Raymond et al. 2011; Raymond et al 2024). Upper-level warming, either through compensating subsidence from deep convection or latent heating, also favors surface pressure falls and enhanced low-level convergence (Zhang and Zhu 2012), which is required to overcome surface divergence that would otherwise persist from mesoscale downdrafts (Komaromi 2013).

A similar evolution was observed by Rogers et al. (2020) in the case of the alignment and intensification of Tropical Storm Hermine (2016). Though that case study was technically not about tropical cyclogenesis, it is apparent to some extent that the processes that led to the vortex alignment and subsequent intensification of Hermine are an extension of the genesis processes listed above. For example, Rogers et al. (2020) found a sequence of events whereby repeated cycles of mesoscale convective systems downshear of Hermine’s existing low-level circulation resulted in a strengthening of the midlevel circulation downshear, moistening of the local environment, development of a mid- to upper-level warm anomaly, subsequent increased static stability in the vicinity of the midlevel circulation, and a lowering of the peak vertical mass flux from top-heavy to bottom-heavy. A similar transition to a bottom-heavy mass flux profile prior to rapid alignment occurred for Sally (2020; Stone et al. 2023). Similarly, Bell and Montgomery (2019), in an observational study of the genesis of Hurricane Karl (2010), found diurnally-varying modes of precipitation, with deep convection and low-level convergence occurring overnight while stratiform precipitation with midlevel convergence occurring during the daylight hours. After repeated cycles of this diurnally-varying precipitation, the tropical depression that became Karl formed. The formation of a nearly-saturated core was found to be a necessary condition for the rapid intensification of a reformation case (Chen et al. 2019).

In summary, the research above shows that the evolution of convection (precipitation), and thus the structure and distribution of latent heating, varies by the characteristics and evolution of the thermodynamic environment (humidity, stability), with the end result being a structural change in the low- and mid-level vortex. Despite these promising results, more robust observational analysis is needed to more confidently link vortex development to the precipitation characteristics and evolution within the incipient circulation, particularly during the genesis stage where the historical record of observations is relatively sparse compared to developed TCs. Research using observations from developing cases (Karl, Matthew, and Fiona) and nondeveloping cases (ex-Gaston, PREDICT/GRIP/IFEX -27, -30) in 2010 (Davis and Ahijevych 2013; Zawislak and Zipser 2014b), suggest that (at least initially) contributions from the larger, more persistent stratiform raining areas (favoring spin-up at midlevels) could initially be more influential during the genesis stage, particularly since the Rossby radius of deformation is large. Once the troposphere stabilizes and the Rossby radius is reduced, it is possible the role of deep convection becomes more influential (favoring low-level spin-up and overall deepening of the circulation).

An alternate pathway to genesis, that does not require the pre-existence of a midlevel vortex, has been proposed based on numerical modeling studies (e.g., Montgomery et al. 2010; Wang et al. 2010a; Wang 2012; Kilroy et al. 2017). This pathway employs the rotating convection paradigm, similar to that invoked for intensification, and it emphasizes the merger and symmetrization of cyclonic vorticity within deep convection.

Satellite studies have also been conducted to examine the relationship between precipitation structure and distribution and genesis. Using a multi-year, multi-sensor passive microwave satellite dataset, Zawislak (2020) highlighted the importance of increased precipitating (including deep convective) area that differentiates developing disturbances from non-developing disturbances. The limitations of passive microwave sensing, however, prevented them from separating multiple precipitation modes (e.g., stratiform from shallow and moderate convection). Fritz et al. (2016), however, was able to identify these modes (i.e., shallow, mid-level, and deep convection, as well as stratiform rain) using the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data. Their conclusion was that multiple precipitation modes are responsible for tropical cyclogenesis. Although stratiform rain accounted for 80% of the raining area, convective precipitation made a nearly equal contribution to overall rainfall, given the larger rain rate. While they did not discount the important role of deep convection, they highlighted the potentially larger and unique role of moderately-deep convection, which was to moisten the lower to middle troposphere and spin up the surface circulation. Such an evolution is consistent with the notion that moistening of the lower to middle levels is a key step in the genesis process, something that was hypothesized in the Tropical Experiment in Mexico (TEX-MEX), a genesis experiment conducted in 1991 (Bister and Emanuel 1997).

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The goal of this experiment is thus to obtain observations on the mesoscale distributions of various precipitation modes and the local environmental (thermodynamic and kinematic) characteristics that influence those modes. Then, through a sequence of missions, measure the time evolution of those modes and the vortex kinematic and thermodynamic responses.

Goal(s): 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, intensity, and mass flux/divergence profiles), and how they are involved in the development and intensification of an incipient tropical storm circulation by also understanding the link between precipitation properties, kinematic structure and evolution of the incipient vortex, and environmental thermodynamic (moisture/stability) and kinematic characteristics (e.g., vertical wind shear).

Hypotheses:

1. The presence of a midlevel circulation, either pre-existing (e.g., African easterly waves) or developed in-situ in response to convection, is a necessary condition for a TC to develop.
2. Widespread areas of stratiform precipitation in the vicinity of a midlevel circulation moisten the local environment, increase static stability, strengthen the midlevel circulation, and transition the vertical mass flux profile from subsequent convective development from top-heavy to bottom-heavy, with an associated transition from midlevel to lower-tropospheric convergence from precipitation occurring within the mesoscale domain encompassing the midlevel circulation prior to tropical cyclogenesis.
3. A low-level center can develop rapidly as a result of persistent convection possessing a bottom-heavy mass flux profile in a region of anomalously high vorticity.

Objectives:

1. Measure the precipitation characteristics, including the relative contributions of stratiform precipitation and various modes of convection (shallow, moderately deep, and deep) to the total precipitating area and area-averaged mass flux profiles.

2. Quantify the temperature and moisture characteristics of the circulation, in particular at midlevels (700 to 400 hPa), relate those characteristics to the precipitation observed, and measure their evolutions over multiple days.

3. Identify the location, strength, and potential origins of circulations from the low to middle troposphere and relate changes to the precipitation observed and associated mass flux and divergence profiles over a mesoscale domain.

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

Scenario 1 [“2-airplane”], ideally one P-3 and the G-IV is available -or- use both P-3s: When the G-IV or 2nd P-3 is available for coordinated research operations, a P-3 will target observations of the relevant mesoscale convective system (MCS) or open wave, while the G-IV or 2nd P-3 will simultaneously fly a circulation-scale pattern that includes the near environment of the convection system. If using two P-3s, this scenario is limited to coordinated missions once a day. If using one P-3 and the G-IV, it provides the possibility of twice-a-day (separated by 12 hours) coordinated missions. In this scenario:

P-3 Pattern #1: This pattern ideally uses a repeated, standard (shortened) single Figure-4 to maximize coverage and repeated sampling of precipitation features of interest. The pattern should be centered on the convective burst center (or in close proximity to it, if one exists) for larger, more organized MCSs, which can be determined from satellite imagery. If a midlevel center is identified in the TDR analysis, the pattern can be subsequently centered at that location (accounting for translation speed, if possible, to determine). Adequate sampling of the convective burst remains the priority, though, since the goal of the pattern is optimizing precipitation returns to complete a TDR analysis of the winds within the MCS. This pattern is ideally flown with a coinciding P-3 (P-3 Pattern #2 or #3) or G-IV mission (G-IV Pattern #1 or #2) in the surrounding environment for context. The Flight Pattern document provides an example (Fig. PREFORM-1). An AXBT is released at the center of the storm and end points for a total of 5 AXBTs.

P-3 Pattern #2: This is a modified, high-altitude lawnmower pattern that samples the wave region. It ideally encompasses the convection flown in P-3 Pattern #1 under this scenario. The P-3 would need to fly at roughly 20,000 ft or as high as could be safely done. The proposed pattern is similar to the standard Lawnmower pattern, but would include a few modifications such as focusing on the near-core environment (within a ~3° × 3° domain), and double the number of drops per zonal leg than standard, with *optimal* drops spacing of 0.6° longitude (can adjust to 0.75° longitude if required as a minimum requirement) for a total of 36 (25) drops in the lawnmower pattern. The fine resolution is required for a moist static energy budget analysis. An AXBTs is released at starting and end points of this pattern for a total of 2 AXBTs.

P-3 Pattern #3: This is a standard butterfly pattern with the length of each inbound and outbound legs of ~1.5°. An AXBT is released in the middle of each inbound and outbound legs, for a total of 6 AXBTs. [Note: pair with P-3 Pattern #2 (or G-IV Pattern #1) to form the *“Thermodynamic Precursors of Intensity Change (TPIC) module”*].

P-3 Pattern #4: With a more accurate positioning of the circulation center, this pattern utilizes the standard square-spiral. Again, the P-3 would need to fly relatively high, around 20,000 ft. Increasing the drop resolution in the standard pattern to about 1° latitude/longitude would double the number of drops to 26 in the square, and optionally including three additional drops in each of the inbound/outbound leg would total 32 drops. An example of sampling is provided in Figure PREFORM-1. An AXBT is released, if external launching is available, at the end point of the square pattern for a total of 4 AXBTs.

G-IV Pattern #1: As with the P-3 Pattern #2, alternatively the G-IV would fly a modified lawnmower at typical operating altitudes. The proposed pattern is similar to the standard lawnmower pattern, but could include a few modifications such as focusing on the near-core environment (~3° × 3°), and double the number of drops per zonal leg than standard, with *optimal* drops spacing of 0.6° longitude (can adjust to 0.75° longitude if have to as a minimum requirement) for a total of 36 (25) drops in the lawnmower portion of the pattern. The fine resolution is required to perform a moist static energy budget analysis. [Note: pair with P-3 Pattern #3 to form the *“Thermodynamic Precursors of Intensity Change (TPIC) module”*]

G-IV Pattern #2: With a more accurate positioning of the circulation center, and indications of some recurrent convective activity near that center, this pattern uses the standard square-spiral, flown at typical G-IV operating altitudes as safety permits. Increasing the drop resolution in the standard pattern to about 1° latitude/longitude would double the number of drops to 26 in the square, and optionally including three additional drops in each of the inbound/outbound leg would total 32 drops. An example of sampling is provided in Figure PREFORM-1.

Scenario 2 [“Single airplane”], only one P-3 or the G-IV is available: When the G-IV or 2nd P-3 is not available for coordinated operations with the other P-3, either because of operational tasking requirements or aircraft unavailability, this scenario provides P-3 or G-IV targeted observations in the near environment and relevant convective complex that can still contribute towards the objectives of the experiment. Missions should be flown with as little temporal gap as possible, within operational constraints (minimally, once-a-day sampling at approximately the same UTC, optimally missions every 12 hours). In this scenario, the single aircraft will fly:

P-3 Pattern #1: Same as in Scenario 1, but with radial legs extended farther into the environment to sample the circulation to a greater extent, flying as high as possible outside of the precipitation.

P-3 Pattern #2: Same as in Scenario 1.

P-3 Pattern #3: Same as in Scenario 1.

G-IV Pattern #1: Same as in Scenario 1.

G-IV Pattern #2: Same as in Scenario 1.

Links to Other Genesis Stage Experiments/Modules: This experiment is ideally suited to include sampling of the precipitation within the proximity of the midlevel vorticity maximum/circulation center, such that the precipitation properties identified from the TDR can be placed in the context of the thermodynamic and kinematic characteristics of the potentially developing disturbance. The experiment can also be flown in conjunction with the 2024 HFP Experiments: *Favorable Air Mass* experiment, *Evaluation of Tropical Cyclone Environment Using Satellite Soundings Experiment*, and the *TROPICS Satellite Validation Module*. The PREFORM observing strategy is ideally flown in coordination with flights for the Impact of Targeted Observations on Forecasts, especially the 2024 ITOFS – East Atlantic (ITOFS-East) experiment (description below) that will be flown from the Cabo Verde Islands.

Moisture and Aerosol Gradients / Physics of Inversion Evolution (MAGPIE): In addition to ITOFS-East, PREFORM could be flown in coordination with the ONR-supported mission MAGPIE using 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 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 PREFORM. 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: Three-dimensional analyses of wind and reflectivity from the TDR will facilitate an analysis of the precipitation structure (i.e., precipitation mode) within precipitation areas of the disturbance, and the identification of low- and mid-tropospheric circulation centers. If possible, repeated sampling of a convective burst area over multiple missions (every 12 h) will allow us to identify the relationships between low- and mid-level circulations, the precipitation mode evolution (e.g., stratiform v. deep, moderately-deep, and shallow convective fractions), and the vertical mass flux profiles. Dropsonde observations (ideally from both the G-IV and P-3) provide key measures of the thermodynamic (e.g., moisture/relative humidity) properties in, and around, the burst and mid-level circulation centers. They will allow us to identify if (when) the low and middle troposphere become nearly saturated, the timing and vertical location of the formation of the warm anomaly, quantify the vertical mass flux profiles, and characterize any potential relationships between observed vortex and precipitation evolutions.

When available, numerical model output from the NOAA HAFS model can provide guidance on the anticipated timing and location in terms of the potential for MCS development and midlevel vortex amplification. This information could be used to identify target locations and times for aircraft sampling, provided that information is provided in a timely fashion (i.e., several hours prior to mission beginning).

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