GENESIS STAGE EXPERIMENT
Science Description

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

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Requirements: Pre-genesis disturbances (pre-TDs), including NHC-designated “Invests”

Plain Language Description: An accurate prediction of hurricane formation requires an improved knowledge of the precipitation (rainfall) 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 (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 moisture, relative humidity, and wind structure of the circulation. It also assesses a new model for understanding how tropical storms form; a model that is colloquially referred to as the “marsupial paradigm” in which developing tropical disturbances have a closed re-circulation region that provides a favorable environment to support sustained precipitation around a preferred “sweet spot.”

Genesis Stage Science Objective(s) Addressed:

The overarching objective is to investigate if a pre-genesis disturbance has matured 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 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 [*APHEX Goal 3*].
3) 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-TD, especially the downstream environment [*APHEX Goal 3*].
4) 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*]

GENESIS STAGE EXPERIMENT
Science Description

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 prediction, and understanding, of tropical cyclogenesis events is an improved knowledge of the precipitation organization and the developing vortex response, in the context of environmental forcing, during the formation process.

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 and pouch. 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 a convenient 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 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) 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 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 profile, 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). 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 potentially developing TC has also been linked to an incipient area, a “pouch,” that is defined in a semi-Lagrangian framework as a proto-vortex cyclonic eddy associated with a parent wave’s critical latitude in the lower troposphere that is protected to some degree from lateral intrusion of dry air and impinging vertical wind shear (Dunkerton et al. 2009; Montgomery et al. 2012, Smith and Montgomery 2012, Wang 2012, and Rutherford and Montgomery 2012). Subsequent work by Rutherford et al. (2015) defined a new key tool, called the Lagrangian Okubo-Weiss OW (OW_{Lag}) parameter, that shows frame-independent saddles and flow boundaries, along with solid-body vortex cores in a single scalar field. In Rutherford et al. (2017) these principles were applied to six years of ECMWF forecasts to determine objective values for the OW_{Lag} parameter indicative of TC genesis. Another noteworthy finding from the latter work was the existence of a "shear sheath" of negative OW_{Lag} at 700 hPa that develops as a protective ring around a pouch at the onset of tropical storm intensity.

Questions, however, remain as to how vortex development is linked to the precipitation characteristics and evolution within the incipient circulation (pouch). 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's possible the role of deep convection becomes more influential (favoring low-level spin-up and overall deepening of the circulation). Another pathway to genesis emerges from scientific hypothesis and numerical modeling studies (e.g., Montgomery et al. 2010; Wang et al. 2010a; Wang 2012; Kilroy et al. 2017), and suggest a greater influence from intense, deep convection throughout the genesis process.

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 mid-level convection, which was to moisten the lower to middle troposphere and spin up the surface circulation.

The goal of this objective is, thus, to obtain observations on the mesoscale distributions of various precipitation modes and the local environmental characteristics (humidity and vorticity) 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 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).

GENESIS STAGE EXPERIMENT
Science Description

Hypotheses:

1. A low-level center can develop rapidly as a result of deep convective bursts in a region of anomalously high vorticity.
2. Mid-tropospheric moistening through stratiform and/or moderately deep convection enhances the mid-tropospheric circulation, reduces downdrafts through saturation, and favors lower-tropospheric convergence prior to tropical cyclogenesis.
3. The presence of a mid-level circulation, either pre-existing (e.g., African easterly waves, upper-level lows) or developed in situ in response to convection, is a necessary condition for a TC to develop.
4. The pouch provides a set of quasi-closed material contours inside of which air is repeatedly moistened by convection and contains a favorable region of cyclonic rotation and weak straining/shearing deformation in which synoptic waves and mesoscale vorticity anomalies, moving westward together, amplify and aggregate on a nearly zero relative mean flow in the lower troposphere.
5. The time at which the protective boundary transforms from one that is determined by the pouch's wave to that of the shear sheath indicates a system that can be self-sustaining without the parent wave (this change can be seen as the Lagrangian manifolds transition from a cat's eye pattern to a circular shear sheath visible in the Lagrangian OW field).

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.
2. Quantify the moisture and relative humidity characteristics of the circulation/pouch, 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 (pouch) from the low to middle troposphere, and relate changes to the precipitation observed.

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

<u>*Scenario 1 ["2-airplane"], ideally one P-3 and the G-IV is available -or- use both P-3s:*</u> 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), while the G-IV or 2nd P-3 will simultaneously fly a circulation/pouch-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) 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). The goal of the pattern, though, 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 pouch/circulation environment for context. An example of sampling is provided in Figure PREFORM-1.

P-3 Pattern #2: This is a standard lawnmower pattern that samples the wave-pouch region and can be centered on the sweet spot as determined from the NPS Lagrangian pouch products provided by the Montgomery Research Group daily using GFS-FV3 global forecast model. 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 higher.* The proposed pattern is similar to the standard Lawnmower pattern, but could include a few modifications such as extending the zonal legs an additional degree longitude, and double the number of drops per zonal leg than standard, spaced approximately every degree longitude. After extending the legs and adding more drops, each zonal leg would have six drops, for a total of 24 drops in the lawnmower portion of the pattern. Finally, dropsondes can optionally be included at the same resolution (~1° latitude/longitude) for three degrees on both the inbound and outbound legs in order to capture some environmental context, resulting in a total of 30 drops.

P-3 Pattern #3: With a more accurate positioning of the pouch/circulation center, and indications of some recurrent convective activity near the sweet spot location, 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.

G-IV Pattern #1: As with the P-3 Pattern #2, alternatively the G-IV would fly a lawnmower at typical operating altitudes. The proposed pattern is similar to the standard lawnmower pattern, but could include a few modifications such as extending the zonal legs an additional degree longitude, and double the number of drops per zonal leg than standard, spaced approximately every degree longitude. After extending the legs and adding more drops, each zonal leg would have six drops, for a total of 24 drops in the lawnmower portion of the pattern. Finally, dropsondes can optionally be included at the same resolution (~1°

latitude/longitude) for three degrees on both the inbound and outbound legs in order to capture some environmental context, resulting in a total of 30 drops.

G-IV Pattern #2: With a more accurate positioning of the pouch/circulation center, and indications of some recurrent convective activity near the sweet spot location, this pattern utilizes the standard square-spiral, flown at typical G-IV operating altitudes. 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.

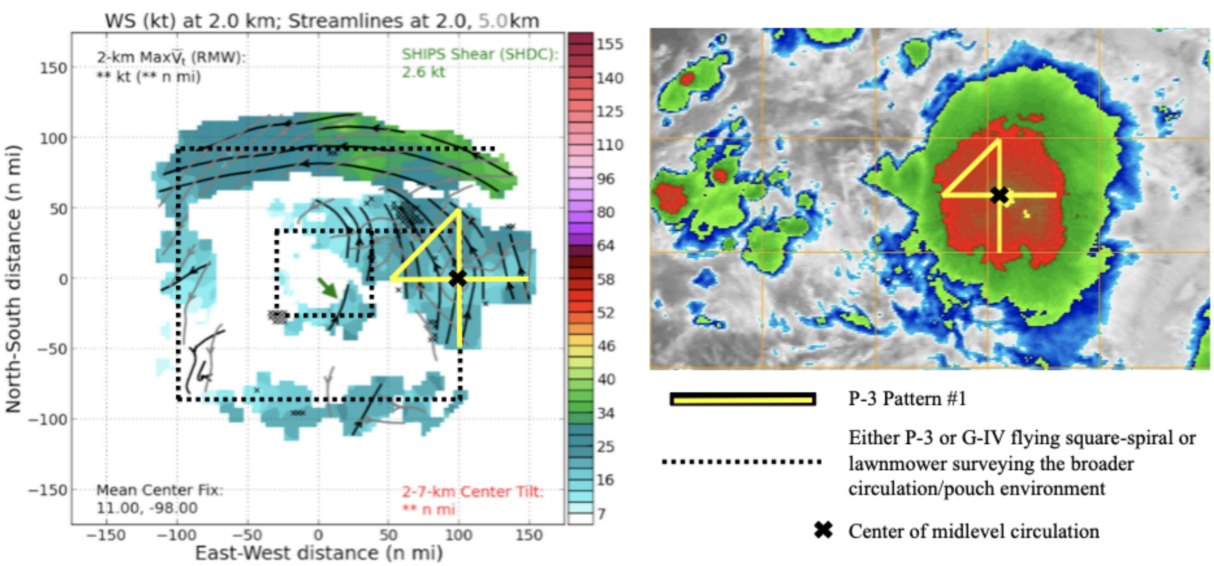

Figure PREFORM-1. *Examples of P-3 Pattern #1 (yellow lines) and P-3 Pattern #3 (or G-IV Pattern #2) (black dotted lines) overlaid on a (left) tail Doppler radar composite analysis of 2-km (black) and 5-km (gray) streamlines and 2-km windspeed (shaded), and (right) IR imagery of the mesoscale convective system where P-3 Pattern #1 is sampling. The overlap between the survey pattern and P-3 Pattern #1 will depend on how well the low-level circulation/pouch and the midlevel circulation associated with the MCS are aligned.*

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 further into the environment to sample the pouch/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 air masses ahead of the potentially developing disturbance (AEW), and therefore the Favorable Air Mass (FAM) 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 PREFORM observing strategy could also consider sampling in support of the, "Impact of Targeted Observations on Forecasts (ITOFS)" experiment, or contribute to satellite validation in the, "ADM-Aeolus Satellite Validation Module," "Evaluation of Tropical Cyclone Environment using Satellite Soundings," or the, "TROPICS Satellite Validation Module."

Link to NASA's Convective Processes Experiment - Aerosols and Winds (CPEX-AW): When the CPEX-AW mission occurs (anticipated to be summer of 2021), PREFORM could be flown in coordination with CPEX-AW and their NASA DC-8 aircraft. The NASA DC-8 will be flying DAWN (Doppler Aerosol Wind Lidar), APR-3 (the Airborne Third Generation Precipitation Radar), HALO (High Altitude Lidar Observatory), HAMSR (High Altitude MMIC Sounding Radiometer), and will be able to deploy dropsondes. The CPEX-AW science objectives include the following:

- Better understanding interactions of convective cloud systems and tropospheric winds as part of the joint NASA-ESA Aeolus Cal/Val effort over the tropical Atlantic.
- Observing the vertical structure and variability of the marine boundary layer in relation to initiation and lifecycle of the convective cloud systems, convective processes (e.g., cold pools), and environmental conditions within and across the ITCZ.
- Investigating how AEWs and dry air associated with the SAL control the convectively suppressed and active periods of the ITCZ.
- Investigating interactions of wind, aerosol, clouds, and precipitation and effects on long range dust transport and air quality over the western Atlantic.

Analysis Strategy: Three-dimensional analyses of wind and reflectivity from the TDR will facilitate an analysis of the precipitation structure (i.e., 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 relationship between low- and mid-level circulations and the precipitation mode evolution (e.g., stratiform v. deep, moderately-deep, and shallow convective fractions). 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.

Kinematics of the developing pouches will be revealed by circulation calculations using the wind data from the dropsondes around circuits in the resulting drop pattern. Analyses of observed wind and thermodynamic dropsonde data will provide information about how the protective shear sheath serves as a barrier to lateral mixing. Thermodynamic information from the drops can be partitioned by location and assigned to the pouch center, shear sheath, or environment. An example of such analysis is given here in Fig. PREFORM-2 below for Cristobal (2014) using model analysis, along with actual research flight data. The results highlight the relatively moist central core, dry outer environment, and details in the profiles of the shear sheath and partial pouch regions, such as relatively moist lower and upper levels but drier midlevels. Fig. PREFORM-2 shows that the core, shear sheath, and environment have different moisture values. The foregoing sampling strategies will help ensure that we are able to capture each of these important regions.

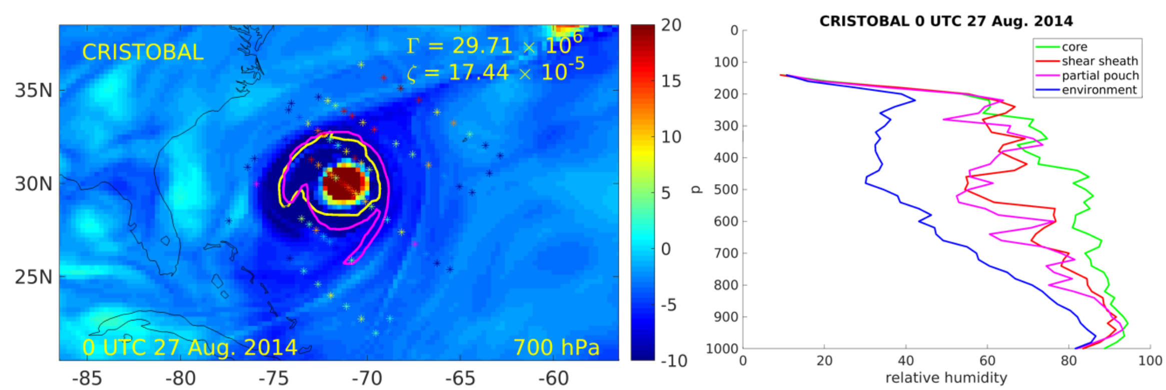

Figure PREFORM-2. *(Left) GFS 700-hPa OWLag field for Hurricane Cristobal at 0000 UTC 27 August 2014. OWLag units are dimensionless. Positive values (red) in the center are surrounded by negative values of the shear sheath (blue). The overlaid 700-hPa (yellow) and 850-hPa (magenta) manifolds also indicate pouch boundaries. 700-hPa circulation and relative vorticity values calculated along a circuit corresponding to the 700-hPa manifold are in the upper-right corner. Overlaid drops (*) are color-coded by their 700-hPa relative humidity values, with darkest red indicating 100% and blue indicating anything less than 40%. (Right) Corresponding composite of the drops in four regions: Inside the core (green), in the shear sheath and either within both manifolds (red) or just one manifold (magenta), and outside of both manifolds (blue).*

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