2018 NOAA/AOML/HRD Hurricane Field Program - IFEX

GENESIS STAGE EXPERIMENT
Science Description

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

Science Objectives:

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 [*IFEX 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 [*IFEX 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 [*IFEX Goal 3*]

Description of Science Objectives:

SCIENCE OBJECTIVE #1: *To investigate the precipitation modes that are prevalent during the genesis stage and the response of the vortex to that precipitation organization*
[Precipitation Mode, PMODE]

Motivation: 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 nondeveloping 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 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.

Background: Results from previous observational case studies suggest that convergence (spin-up) is initially maximized in the midtroposphere, 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). 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 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, the role of deep convection becomes more influential. Another pathway to genesis has emerged from modeling studies (e.g., Montgomery et al. 2010; Wang et al. 2010a; Wang 2012), and suggest a greater influence from intense deep convection throughout the genesis process.

Using Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data, Fritz et al. (2016) identified the evolution of various precipitation modes (i.e., shallow, mid-level, and deep convection, as well as stratiform rain) during the genesis stage. 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 distributions of various precipitation modes and the environmental characteristics that govern those modes. Then, through a sequence of missions, measure the time evolution of those modes and the vortex kinematic and thermodynamic responses.

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 precipitation enhances the mid-tropospheric circulation, reduces downdrafts through saturation, and favors lower-tropospheric convergence prior to tropical cyclogenesis.
3. Persistent latent heating in the middle-to-upper troposphere focuses convergence in the lower troposphere.
4. 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.

Aircraft Pattern/Module Descriptions:

P-3 Pattern #1: PMODE

This pattern ideally uses a repeated, standard (repeated) single Figure-4 or a standard Rotated Figure-4 pattern to maximize coverage of the pre-TC disturbance and convective features of interest. The pattern should be centered on either: a) the convective burst center (or in close proximity to it) for larger, more organized mesoscale convective systems (MCSs) or b) the estimated mid-level circulation center, which can be determined from a model analysis or satellite imagery. The pattern should translate with the phase speed of disturbance (circulation) center, as determined by satellite or model analysis. This pattern is ideally flown with a coinciding G-IV mission in the environment (consistent with other Genesis Stage objectives and their flight patterns).

G-IV Pattern #1: PMODE

P-3 Pattern #1: PMODE may be adapted for the G-IV, while ensuring hazard avoidance around the convective areas. The G-IV mission will only be necessary if the P-3 is unavailable, and is not otherwise chosen to fly other objectives in the Genesis Stage Experiment.

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, and whether there is a relationship with the observed precipitation evolution.

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GENESIS STAGE EXPERIMENT
Science Description

SCIENCE OBJECTIVE #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* [Pouch]

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. The Naval Postgraduate School (NPS) Montgomery Research Group (MRG) has been tracking pouches in the Atlantic since 2008 in numerical models. Airborne observations 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: The scientific basis for the methodology is given in Dunkerton et al. (2009), which describes how to view genesis in the semi-Lagrangian frame co-moving with a parent wave. Recent years have seen several field campaigns aimed at understanding the science of tropical cyclogenesis and new lessons have emerged from these experiments, as summarized by 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. The new Lagrangian characterization tested extensively during 2017 allows many pouch products to be automated and objectively defined in order to produce more accurate forecast evaluations. These evaluations should provide reliable, consistent targets for research flight operations. The "pouch" is defined 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.

Hypotheses:

1. The pouch 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.
2. The pouch provides a set of quasi-closed material contours inside of which air is repeatedly moistened by convection.
3. The parent wave is maintained and possibly enhanced by diabatically amplified eddies within the wave (proto-vortices on the mesoscale), a process favored in regions of small intrinsic phase speed.

4. 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).

Aircraft Pattern/Module Descriptions: Advanced staging in Barbados would most likely be required for pouches tracking westward in the Atlantic main development region (MDR), but flights from Lakeland may be possible for tropical transition cases east of Florida. Patterns discussed below would be centered on the consensus forecast pouch center location based upon all available numerical models used in the pouch-tracking routine.

P-3 Pattern #1: Pouch

A lawnmower pattern would be appropriate for an initial flight into a wave-pouch exhibiting scattered convective activity without much organized convective activity near the pouch sweet spot. *The P-3 would need to fly at roughly 20,000 ft.* The proposed pattern is similar to the standard Lawnmower pattern with a few modifications. First, if possible, extend the zonal legs an additional degree longitude. Second, double the number of drops per zonal leg. 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, include dropsondes at the same resolution (~1° latitude/longitude) for three degrees on both the inbound and outbound legs in order to capture a cross-section of the outer boundary of the pouch, resulting in a total of 30 drops.

P-3 Pattern #2: Pouch

Observations from the first lawnmower flight, accurate positioning of the pouch center, and indications of some recurrent convective activity near the sweet spot location would allow subsequent flights to utilize the standard square-spiral. Many follow-on flights, with as little temporal gap as possible within operational constraints would be ideal (ideally, once-a-day sampling at approximately the same UTC is optimal). Again, *the P-3 would need to fly relatively high, around 20,000 ft.* Increasing the drop resolution to about 1° latitude/longitude would double the number of drops to 26 in the square, and including three additional drops in each of the inbound/outbound leg would total 32 drops. The sequential combination of the lawnmower and square-spiral patterns, with the suggested number of dropsondes, proved invaluable during the 2010 PREDICT field experiment. These observations proved adequate for sampling the meso-alpha and meso-beta scale flow kinematics and thermodynamics of the targeted wave pouch.

GENESIS STAGE EXPERIMENT

Science Description

G-IV Pattern #1: Pouch

As with the P-3 lawnmower pattern, a lawnmower pattern would be appropriate for an initial flight into a pouch with scatted convective activity. The G-IV would fly at typical operating altitudes. The proposed pattern is similar to the standard Lawnmower pattern with a couple of modifications. First, if possible, extend the zonal legs an additional degree longitude. Second, double the number of drops per zonal leg. After extending the legs and adding more drops, each zonal leg would have six drops, for a total of 24 drops. Adding three drops to each inbound/outbound leg would result in 30 total drops.

G-IV Pattern #2: Pouch

Using observations from the first lawnmower flight, accurate positioning of the pouch center would allow subsequent flights to utilize the standard square-spiral pattern. As many follow-on flights, with as little temporal gap as possible within operational constraints would be ideal. Again, the G-IV would fly at the typical operating altitudes. Increasing the drop resolution to about 1° latitude/longitude would double the number of drops to 26 in the square. Including three additional drops in each of the inbound/outbound leg would total 32 drops.

Analysis Strategy: 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 pouch center, shear sheath, or environment. An example of such analysis is given here in Fig. GN-1 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. GN-1 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.

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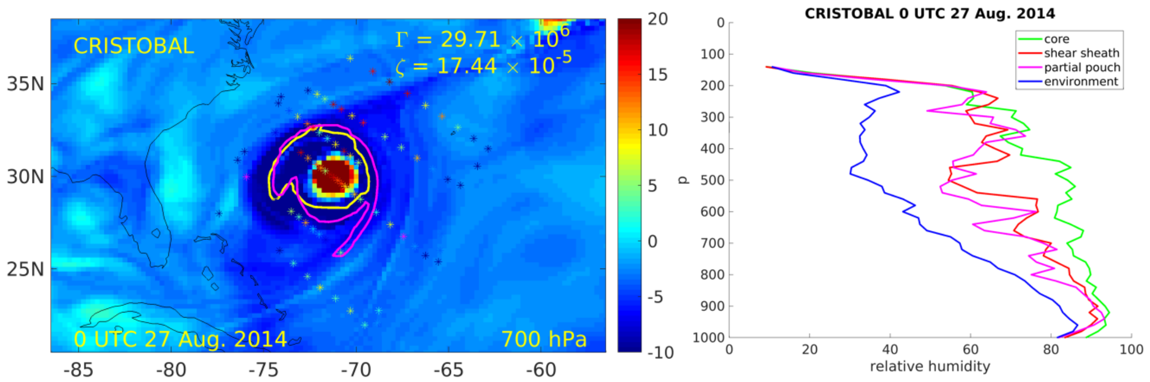

Figure GN-1. *(Left) GFS 700-hPa* OW_{Lag} *field for Hurricane Cristobal at 0000 UTC 27 August 2014.* OW_{Lag} *units are dimensionless. Positive values (red) in the center are surrounded by negative values of the shear sheath (blue). The overlaid 700-hPa (yellow) and 850-hPa (magenta) manifolds also 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).*

GENESIS STAGE EXPERIMENT
Science Description

SCIENCE OBJECTIVE #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* [Favorable Air Mass, FAM]

Motivation: The environment near a pre-TD is critical to the favorability for tropical cyclogenesis to occur. The probability of cyclogenesis for a given pre-TD is dependent upon thermodynamics (e.g., moisture) and dynamics (e.g., vertical wind shear) in the adjacent air mass. Increased observations of lower-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-TD 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 depressions (pre-TDs), 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 (Fig. GN-3). 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 (Fig. GN-4). Preliminary results by Brammer (2015) suggest that as AEWs leave the West African coast, these troughs typically possess closed circulations at 700–600 hPa. Yet, these troughs 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.

Hypotheses:

1. Environmental air downstream from a pre-TD is ingested before the low-level circulation is closed.
2. Environmental relative humidity to the west and northwest of a pre-TD is critical to the development of that disturbance.
3. Environmental vertical wind shear in the vicinity of a pre-TD is critical to the development of that disturbance.
4. Dry air associated with the Saharan Air Layer (SAL) inhibits or delays genesis of pre-TDs.
5. Dynamical models (e.g., GFS) are consistently too moist in the inflow layer to the west of a pre-TD, resulting in genesis false alarms.

Aircraft Pattern/Module Descriptions:

G-IV Pattern #1: FAM

Sample the *environment* to the west of an easterly wave, especially if dry air is detected in that region. Sample when easterly wave is forecast to develop in reliable computer models or is showing signs of development in observations. Sample when easterly wave is located at or west of 35°W (to be within range of G-IV). Standard Lawnmower pattern should be used to setup a grid of observations and dropsondes, with drops every 150 n mi (Fig. GN-2). The most likely orientation of the lawnmower pattern will be to the West or Northwest of the tropical disturbance/cyclone. Flight level is 40–45 kft. Long legs of pattern should be 600–1000 n mi (depending on flight time and resources) and short legs should be 150 n mi. To maximize the usefulness of the data, a minimum of two boxes should be flown. In some situations, the same box could be flown twice to maximize data coverage in a more specific region.

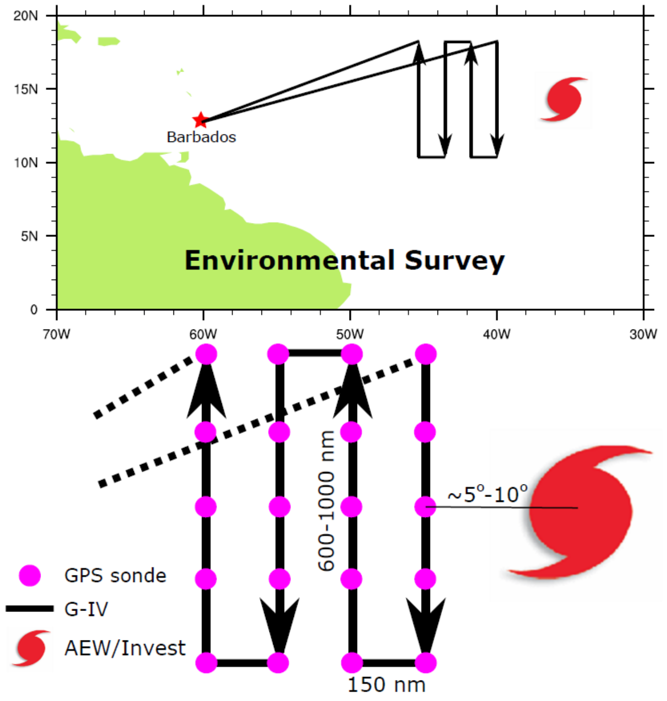

Figure GN-2. *Example lawnmower pattern to be flown (track in black) by the G-IV, dropsonde locations within the pattern (purple), and the relative location of the AEW/Invest center (hurricane symbol)*

P-3 Pattern #1: FAM

The Lawnmower pattern described above (and illustrated in Fig. GN-2) can be modified to accommodate the P-3. *Flight level should be 20 kft* to maximize the altitude of dropsonde data. P-3 missions will likely have to start later than G-IV missions since the range of the G-IV is larger, especially if the disturbance is in the Atlantic Main Development Region (east of 50°W)

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 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, HWRF).

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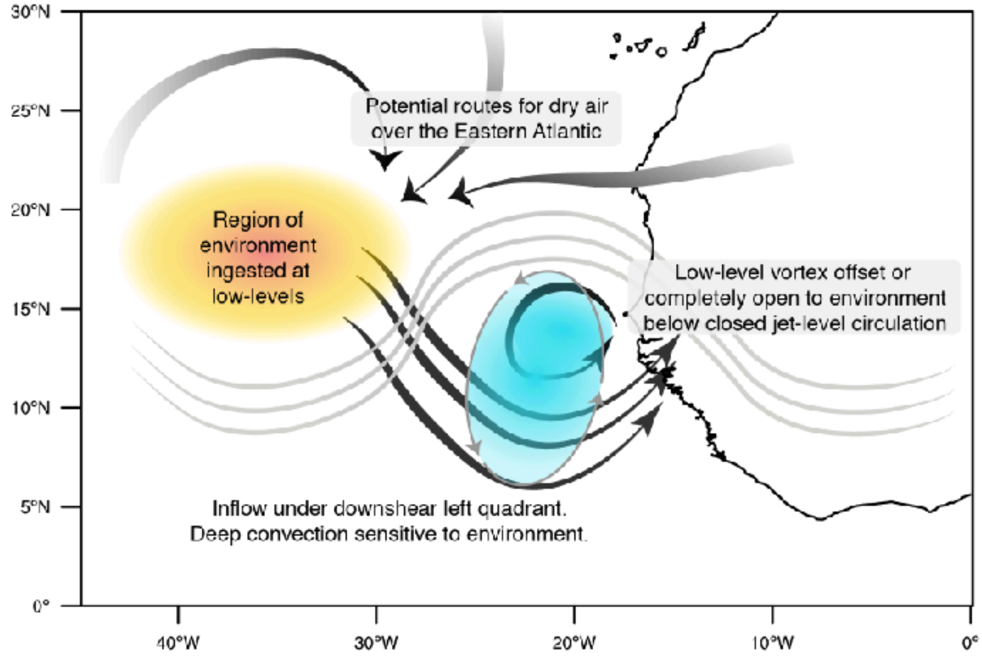

Figure GN-3. *Schematic of the ingestion of dry environmental air by an AEW*

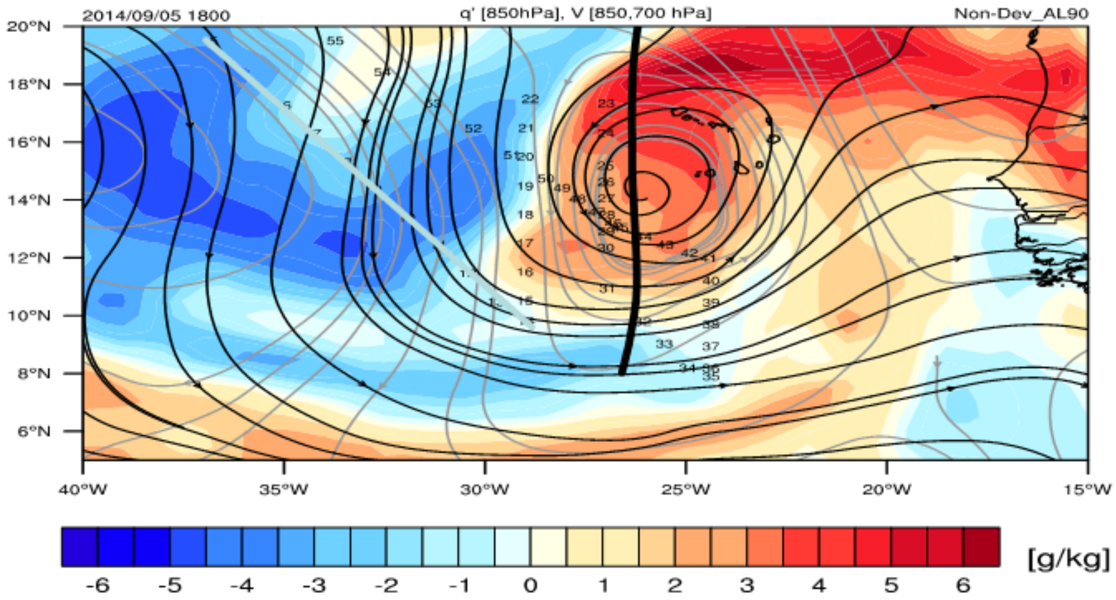

Figure GN-4. *850-hPa specific humidity anomalies (shading), 850-hPa streamflow (black contours) and 700-hPa streamflow (grey contours) are shown for a non-developing case (AL90) at 1800Z 5 September 2014*