10. Tropical Cyclone in Shear Experiment

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Links to IFEX:

- **Goal 1:** Collect observations that span the TC lifecycle in a variety of environments
- **Goal 3:** Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

Motivation:

Forecasting of TC intensity remains a great challenge in which the gains in skill over the past decade have significantly lagged those of track at most forecast intervals (Rogers et al. 2006, DeMaria et al. 2005). As a multiscale atmospheric and oceanic problem, one of the constraints on TC intensity change is the vortex's interaction with the evolving environmental flow. Vertically-sheared flow in particular is generally acknowledged to limit storm intensity, especially when combined with other environmental factors like low sea-surface temperature and mid-tropospheric dry air (e.g., Tang and Emanuel 2012). In observation-based statistical models of intensity prediction (Kaplan and DeMaria 2003; DeMaria et al. 2005), the vertical wind shear (VWS) is an important predictor.

Although most TCs in HRD's data archive experience some degree of VWS, the timing of flights with respect to the shear evolution and the spatial sampling of kinematic and thermodynamic variables have not always been carried out in an optimal way for testing hypotheses regarding shear-induced modifications of TC structure and their impact on intensity change (see below). This experiment will sample the TC at distinct phases of its interaction with VWS and measure kinematic and thermodynamic fields with the azimuthal and radial coverage necessary to test existing hypotheses.

In addition to enhancing basic understanding, the dataset collected will guide improvements in initial conditions and the representation of moist physical processes in models. These improvements are likely necessary to increase the accuracy of short-term (<24 h) numerical intensity guidance for vertically sheared TCs. Initial conditions within the core region are important because the resilience of a TC (i.e., its ability to maintain a vertically-coherent structure under differential advection by the VWS) is sensitive to the strength, depth, and radial profile of the vortex (Reasor et al. 2004; Reasor and Montgomery 2015). Properly representing the flow outside the core region is also important since the flow topology there is critical to the thermodynamic interaction of the TC with surrounding dry environmental air (Riemer and Montgomery 2011). Physical processes in the model must also be well-represented so that 1) the structure on which the vortex resilience depends is not errantly transformed over short periods (< 6 h), 2) the convective response of the TC to vertical shearing and its feedback on vortex resilience are properly simulated, and 3) the shear-induced intensity modification mechanisms are permitted to operate as in nature.

Background:

Vertical wind shear impacts TC structure directly through vertical tilting of the vortex wind field and indirectly through modulation of the convective field (Black et al. 2002; Reasor et al., 2009; Reasor and Eastin 2012; Reasor et al. 2013). The impact of VWS on TC intensity is less certain and depends, in part, upon the timescale over which one considers the response (Frank and Ritchie 2001; Wang et al. 2004; Wong and Chan 2004; Riemer et al. 2010). The view of VWS as a generally negative influence on TC formation and intensification is supported by observational studies (e.g., Gray 1968) and observation-based statistical models of intensity prediction (Kaplan and DeMaria 2003; DeMaria et al. 2005). During the early stages of TC development, however, VWS can play a potentially positive role by organizing deep convection and vorticity production in the downshear region of the weak, pre-existing vortex (Molinari et al. 2004, 2006).

Early studies of shear-induced intensity change mechanisms focused on the role of VWS in ventilating the warm core (Simpson and Riehl 1958). Frank and Ritchie (2001) simulated the development of pronounced convective

asymmetry in a vertically-sheared TC and argued that weakening occurs through the hydrostatic response to outward fluxes of upper-level potential vorticity (PV) and equivalent potential temperature. An alternative explanation by DeMaria (1996) focused on the balance-dynamics response of the vortex to vertical tilting. To maintain thermal wind balance as the wind structure is tilted, static stability must increase at low levels in the eyewall region. The negative impact on intensity was then hypothesized to arise through suppression of eyewall convection. Using a multi-level adiabatic primitive equation model, Jones (1995, 2000) demonstrated that low-level static stability evolves in a manner consistent with balance dynamics but does so asymmetrically within the eyewall. An asymmetrically balanced thermal anomaly develops in phase with the distortion of the wind field caused by vertical tilting, resulting in anomalously low (high) values of static stability located downtilt (uptilt). Thus, while convection might be suppressed on one side of the eyewall, it can be enhanced on the other. Jones additionally implicated the mesoscale transverse circulation (required to maintain asymmetric balance) in the development of convective asymmetry in the eyewall (see also Braun et al. 2006; Davis et al. 2008). The net impact of such static stability and vertical motion asymmetry on convective asymmetry and intensity change remains unclear.

Recently, Riemer et al. (2010) and Riemer et al. (2013) have proposed an intensity modification mechanism also rooted in a balance-dynamics framework. They argue that balanced vorticity asymmetry at low levels, generated outside the core through shear forcing, organizes convection outside the eyewall into a wavenumber-1 pattern through frictional convergence. Downdrafts associated with this vortex-scale convective asymmetry arise as precipitation generated by the convective updrafts falls into unsaturated air below. In their simulations, the downdrafts led to a vortex-scale transport of low equivalent potential temperature (θ_e) air into the inflow layer and disruption of the TC heat engine (Emanuel 1986, 1991). If particularly low θ_e air at lower to middle levels of the environment is able to reach the core region where the convective enhancement occurs, it is anticipated that the thermodynamic impacts of the downward transport of low θ_e air would be enhanced. Riemer and Montgomery (2011) proposed a simple kinematic model for this environmental interaction, quantifying the shear-induced distortion of the "moist envelope" surrounding the TC core as a function of shear strength, vortex size, and vortex intensity.

In the simulations of Riemer et al. (2010), the TC core region developed vertical tilt following its initial encounter with VWS, but then realigned, i.e., the vortex was resilient. The problem of dynamic resilience focuses on the ability of the TC to maintain a vertically-coherent vortex structure as it experiences vertical shearing. Jones (1995) found that coupling between vertical layers, and the tendency for the upper- and lower-level potential vorticity (PV) of the cyclonic core to precess upshear, restricts the development of vertical tilt that would otherwise occur through differential advection. For small-amplitude tilt, Reasor et al. (2004) developed a balance theory for the shear forcing of vortex tilt in which the tilt asymmetry behaves as a vortex-Rossby wave. In this vortex-Rossby wave framework, they developed a heuristic model for the TC in shear which predicts a left-of-shear tilt equilibrium. Furthermore, they demonstrated that the evolution towards this equilibrium tilt state depends not only on intrinsic scales of the flow (e.g., Rossby number and Rossby deformation radius), but also on the radial distribution of (potential) vorticity in the core region. Reasor and Montgomery (2015) have recently evaluated this heuristic model. The model is capable of predicting the enhancement of resilience that arises as the PV gradient outside the core increases. Even when moist neutral conditions exist within the eyewall, the model still describes the long-time evolution of the tilt asymmetry outside the eyewall.

Hypotheses: (Regarding a TC encountering a large increase in environmental VWS over a short period of time)

1) **<u>Structure evolution:</u>** <u>The vertically-tilted vortex structure which develops following a significant increase in VWS is governed by balance-dynamics theory.</u> [There are two components here: 1) determine whether the wavenumber-1 vorticity and thermodynamic structures of the tilt asymmetry within the eyewall region are consistent with the expectations of asymmetric balance (see **Background**); and 2) document, to the extent possible, the structural evolution of the tilt asymmetry on the timescale of a vortex circulation period (~1 h) and over the longer timescale dictated by the mission frequency (~12 h), and then compare the observed evolution with expectations from idealized modeling (Reasor et al. 2004; Reasor and Montgomery 2015). Core-region kinematic structure is sampled out to ~ 4xRMW with Doppler radar at specific times relative to the VWS evolution. Thermodynamic structure is sampled with flight-level instruments and closely-spaced dropsondes.]

2) **Convective asymmetry:** Eyewall convective asymmetry is organized by shear-forced, balanced mesoscale ascent. [Several explanations have been proposed for shear-forced convective asymmetry, including balanced ascent associated with vortex tilting, vorticity budget balance, and interaction of mesovortices with the flow outside the eyewall. While it may not be possible (given our current limited understanding of shear-forced eyewall convective asymmetry) to determine the predominance of one mechanism over another using only observed data, at a minimum we may assess whether each mechanism is plausible in a given case. This data will aid future theoretical and numerical investigations designed to understand why convection is preferred in shear-relative locations of the TC eyewall. Core kinematic and precipitation structures are sampled with Doppler radar during a period when VWS is the dominant forcing of low-wavenumber asymmetry. Thermodynamic structure is sampled with flight-level instruments and closely-spaced dropsondes. Satellite observations of convective activity should also be archived during the observation periods.]

3) **Intensity modification:** As stated in Riemer et al. (2010), VWS inhibits intensification through the downward transport of low-θ_e air into the inflow layer outside the core, brought on by the wavenumber-1 organization of convection outside the core via balance-dynamics mechanisms. [The proposed link between balance-dynamics mechanisms and weakening through modification of inflow layer thermodynamic properties has not been demonstrated in the observational context. Core-region kinematic structure of the vortex (e.g., the tilt asymmetry) must be sampled out to ~ 4xRMW with Doppler radar at specific times relative to the VWS evolution. Reflectivity data collected during the flight will also provide insight into the convective structure outside the eyewall. Thermodynamic structure of the inflow layer is sampled with closely-spaced dropsondes. Near-core thermodynamic structure of the lower to middle troposphere is sampled by flight-level and dropsonde measurements, especially before and during the period of increasing VWS.]

4) **TC isolation:** As stated in Riemer and Montgomery (2011), the shape of the moist envelope (i.e., high-θ_e air) surrounding the eyewall above the inflow layer (and below the outflow layer) is at first approximation closely related to the horizontal flow topology, and is distorted by VWS; for environmental air to impact eyewall convection, time-dependent and/or vertical motions outside the core (see Hypothesis 3) are generally necessary for all but the weakest TCs in VWS. [For a strong hurricane in VWS, the closest approach of environmental air is expected to be well-removed from the eyewall. If low- to mid-level low-θ_e air intrudes far enough into the core region, and undercuts near-core convection, the mechanism identified in Hypothesis 3 may operate in an amplified manner. The moist envelope is defined using P-3 flight-level and P-3/G-IV dropsonde data within and surrounding the eyewall out to 2 deg, before and after the shear increase. Similarly, the low- to mid-level storm-relative horizontal flow topology outside the core is examined using flight-level, dropsonde, and Doppler radar measurements.]

Experiment Description:

The experiment design is motivated through the use of fields from an example sheared hurricane simulated by HWRF. These fields will be treated as atmospheric observations for the purpose of the discussion below. The mission details at each stage of the experiment are also described below.

The optimal experiment is one in which the VWS increases significantly over a short period of time, approximating the canonical idealized numerical experiment of a TC in VWS (e.g., Bender 1997; Frank and Ritchie 2001; Riemer et al. 2010, 2013). In the canonical numerical experiment, a *hurricane-strength* TC encounters an instantaneous increase in VWS and undergoes an immediate structural change in response to sustained shear forcing. **Figure HWRF-1** illustrates the large-scale, deep-layer VWS evolution in a case (Hurricane Michael, initialized at 00Z on 7 Sept., 2012) that would constitute an acceptable target for this experiment. The VWS increases approximately 30 kts over 24 h, or at a rate of 1.25 kts/h.
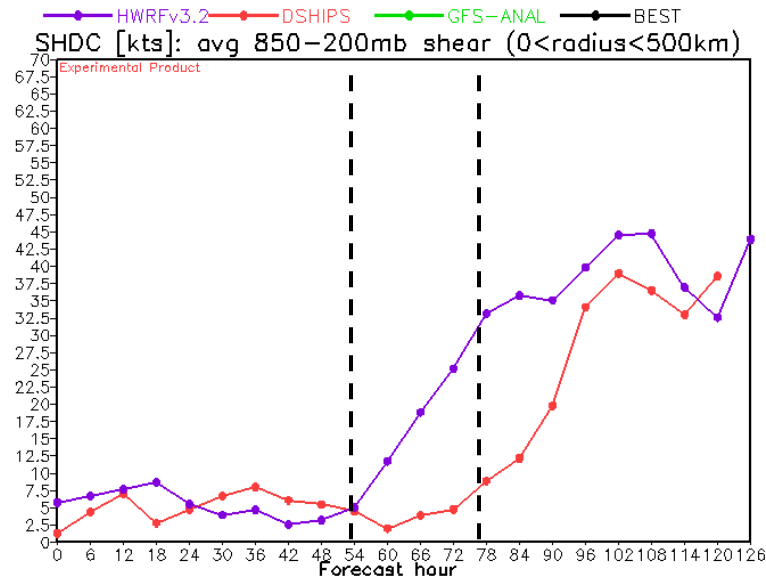
Figure HWRF-1: Ideal shear evolution from HWRF (purple).

Pre-shear sampling:

The TC is sampled just prior to the shear increase (~54 h in this case) to obtain the pre-shear vortex and environmental structure. **Figure HWRF-2** shows that the TC's vorticity structure is vertically aligned through a deep layer at this time.

Mission 1: The G-IV aircraft performs storm-relative environmental TDR and dropsonde sampling (**Fig. 10-1**) through clockwise octagonal circumnavigation, starting at 2 deg, moving inward to 1.5 deg, and finishing at 1 deg. A coordinated P-3 aircraft performs a single Figure-4 pattern (orientation chosen for efficiency) with TDR to obtain the TC core structure (**Fig. 10-2**). Radial legs are scaled by the RMW, and go out to 4.5xRMW (e.g., for an 18-nm RMW, radial legs go out ~80 nm). At the completion of the final outbound leg, the P-3 turns inbound to a radius of 2xRMW for a counter-clockwise octagonal circumnavigation to obtain the azimuth-height thermodynamic structure of the boundary layer and free atmosphere (up to flight level) outside the eyewall. The straight segments permit a second TDR look at the eyewall (an 18-nm RMW would just be resolved by radar for a typical 48-nm wide swath). As time permits, a final Figure-4 pattern may be performed following the octagonal pattern. A primary objective of the P-3 and G-IV dropsonde sampling is to document the initial "pre-shear" moist envelope surrounding the core.
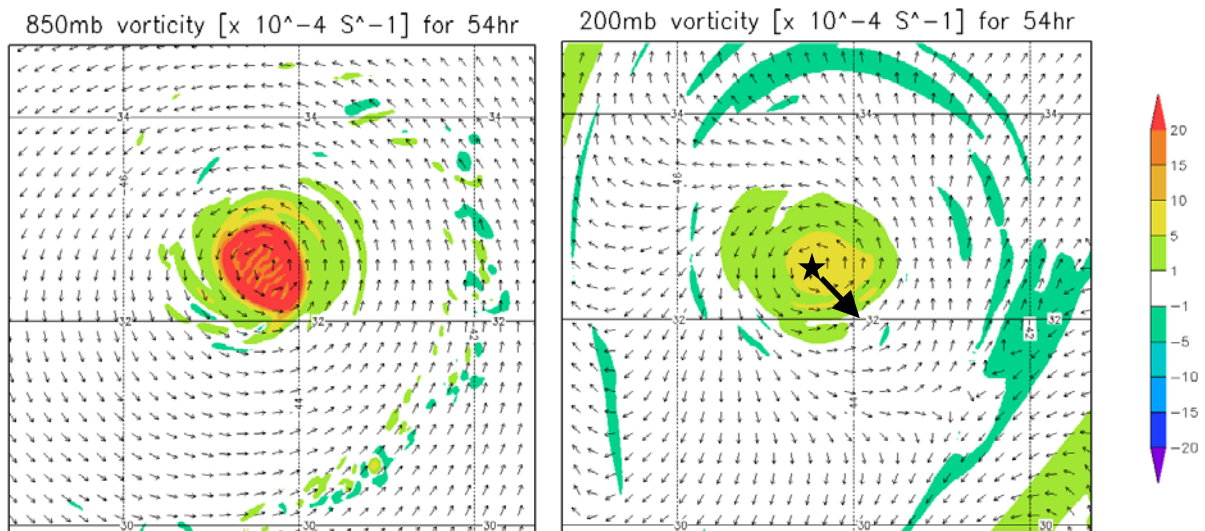

Figure HWRF-2: Anticipated "pre-shear" vortex structure from HWRF.

<u>Threshold shear and large tilt sampling:</u>

The TC's kinematic structure responds to increasing VWS in one of three ways: 1) maintain a vertically upright vortex core throughout the troposphere (note: this does not mean that a tilt asymmetry fails to develop on the broader scale of the vortex, but rather that the core remains resilient), 2) develop significant tilt of the vortex core, but then realign into a steady-state tilt configuration (esp. if the shear is sustained), and 3) exhibit continuous and irreversible separation of the upper- and lower-level vortex cores, resulting in a shallow low-level circulation usually void of deep convection.

If a sufficiently high threshold value of VWS is employed, scenario 1) is least likely. For a TC that follows scenario 2), determining the target time of maximum tilt is critical. If the TC is sampled after realignment has already completed, the structural changes we wish to document may be greatly diminished. Furthermore, it would not be possible to fully test the intensity modification Hypothesis 3. For a TC that follows scenario 3), 12-h sampling of the TC until the low-level circulation becomes completely exposed (and void of deep convection) is adequate.

Since the possibility of scenario 2), and the precise timing of maximum tilt, depend on a variety of factors, as discussed in the **Background**, time series of forecast shear from a number of different sources (e.g., SHIPS, HWRF coarse grid, etc.) should be used in conjunction with a threshold shear value to guide the timing of flights subsequent to the pre-shear sampling. For the Category 2-3 hurricane in the example, a noticeable tilt in the circulation center with height becomes evident between 12-18 h after the shear increase begins, or when the shear reaches a value between 20-25 kts (not shown). An indication that the shear is beginning to strongly influence storm structure is the development of a pronounced convective asymmetry within the core region. **Figure HWRF-3** illustrates this convective asymmetry at the time the shear threshold is reached (and the core begins to tilt). In this example, <u>the second P-3 mission would commence ~12 h after the first</u>.

Mission 2: A second P-3 will be prepared to sample the TC when the shear reaches a threshold value (20-25 kts in the example). The objective is to document the initial development of shear-induced vertical tilt. The P-3 performs a single Figure-4 pattern with TDR to obtain the TC core structure (**Fig. 10-3**). The first inbound leg should be oriented along the shear vector. A quick comparison of SFMR and flight-level winds will reveal the tilted wind structure. The subsequent Doppler analysis will confirm the tilt. Radial legs are scaled by the RMW, and go out to 4.5xRMW (e.g., for an 18-nm RMW, radial legs go out ~80 nm). At the completion of the final outbound leg, the P-3 turns inbound to a radius of 2xRMW for a counter-clockwise octagonal circumnavigation to obtain the azimuth-height thermodynamic structure of the boundary layer and free atmosphere (up to flight level) outside the eyewall. The straight segments permit a second TDR look at the eyewall (an 18-nm RMW would just be resolved by radar for a typical 48-nm wide swath). As time permits, a final Figure-4 pattern may be performed following the octagonal pattern. A primary objective of the P-3 sampling is to document the initial response of the core-region kinematic structure to increased shear.
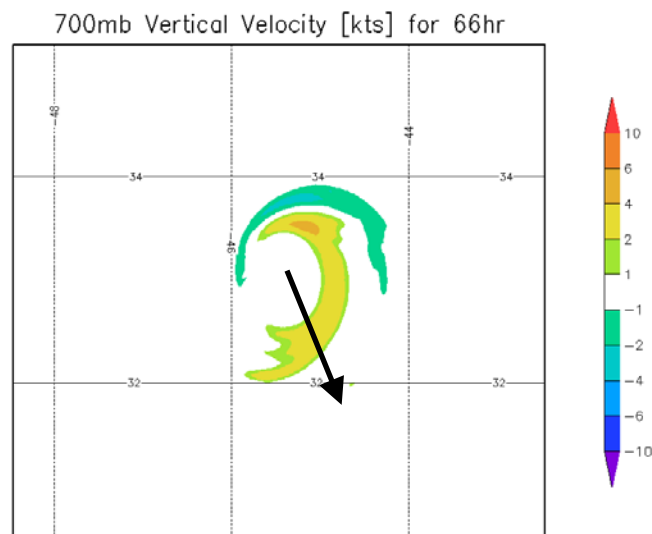

Figure HWRF-3: Anticipated "threshold shear" convective asymmetry from HWRF.

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Figure HWRF-4 shows the tilted vorticity structure 12 h after the TC begins to develop a visible vertical tilt of the core (i.e., through the displacement of circulation centers with height). By this time, the shear magnitude is 30-35 kts. The vortex tilts to the left of the large-scale, deep-layer shear vector, as expected based upon work cited in the **Background**. In this example, the upper-level vorticity of the TC ultimately weakens and merges with an upper-level, north-south oriented vorticity feature to its west (not shown). This behavior is closest to that in scenario 3).

Mission 3: The P-3 used in the "pre-shear" mission will be prepared to sample (at least 24 h after the pre-shear mission) the TC when the vertical tilt of the core has reached a large value. The P-3 performs a single Figure-4 pattern with TDR to obtain the TC core structure (**Fig. 10-4**). The first inbound leg should be oriented along the shear vector. A quick comparison of SFMR and flight-level winds will reveal the tilted wind structure. The subsequent Doppler analysis will confirm the tilt. Radial legs are scaled by the RMW, and go out to 4.5xRMW (e.g., for an 18-nm RMW, radial legs go out ~80 nm). At the completion of the final outbound leg, the P-3 turns inbound to a radius of 2xRMW for a counter-clockwise octagonal circumnavigation to obtain the azimuth-height thermodynamic structure of the boundary layer and free atmosphere (up to flight level) outside the eyewall. The straight segments permit a second TDR look at the eyewall (an 18-nm RMW would just be resolved by radar for a typical 48-nm wide swath). As time permits, a final Figure-4 pattern may be performed following the octagonal pattern. A coordinated G-IV performs storm-relative environmental TDR and dropsonde sampling (**Fig. 10-1**) through clockwise octagonal circumnavigation, starting at 2 deg, moving inward to 1.5 deg, and finishing at 1 deg. A primary objective of the P-3 and G-IV dropsonde sampling is to document the distortion of the moist envelope surrounding the core. In addition, we seek evidence for a broad-scale tilt asymmetry, up-tilt enhancement of convection outside the core, and modification of boundary layer θ_e in the core region.
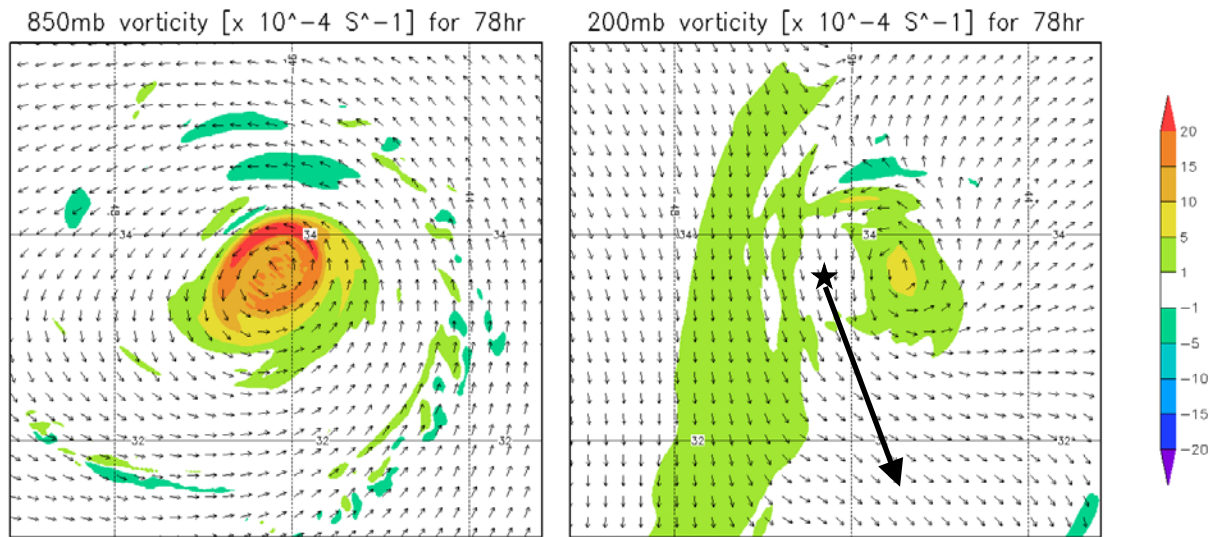

Figure HWRF-4: Anticipated "large-tilt" vortex structure from HWRF.

TC alignment and recovery sampling:

As discussed in the **Background**, some TCs are able to realign once tilted, even under sustained vertical wind shear. In the context of the intensity change Hypothesis 3, negative thermodynamic impacts on the TC should be reduced as the vortex aligns. In numerical simulations (e.g., Riemer et al. 2010), this is followed by re-intensification of the TC. In the example here, the vortex does not realign, and the primary circulation becomes increasingly shallow (not shown). The TC then continues to weaken (**Figure HWRF-5**). Whether the TC is resilient or is progressively sheared apart, a follow-up mission to investigate the continued evolution of the TC is important for a complete understanding of the life-cycle of a vertically-sheared storm.

Mission 4: The P-3 used in the "threshold shear" mission will be prepared to sample the TC after realignment has completed (or the vortex continues to be sheared apart). The objective is to verify vertical alignment in the kinematic field and the thermodynamic recovery of the boundary layer (or the continued deterioration of the circulation). The P-3 performs a single Figure-4 pattern with TDR to obtain the TC core structure (**Fig. 7-5**). The first inbound leg should be oriented along the shear vector. A quick comparison of SFMR and flight-level winds will reveal the tilted wind structure. The subsequent Doppler analysis will confirm the tilt. Radial legs are scaled by the RMW, and go out to 4.5xRMW (e.g., for an 18-nm RMW, radial legs go out ~80 nm). At the completion of the final outbound leg, the P-3 turns inbound to a radius of 2xRMW for a counter-clockwise octagonal circumnavigation to obtain the azimuth-height thermodynamic structure of the boundary layer and free atmosphere (up to flight level) outside the eyewall. The straight segments permit a second TDR look at the eyewall (an 18-nm RMW would just be resolved by radar for a typical 48-nm wide swath). As time permits, a final Figure-4 pattern may be performed following the octagonal pattern. Primary objectives of the P-3 sampling are to document the continued evolution of the core-region kinematic structure under shear forcing and, in the case of realignment, to demonstrate recovery of the hurricane boundary layer to a structure more closely resembling the "pre-shear" state.
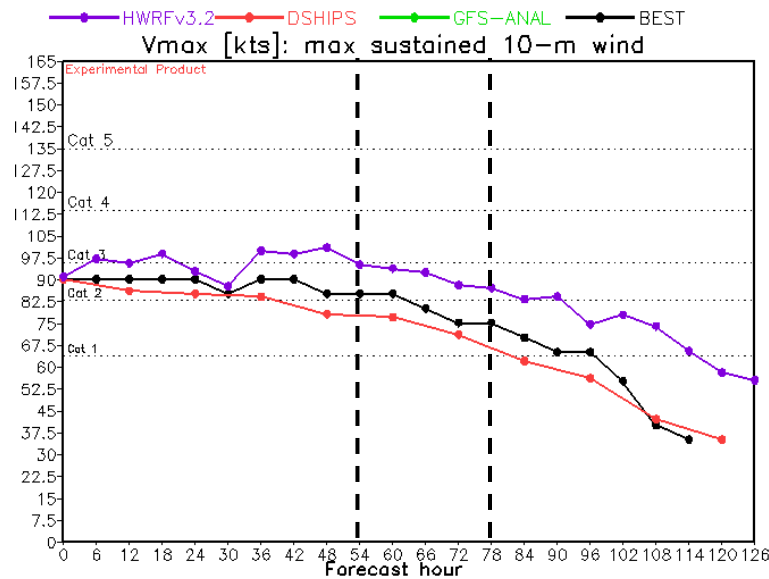

Figure HWRF-5: Anticipated weakening as shear-induced structure changes occur in HWRF (purple).

Analysis Strategy:

The basic analysis follows that presented in recent observational studies of the vertically sheared TC (Reasor et al. 2009; Reasor and Eastin 2012; Reasor et al. 2013; Rogers et al. 2013; Zhang et al. 2013). The analysis includes: low-wavenumber kinematic structure of the core region above the boundary layer, vortex tilt, and local VWS derived from airborne Doppler radar observations; low-wavenumber kinematic structure of the boundary layer derived from SFMR and dropsonde measurements; low-wavenumber thermodynamic structure within and above the boundary layer derived from dropsondes and flight-level measurements; and convective burst statistics derived from Doppler radar observations. New elements of the analysis will include: 3D kinematic structure out to 4xRMW using radar observations; low-wavenumber kinematic, thermodynamic, and moisture structures out to 2 deg using G-IV radar and dropsonde observations; high-azimuthal, vertical, and temporal resolution azimuth-height cross sections of moisture and thermodynamic variables at 2xRMW and below flight level; high-azimuthal, vertical, and temporal resolution azimuth-height cross sections of kinematic variables (using Doppler profiles) at 2xRMW throughout the troposphere.

The above unprecedented dataset will be collected in the context of a TC encountering a large increase in VWS. We first document the basic kinematic evolution of the TC on both short (~1 h) and long (~12 h) timescales. For the optimal set of missions, the initial "pre-shear" vortex structure will be approximately axisymmetric and the vortex tilt should be a negligible fraction of the RMW. The core-region moisture envelope should also be approximately axisymmetric. The analysis may reveal horizontal inhomogeneities in θ_e at large distance from the

core. Diagnostic analyses include: vertical tilt, local shear, azimuth-height θ_e at 2xRMW, Doppler profile vertical velocity at 2xRMW, 3D Doppler-derived vertical velocity and reflectivity, storm-relative streamline analyses out to 2 deg, and 3D θ_e analyses below P-3 flight level within 4xRMW and below G-IV flight level between 1 and 2 deg. We also hope to compute downward θ_e fluxes, as in Riemer et al. (2010). These same diagnostics will also be computed at later stages of the sheared TC evolution.

Using the "threshold shear" mission data we document the development of tilt asymmetry out to 4xRMW, the distortion of the moist envelope, and the evolution of the near-core, storm-relative flow topology. Also at this stage, we document the development of convective asymmetry within and radially outside the eyewall, examine the shear-relative convective statistics (e.g., as in Eastin et al. 2005), and analyze changes in the boundary layer θ_e structure in relation to changes in convective organization outside the eyewall. At the "large tilt" stage, we anticipate asymmetric coverage of radar reflectors about the storm center. Where reflectors are, the analysis proceeds as above. Diagnostics relying on azimuthal coverage of the winds (e.g., the azimuthal-mean winds, tilt, and local shear) may be restricted to limited radial bands. If available, we will explore the benefits of Doppler Wind Lidar measurements in the echo-free regions of the storm. The objective at this stage is to examine whether the tilt asymmetry organizes convection on the vortex scale, how and where low θ_e air is transported into the near-core region, whether low θ_e air is transported into the boundary layer outside the eyewall, the modification of θ_e as parcels move inward towards the eyewall (if they do; see Zhang et al. (2013) and Riemer et al. (2013) for examples where the storm-relative core-region flow within the boundary layer of a sheared storm is radially outward), and changes in azimuthal-mean θ_e within the eyewall region and its relation to intensity change.

At the "realignment and recovery" stage, the optimal experiment will reveal a core kinematic and thermodynamic structure that more closely resembles the "pre-shear" structure than observed during the intermediate missions. The moist envelope may still be distorted, but the mechanism for downward transport of the low θ_e air will be diminished due to the reduction in vortex tilt. If the vortex continues to shear apart during this mission, the analysis will focus on the development of boundary layer "cold pools" using the dropsonde measurements, and, to the extent possible, the deterioration of the vertical structure of the TC's primary circulation (e.g., Reasor et al. 2000; Sec. 4 of Riemer et al. (2013)).

Modules:

1) *Boundary layer inflow*

   Summary: This module is designed to complement standard operationally-tasked P-3 Tail Doppler Radar (TDR) missions by obtaining near-surface wind vector data from GPS dropwindsondes where Doppler winds are not readily available.

   Background: The near-surface inflow is a crucial region of a tropical cyclone (TC), since it is the area of the storm in direct contact with the ocean moisture and heat sources which power the storm. Recent composite analysis of near-surface wind data has led to a more accurate description of general TC inflow characteristics, including asymmetries (Zhang and Uhlhorn 2012). However, it has also become clear that there are few individual cases that contain sufficient observations to develop an accurate synoptic view and comprehensive understanding of boundary layer inflow evolution as a TC intensifies or weakens, changes motion, experiences eyewall/rain-band cycles, and is impacted by shear to varying degrees. To fill this data gap, the proposed modular experiment is developed to augment wind vector observations from Doppler radar that are routinely obtained by NOAA WP-3D aircraft.

   Synopsis: The flight pattern is consistent with a typical rotated "alpha" (Figure-4) pattern flown for TDR missions (**Fig. 10-6**). The rotated pattern (as opposed to the repeated alpha pattern) is preferable to better resolve higher (than 1) wavenumber asymmetric wind field structure. In addition, it is requested to fly the pattern as orthogonal pairs of radials, rather than rotating radials by 45 deg. as the flight proceeds. The initial (IP) and final (FP) points of the pattern are arbitrary. Required instrumentation consists of expendable probes (34 dropwindsondes and 16 AXBTs) as depicted in **Fig. 10-6**. Note that in particular, high-resolution sampling (3 sondes spaced ~1 min apart) is requested across the radius of maximum wind (RMW) on a pair of orthogonal radii to help better estimate boundary layer gradient winds. Center drops are requested on the first and last pass through the eye.

Research plan: The optimal successful experiment will yield a synoptic view of near surface inflow over a series of consecutive missions to document the evolution of boundary layer inflow as a TC progresses through its life cycle. Our research goal is to better understand details about environmental impacts on BL inflow which is not adequately described by the composite analysis constructed from data obtained from numerous independent cases. Specific questions we wish to answer are: 1) How might environmental shear modulate the expected, frictionally-induced inflow asymmetry? 2) What is the relationship between near- surface inflow and inflow above the BL as depicted by Doppler wind analysis? 3) How are near-surface inflow and thermodynamic fields (temperature and moisture and associated fluxes) inter-related?

2) *Extratropical Transition*

Significance: The poleward movement of a tropical cyclone (TC) initiates complex interactions with the midlatitude environment frequently leading to sharp declines in hemispheric predictive skill. In the Atlantic basin, such interactions frequently result in upstream cyclone development leading to high-impact weather events in the U. S. and Canada, as well as downstream ridge development associated with the TC outflow and the excitation of Rossby waves leading to downstream cyclone development. Such events have been shown to be precursors to extreme events in Europe, the Middle East, and may have led to subsequent TC development in the Pacific and Atlantic basins as the waves progress downstream. During this time, the TC structure begins changing rapidly: the symmetric distributions of winds, clouds, and precipitation concentrated about a mature TC circulation center develop asymmetries that expand. Frontal systems frequently develop, leading to heavy precipitation events, especially along the warm front well ahead of the TC. The asymmetric expansion of areas of high wind speeds and heavy precipitation may cause severe impacts over land without the TC center making landfall. The poleward movement of a TC also may produce large surface wave fields due to the high wind speeds and increased translation speed of the TC that results in a trapped-fetch phenomenon.

During this phase of development, hereafter referred to as extratropical transition (ET), the TC encounters increasing vertical wind shear and decreasing sea surface temperatures, factors that usually lead to weakening of the system. However, transitioning cyclones sometimes undergo explosive cyclogenesis as extratropical cyclones, though this process is poorly forecast. The small scale of the TC and the complex physical processes that occur during the interactions between the TC and the midlatitude environment make it very difficult to forecast the evolution of track, winds, waves, precipitation, and the environment. Due to sparse observations and the inability of numerical models to resolve the structure of the TC undergoing ET, diagnoses of the changes involved in the interaction are often inconclusive without direct observations. Observations obtained during this experiment will be used to assess to what extent improvements to TC structure analyses and the interaction with the midlatitude flow improve numerical forecasts and to develop techniques for forecasting these interactions. Improved understanding of the changes associated with ET will contribute to the development of conceptual and numerical models that will lead to improved warnings associated with these dangerous systems.

Objective: The objective is to gather data to study the physical processes associated with ET and the impact of extra observations in and around an ET event on the predictability of the cyclone undergoing transition and of the environment. To examine the relative roles of the TC and midlatitude circulation, aircraft will be used to monitor the changes in TC structure and the region of interaction between the TC and midlatitude circulation into which it is moving.

Specific goals are:
- To obtain a complete atmosphere/ocean data set of the TC undergoing ET and interacting with the midlatitude circulation, especially at the cyclone outflow and midlatitude jet stream interface.
- To examine the interface between the upper-level outflow from the TC and the midlatitude flow, and how the interaction between the two affects the predictability of both the downstream flow and the enhanced precipitation in the pre-storm environment.
- To understand the dynamical and physical processes that contribute to poor numerical weather forecasts of TC/midlatitude interaction, including validation of forecasts with observations.
- To track the thermal and moisture characteristics of the evolving system and assess their impact on the predictability of TC/midlatitude interaction.
- To measure the influence of the increased vertical wind shear associated with the midlatitude baroclinic

environment on the structural characteristics of the TC circulation.

- To gather microphysical and oceanic measurements along aircraft flight paths.

Requirements:
- The TC and its environment must have been sampled continuously by NOAA aircraft for at least one day prior to the ET event. Regular sampling by the P3s to get structure information from the Airborne Doppler Radar is required. Previous environmental sampling by the G-IV is helpful, but not necessary.
- The TC must have been of at least hurricane intensity during the previous sampling.
- The TC must not have had major land interactions during the previous sampling, or during the proposed experimental missions.
- Concurrent P3 and G-IV missions are helpful, but not required. Solo P3 missions would address vortex resilience issues. No solo G-IV missions would occur.

Hypotheses and questions:
ET depends upon the survival of the TC as it penetrates into midlatitudes in regions of increasing vertical wind shear.

- How is the TC vortex maintained in regions of vertical wind shear exceeding 30 ms-1?
- How is the warm core maintained long after the TC encounters vertical wind shear exceeding 30 ms-1?
- How does vertical shear exceeding 30ms-1 alter the distribution of latent heating and rainfall?
- Does vortex resilience depend upon diabatic processes? On subsequent formation of new vortex centers, or by enlisting baroclinic cyclogenesis?
- Does the vertical mass flux increase during ET, as has been shown in numerical simulations?
- Is downstream error growth related to errors in TC structure during ET?
- Is ET sensitive to the sea-surface temperatures?

Description: The mission is designed to use multiple aircraft to monitor interactions between the TC and the midlatitude circulation. The ideal storm will be a poleward-moving hurricane that is offshore the United States mid-Atlantic coastline. The optimal mission is designed to examine the TC core and the TC/midlatitude interface (**Fig. 10-7**). Aircraft will participate in staggered (12-hourly) missions until out of range, because of the possible rapid changes in structure.

TC region: The WP-3D will fly figure-4 or butterfly patterns as high as possible to avoid hazards such as convective icing. The aircraft will make as many passes as possible through the center of the TC undergoing ET, with a minimum of two passes necessary (**Fig. 10-8**). Legs can be shortened to the south of the storm center if necessary to save time. Dropwindsondes will be deployed at each waypoint and at evenly spaced intervals along each leg with optimal spacing near 60 n mi. AXBTs will be deployed at each waypoint and at the midpoint of each leg only in the northern semicircle from the cyclone center.

Due to a trapped fetch phenomenon, the ocean surface wave heights can reach extreme levels ahead of a TC undergoing ET. Therefore, primary importance for the WP-3D in the northeast quadrant of the TC will be the scanning radar altimeter (WSRA) to observe the ocean surface wave spectra, if available. Flight level will be chosen to accommodate this instrument.

TC/Midlatitude interface and pre-storm precipitation region: Ahead of the TC, important interactions between the midlatitude jet stream and the outflow from the TC occur. This region will be investigated by the G-IV releasing dropwindsondes every 120 n mi during its pattern. The Airborne Doppler Radar aboard the G-IV will be very helpful in determining the structure of the rain shield in this region, but is not a requirement.

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Tropical Cyclone in Shear Experiment

Principal Investigator(s): Paul Reasor (lead), Sim Aberson, Jason Dunion, John Kaplan, Rob Rogers, Eric Uhlhorn, Jun Zhang, Michael Riemer (Johannes Gutenberg-Universität)

Objective: Sample the wind, temperature and moisture fields within and around a TC experiencing a significant increase in environmental vertical wind shear.

What to Target: The *environment* of a TC experiencing a significant increase in environmental vertical wind shear, but with minimal land interaction and positioned away from a significant gradient of sea surface temperature.

When to Target: Before a significant increase in environmental vertical wind shear and during the period of maximum vortex tilt. The G-IV should be coordinated with the corresponding P-3 mission.
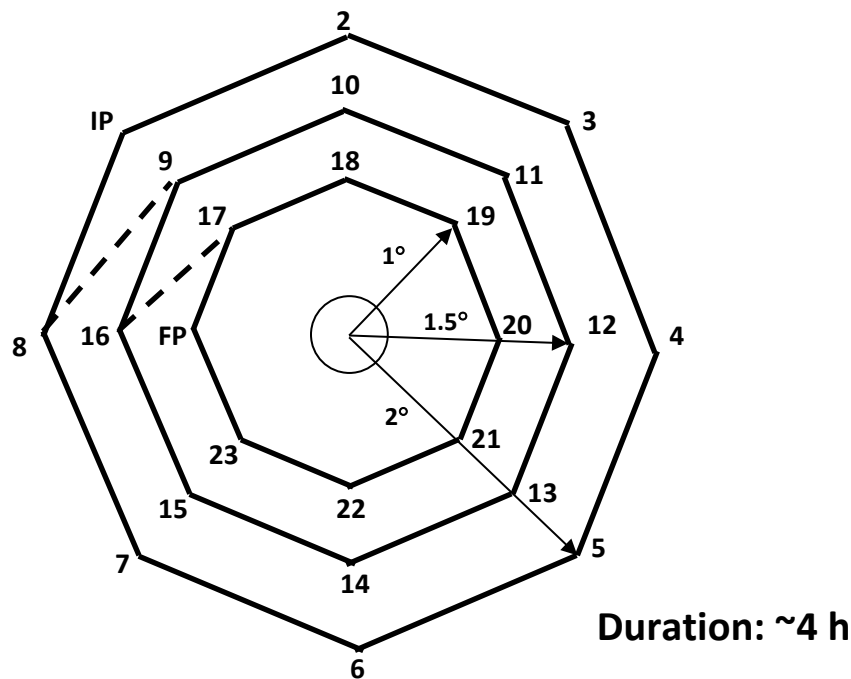
Figure 10-1: G-IV "pre-shear" and "large tilt" outer-core survey pattern

- Altitude: 40-45 kft
- Expendables: Deploy dropsondes at all turn points. No more than 24 GPS drops needed. (18 if suboptimal hexagon pattern is flown)
- Pattern: The pattern is flown with respect to the surface storm center. Three concentric octagons (or suboptimal hexagons) are flown clockwise at decreasing radii of 2 deg, 1.5 deg, and 1 deg. Dashed lines show transitions between rings. If a P-3 is available for sampling out to 1-2 deg, then the radii of the G-IV pattern can be increased to sample on a larger scale. Time permitting, a fourth circumnavigation may be added. The option also exists to rotate the vertices of the middle circumnavigation to increase azimuthal resolution of the dropsonde observations.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

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Objective: Sample the wind, temperature and moisture fields within and around a tropical cyclone experiencing a significant increase in environmental vertical wind shear.

What to Target: The core region of a tropical cyclone experiencing a significant increase in environmental vertical wind shear, but with minimal land interaction and positioned away from a significant gradient of sea surface temperature.

When to Target: Before a significant increase in environmental vertical wind shear. The P-3 should be coordinated with the corresponding G-IV mission.
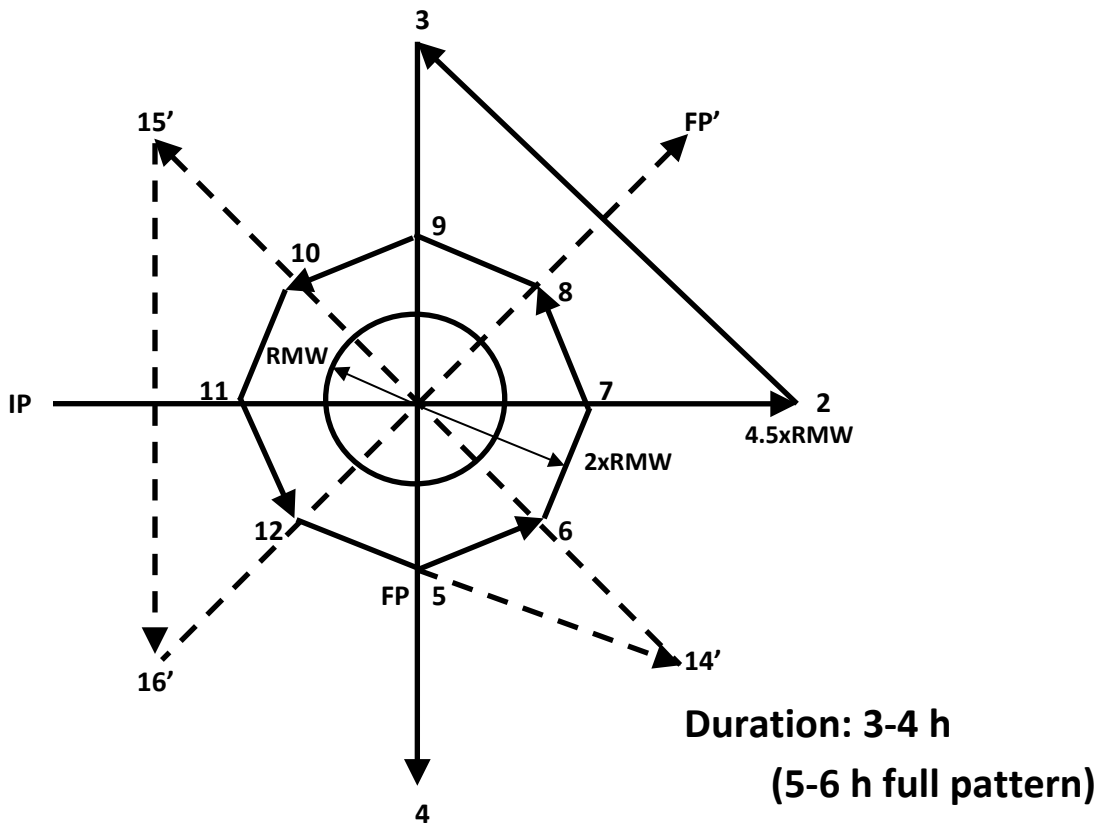
Figure 10-2: P-3 "pre-shear" core-region survey pattern

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Deploy dropsondes at center of first pass, RMW, and 1.2xRMW of Figure-4 legs (if no G-IV, then also at turn points). Deploy dropsondes at turn points (vertices) of octagonal flight pattern legs. No more than 33 drops needed (17 if G-IV present and second Figure-4 not performed).
- Pattern: The pattern is flown with respect to the surface storm center. Radial legs of the initial Figure-4 pattern extend to 4.5xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. Standard 100 nm legs are generally sufficient. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. Safety considerations may require initiation of the circumnavigation on the upshear side in weak echo. If time permits, additional passes may be done from 14' to 15', and from 16' to FP'.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclone in Shear Experiment

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Objective: Sample the wind, temperature and moisture fields within and around a tropical cyclone experiencing a significant increase in environmental vertical wind shear.

What to Target: The core region of a tropical cyclone experiencing a significant increase in environmental vertical wind shear, but with minimal land interaction and positioned away from a significant gradient of sea surface temperature.

When to Target: The large-scale, deep-layer shear reaches a critical threshold value (~20-25 kts). Convective asymmetry should be evident. Ideally, the TC core has just begun to tilt downshear.
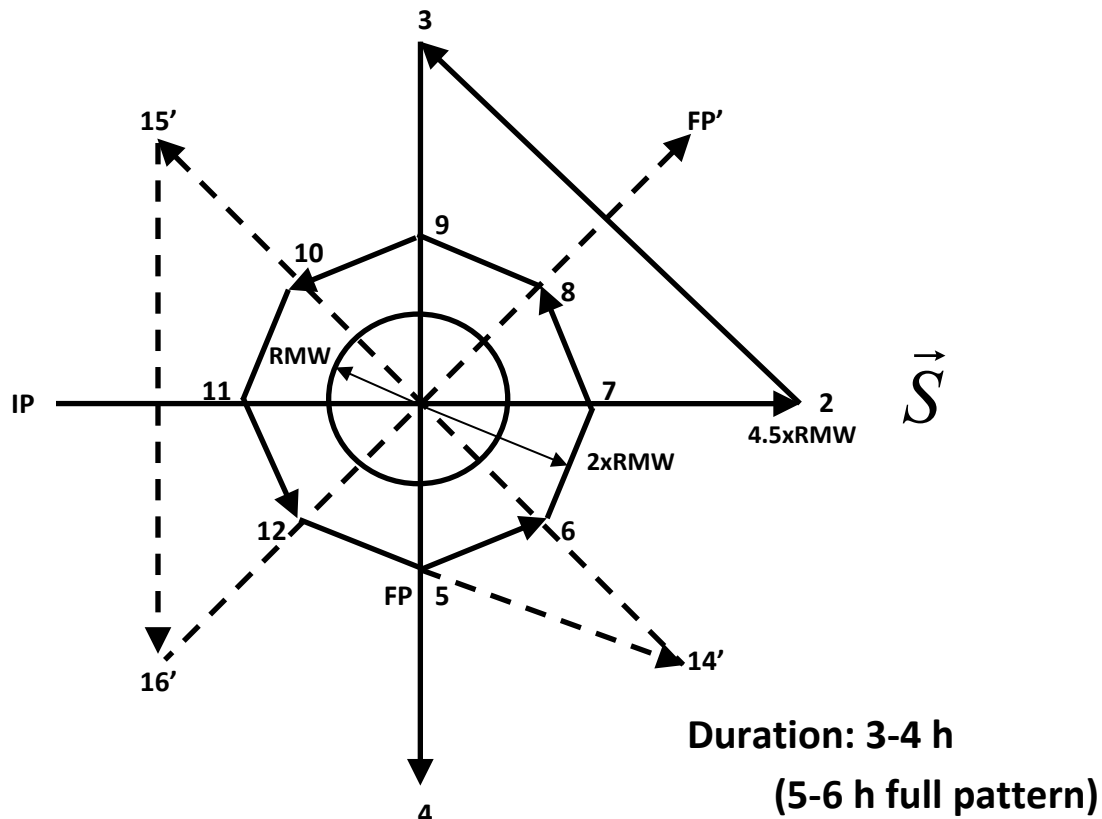

Figure 10-3: P-3 "threshold shear" core-region survey pattern

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Deploy dropsondes at center of first pass, RMW, and 1.2xRMW of Figure-4 legs (if no G-IV, then also at turn points). Deploy dropsondes at turn points (vertices) and mid points of octagonal flight pattern legs. No more than 33 drops needed (17 if G-IV present and second Figure-4 not performed).
- Pattern: The pattern is flown with respect to the surface storm center. The initial inbound leg falls along the large-scale, deep-layer shear vector. Radial legs of the initial Figure-4 pattern extend to 4.5xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. Standard 100 nm legs are generally sufficient. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. Safety considerations may require initiation of the circumnavigation on the upshear side in weak echo. If time permits, additional passes may be done from 14' to 15', and from 16' to FP'.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclone in Shear Experiment

Principal Investigator(s): Paul Reasor (lead), Sim Aberson, Jason Dunion, John Kaplan, Rob Rogers, Eric Uhlhorn, Jun Zhang, Michael Riemer (Johannes Gutenberg-Universität)

Objective: Sample the wind, temperature and moisture fields within and around a tropical cyclone experiencing a significant increase in environmental vertical wind shear.

What to Target: The core region of a tropical cyclone experiencing a significant increase in environmental vertical wind shear, but with minimal land interaction and positioned away from a significant gradient of sea surface temperature.

When to Target: The TC core exhibits large vertical tilt (an intensifying TC may have reduced its rate of intensification or begun to weaken). The P-3 should be coordinated with the corresponding G-IV mission.
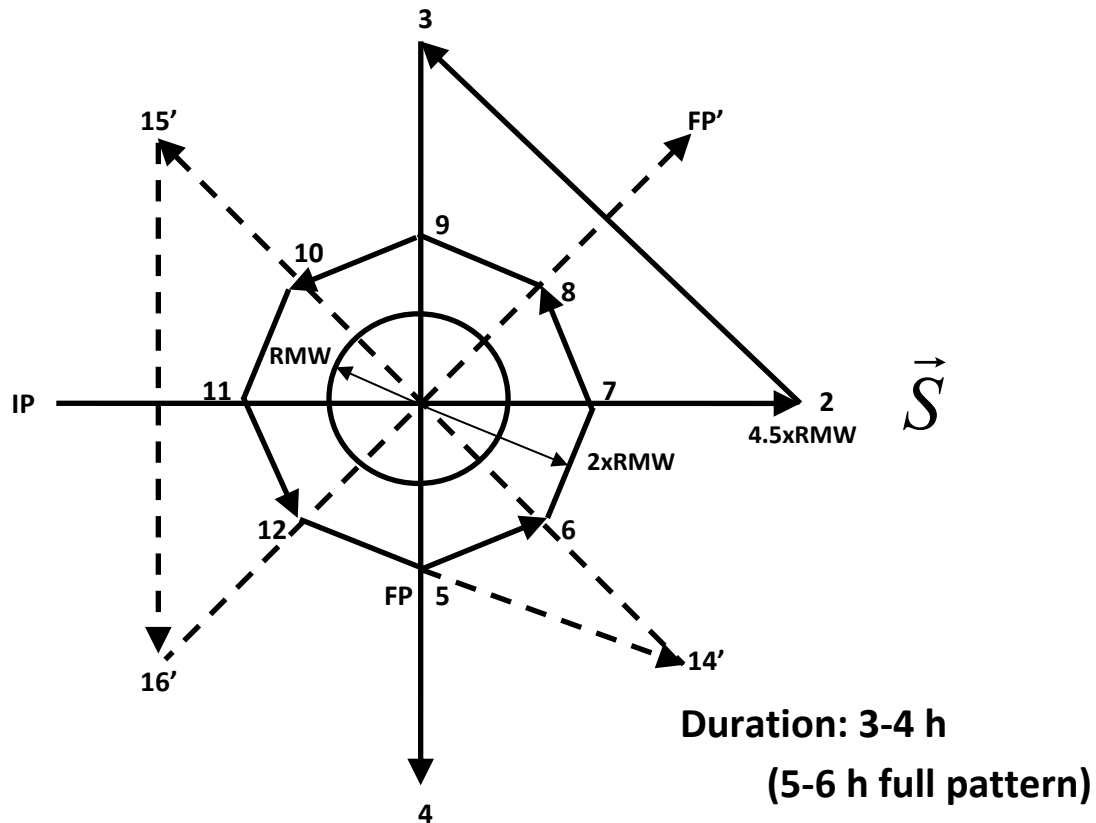

Figure 10-4: P-3 "large tilt" core-region survey pattern

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Deploy dropsondes at center of first pass, RMW, and 1.2xRMW of Figure-4 legs (if no G-IV, then also at turn points). Deploy dropsondes at turn points (vertices) and mid points of octagonal flight pattern legs. No more than 33 drops needed (17 if G-IV present and second Figure-4 not performed).
- Pattern: The pattern is flown with respect to the surface storm center. The initial inbound leg falls along the large-scale, deep-layer shear vector. Radial legs of the initial Figure-4 pattern extend to 4.5xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. Standard 100 nm legs are generally sufficient. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. Safety considerations may require initiation of the circumnavigation on the upshear side in weak echo. If time permits, additional passes may be done from 14' to 15', and from 16' to FP'.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclone in Shear Experiment

Principal Investigator(s): Paul Reasor (lead), Sim Aberson, Jason Dunion, John Kaplan, Rob Rogers, Eric Uhlhorn, Jun Zhang, Michael Riemer (Johannes Gutenberg-Universität)

Objective: Sample the wind, temperature and moisture fields within and around a tropical cyclone experiencing a significant increase in environmental vertical wind shear.

What to Target: The core region of a tropical cyclone experiencing a significant increase in environmental vertical wind shear, but with minimal land interaction and positioned away from a significant gradient of sea surface temperature.

When to Target: The TC core has realigned (a weakening or steady state TC may have begun to intensify).
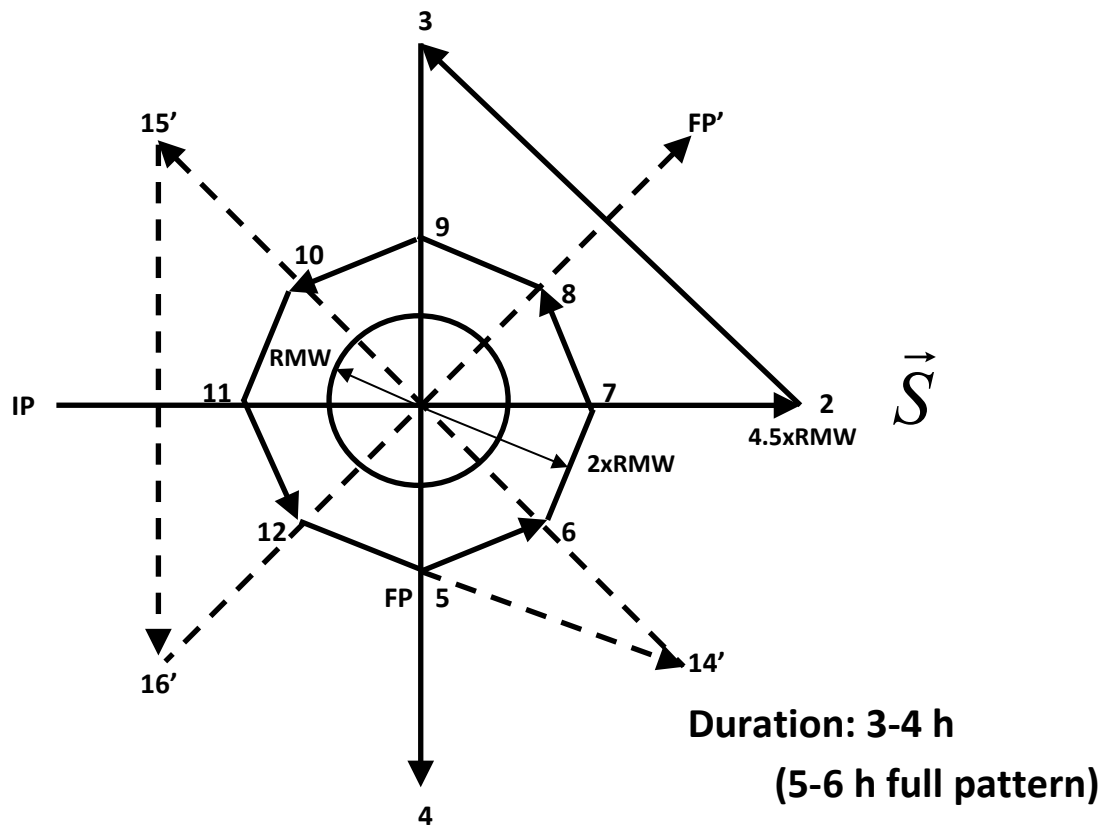

Figure 10-5: P-3 "realignment and recovery" core-region survey pattern

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Deploy dropsondes at center of first pass, RMW, and 1.2xRMW of Figure-4 legs (if no G-IV, then also at turn points). Deploy dropsondes at turn points (vertices) and mid points of octagonal flight pattern legs. No more than 33 drops needed (17 if G-IV present and second Figure-4 not performed).
- Pattern: The pattern is flown with respect to the surface storm center. The initial inbound leg falls along the large-scale, deep-layer shear vector. Radial legs of the initial Figure-4 pattern extend to 4.5xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. Standard 100 nm legs are generally sufficent. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. Safety considerations may require initiation of the circumnavigation on the upshear side in weak echo. If time permits, additional passes may be done from 14' to 15', and from 16' to FP'.
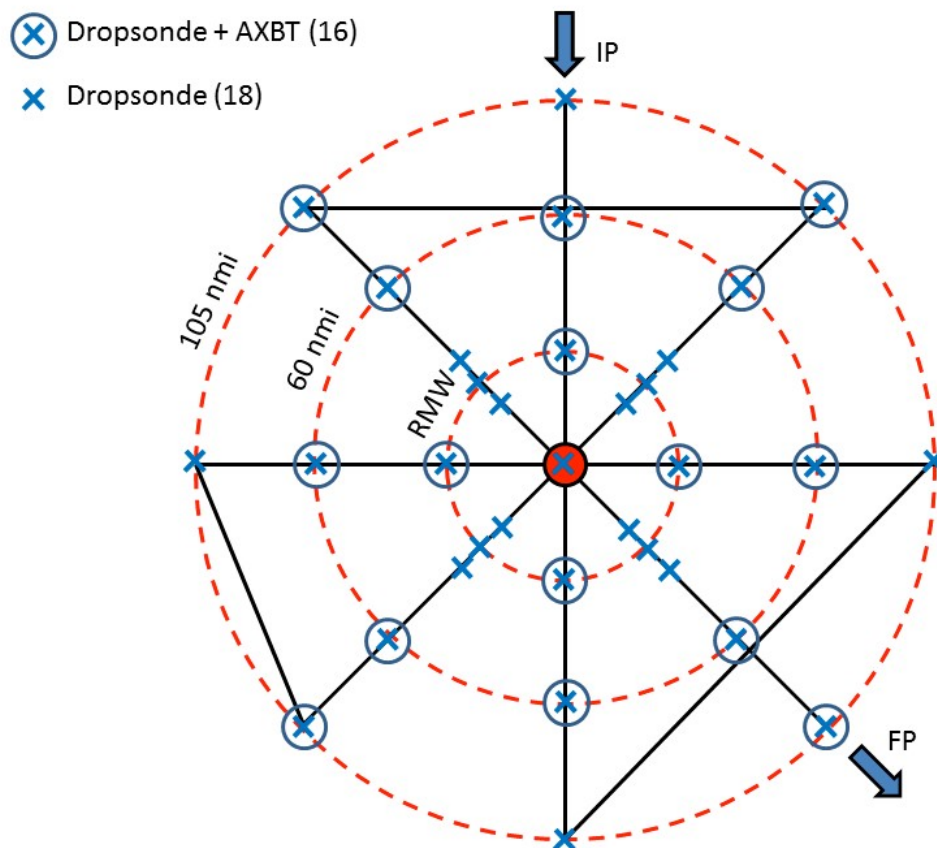- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Figure 10-6: Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/Figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. Center drops are requested on the initial and final pass through the eye. AXBT (16 total) deployments are paired with dropsondes at the indicated locations. Flight altitude is as required for the parent TDR mission, and initial and final points of the pattern are dictated by these same TDR mission requirements.
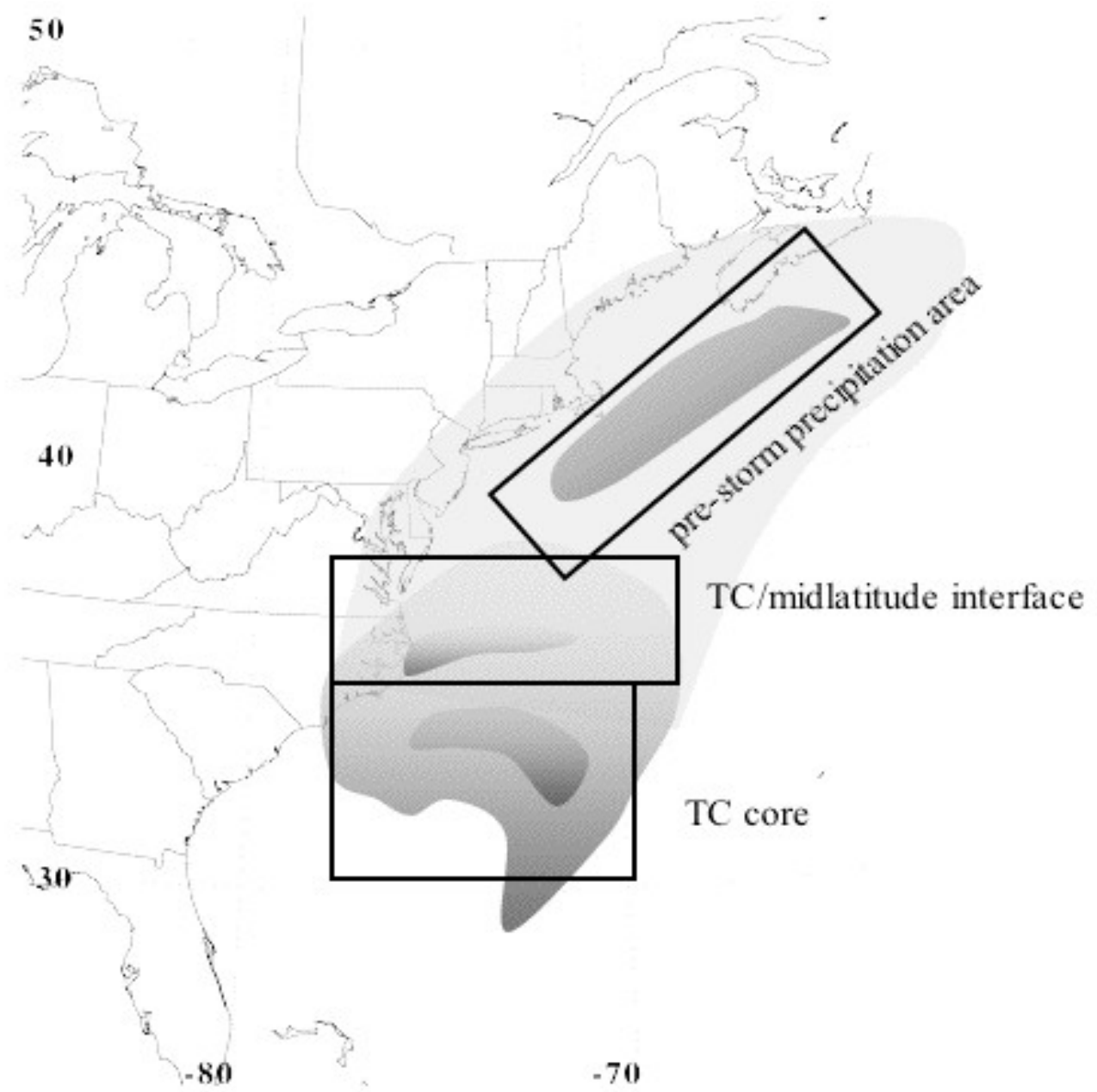
Figure 10-7: Extra-tropical transition module. Schematic of Tropical Cyclone undergoing extra-tropical transition.
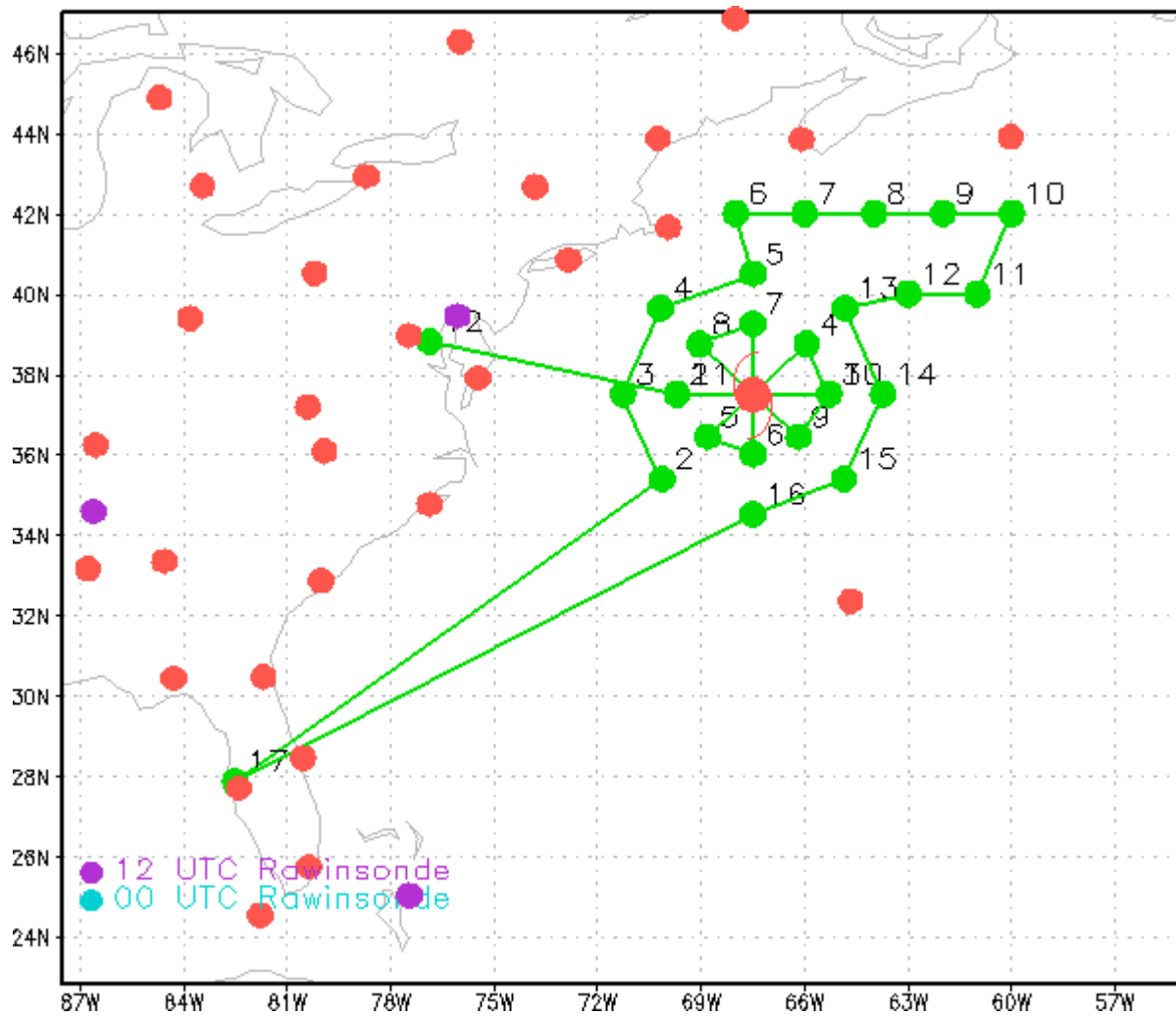
Tropical Cyclone in Shear Experiment

Figure 10-8: Extra-tropical transition module. Proposed flight tracks for G-IV and P3 aircraft.