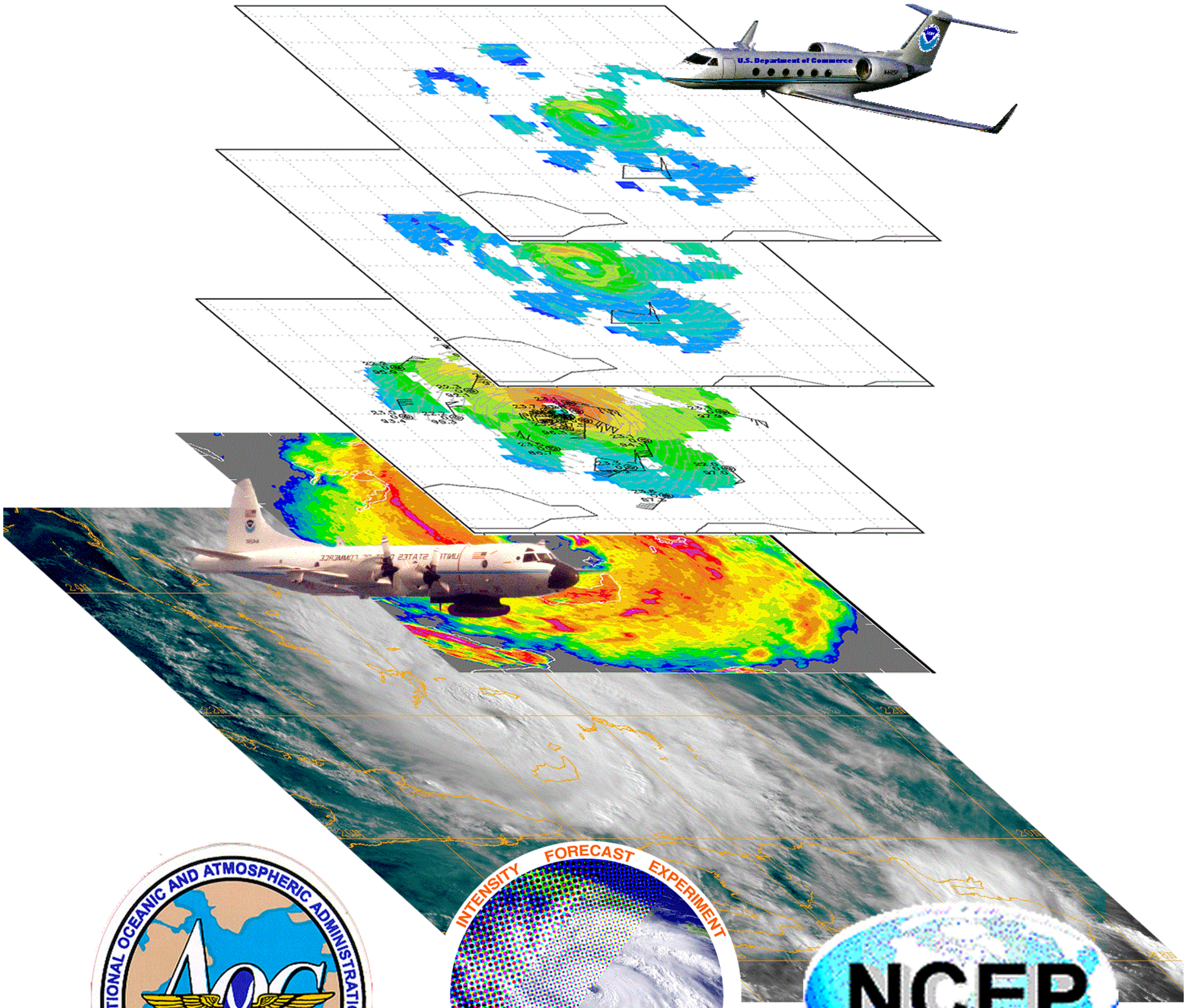
Hurricane Field Program
2013



NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
AOC
AIRCRAFT OPERATIONS CENTER
U.S. DEPARTMENT OF COMMERCE

INTENSITY FORECAST EXPERIMENT
IFEX
EMC - NHC -HRD

NCEP

2013 Hurricane Field Program Plan

Hurricane Research Division
National Oceanographic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
4301 Rickenbacker Causeway
Miami, FL 33149

Prepared by:

Paul Reasor, Sim Aberson, Altug Aksoy, Joe Cione, Peter Dodge, Jason Dunion, John Gamache, Sundararaman Gopalakrishnan, John Kaplan, Mark Powell, Robert Rogers, Eric Uhlhorn, Jun Zhang, Jian-Wen Bao, Gary Barnes, Luca Centurioni, Paul Chang, Chris Fairall, George Halliwell, Rick Lumpkin, Michael Riemer, Nick Shay, and Vijay Tallapragada

Frank D. Marks

1 June 2013

Frank D Marks, Jr
Director, Hurricane Research Division

Date

TABLE OF CONTENTS

IFEX GOAL 1

IFEX GOAL 2

IFEX GOAL 3

2013 HURRICANE FIELD PROGRAM PLAN

INTRODUCTION

National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Hurricane Research Division
Miami, Florida. USA

1. Description of Intensity Forecasting Experiment (IFEX)

One of the key activities in the NOAA Strategic Plan Mission Goal 3 (Reduce Society's Risks from Weather and Water Impacts) is to improve the understanding and prediction of tropical cyclones (TCs). The National Centers for Environmental Prediction (NCEP) National Hurricane Center (NHC) is responsible for forecasting TCs in the Atlantic and East Pacific basins, while the Environmental Modeling Center (EMC) provides NWP guidance for the forecasters. Together they have made great strides in improving forecasts of TC track. With support from the research community, forecast errors of TC track have decreased by about 50% over the past 30 years. However, there has been much less improvement in forecasts of TC intensity, structure, and rainfall. This lack of improvement is largely the result of deficiencies in routinely collecting inner-core data and assimilating it into the modeling system, limitations in the numerical models themselves, and gaps in understanding of the physics of TCs and their interaction with the environment. Accurate forecasts will rely heavily on the use of improved numerical modeling systems, which in turn will rely on accurate observational datasets for assimilation and validation.

The operational Hurricane Weather Research and Forecasting (HWRF) model is run at 3 km grid length using an assortment of physical parameterizations intended to represent subgrid-scale processes important in TC evolution. Such a modeling system holds the potential of improving understanding and forecasting of TC track, intensity, structure, and rainfall. In order to realize such improvements, however, new data assimilation techniques must be developed and refined, physical parameterizations must be improved and adapted for TC environments, and the models must be reliably evaluated against detailed observations from a variety of TCs and their surrounding environments.

To conduct the research necessary to address the issues raised above, since 2005 NOAA has been conducting an experiment designed to improve operational forecasts of TC intensity, called the Intensity Forecasting EXperiment (IFEX; Rogers et al., BAMS, 2006). The IFEX goals, developed through a partnership involving the NOAA Hurricane Research Division (HRD), NHC, and EMC, are to improve operational forecasts of TC intensity, structure, and rainfall by providing data to improve the operational numerical modeling system (i.e., HWRF) and by improving understanding of the relevant physical processes. These goals will be accomplished by satisfying a set of requirements and recommendations guiding the collection of the data:

- **Goal 1**: Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation;
- **Goal 2**: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment;
- **Goal 3**: Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle.

A unique, and critical, aspect of IFEX is the focus on providing measurements of TCs at all stages of their life cycle. The focus of hurricane research flights during the past 30 years has been on mature storms, leading to a dataset biased toward these types of systems. The strategy of observing the entire life cycle of a TC is new and unique, and will provide invaluable information, particularly in sparsely observed environments.

2. Experiment and module summaries

The field program aircraft missions presented in this document are separated into three distinct sections, corresponding to the primary IFEX goal being addressed (note that most experiments address multiple IFEX goals). The flight patterns that comprise these research and operational missions address various aspects of the TC lifecycle, and they all specifically address the main goals of IFEX. A detailed description of each research or operational mission follows, including clarification of the scientific objectives and details of the associated flight patterns.

In this document, reference is made to either "experiments" or "modules." For this discussion, "experiments" refer to missions in which research scientists (i.e., from HRD) set the flight pattern for the duration of the mission. Operational needs take priority in this scenario. "Modules" refer to short patterns that can be flown as a part of a larger experiment (either operational- or research-oriented). Modules generally take 1 h or less for completion.

IFEX GOAL 1: *Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation*

(1a) P-3 Three-Dimensional Doppler Winds Experiment: This is a multi-option, single-aircraft operational mission designed to use the NOAA P-3 to sample TCs ranging in intensity from tropical depression to major hurricane. The definition is intended to separate this category from tropical waves and disturbances that have yet to develop a well-defined warm-core circulation. The main goals of these missions are: 1) to improve understanding of the factors leading to TC intensity and structure changes, 2) to provide a comprehensive data set for the initialization (including data assimilation) and validation of numerical hurricane simulations (in particular HWRF), 3) to improve and evaluate technologies for observing TCs, and 4) to develop rapid real-time communication of these observations to NCEP.

(1b) G-IV Tail Doppler Radar Experiment: This experiment uses the G-IV aircraft. The goals are to 1) to evaluate the G-IV as a platform for observing the cores of TCs, 2) to improve understanding of the factors leading to TC structure and intensity changes, 3) to provide a comprehensive data set for the initialization (including data assimilation) and validation of numerical hurricane simulations (in particular HWRF), and 4) to develop rapid real-time communication of these observations to NCEP.

(2) HWRF Model Evaluation Experiment: This multi-aircraft experiment is designed to improve NOAA's HWRF model performance through a systematic evaluation process, whereby model biases are documented, understood, and ultimately eliminated by implementing accurate observation-based physical parameterizations.

IFEX GOAL 2: *Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment*

(3) Doppler Wind Lidar (DWL) SAL Module: The main objectives of the P-3 DWL SAL Module are to: 1) characterize the suspended Saharan dust and mid-level (~600-800 hPa) easterly jet that are associated with the Saharan Air Layer (SAL) with a particular focus on SAL-TC interactions; 2) observe possible impingement of the SAL's mid-level jet and suspended dust along the edges of the storm's (AEW's) inner core convection (deep convection).

(4) W-Band Radar Sea-Spray Module: Measurements of sea spray using a profile Doppler cloud radar operating at W-band frequency will be collected in regions absent of precipitation. These observations will be used to investigate the influence of sea spray on surface flux interactions.

(5) NESDIS Ocean Winds and Rain Experiment: This will be executed by NESDIS and aims to improve understanding of microwave scatterometer retrievals of the ocean surface wind and to test new remote sensing techniques. The NESDIS/Center for Satellite Research and Applications in conjunction with the University of

Massachusetts (UMASS) Microwave Remote Sensing Laboratory and AOC have been conducting flights as part this experiment for the past several years. Collecting the raw data allows spectral processing to be done which will allow the rain and surface contributions in the AWRAP data to be decoupled. This is critical in understanding the impacts of rain on the measurements, and thus, the ocean surface wind vector retrievals.

(6) Small Unmanned Aerial Vehicle Experiment (SUAVE): The primary objective of this experiment is to further demonstrate and utilize the unique capabilities of a low latitude UAS platform in order to better document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. For this purpose, we will be using the Coyote UAS. Since the Coyote will be deployed from the manned P-3 aircraft, no UAS-specific forward deployment teams will be required.

IFEX GOAL 3: *Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle*

(7) TC in Shear Experiment: The objective of this multi-aircraft experiment is to sample the TC at distinct phases of its interaction with vertical wind shear, measuring the kinematic and thermodynamic fields with the azimuthal and radial coverage necessary to test structure and intensity change hypotheses motivated by recent theoretical and numerical studies.

(8) TC Diurnal Cycle Experiment: To employ both NOAA P-3 and G-IV aircraft to collect kinematic and thermodynamic observations both within the inner-core (i.e., radius < 200 km) and in the surrounding large-scale environment (i.e., 200 km < radius < 600 km) for systems that have exhibited signs of diurnal pulsing in the previous 24 hours.

(9) TC-Ocean Interaction Experiment: This is a multi-option, single aircraft experiment designed to address questions regarding the general role of various upper-ocean processes on TC intensification. It consists of: i) Pre-storm and post-storm expendable probe surveys associated with TC passage; and ii) Support of upper ocean and air-sea flux measurements made by oceanic floats and drifters. Specifically, one to three float and drifter arrays will be deployed into one or two mature storms by an AFRC C-130J and provide real-time ocean data, and, a NOAA P-3 will deploy dropwindsondes and make SFMR and Scanning Radar Altimeter (SRA) measurements within the float and drifter array as the storm passes over it.

(10) Tropical Cyclogenesis Experiment (GENEX)*:* This multi-option, multi-aircraft experiment is designed to study how a tropical disturbance becomes a tropical depression with a closed surface circulation. It seeks to answer the question through multilevel aircraft penetrations using dropwindsondes, flight-level data, and radar observations on the synoptic, mesoscale, and convective spatial scales. It will focus particularly on dynamic and thermodynamic transformations in the low- and mid-troposphere and lateral interactions between the disturbance and its synoptic-scale environment.

(11) Rapid Intensity Change Experiment (RAPX): This multi-option, multi-aircraft experiment is designed to collect datasets that encompass multiple scales with the overarching goal of improving our ability to predict the timing and magnitude of RI events. This experiment is designed to employ both NOAA P-3 and G-IV aircraft to collect oceanic, kinematic, and thermodynamic observations both within the inner-core (i.e., radius < 120 nm) and in the surrounding large-scale environment (i.e., 120 nm < radius < 240 nm) for systems that have been identified as having the potential to undergo RI within 24-72 h. The SHIPS RI index will be the primary guidance that is used for selecting candidate systems for the short-term time periods (24-36 h), while both the RI index and 3-D numerical models will be used for the longer time ranges (i.e. beyond 36 h).

(12) Tropical Cyclone Landfall Experiment: This is a multi-option, single-aircraft experiment designed to study the changes in TC surface wind structure near landfall. It has several modules that could also be incorporated into operational surveillance or reconnaissance missions. An accurate description of the TC surface wind field is important for warning, preparedness, and recovery efforts.

(13) Saharan Air Layer Experiment (SALEX): Arc Cloud Module: This is a single-aircraft experiment,

designed to investigate how the thermodynamics and kinematics in the environment surrounding a TC are modified when low to mid-level dry air interacts with convection in the TC periphery. Objectives include improving our understanding of how arc clouds and the processes leading to arc cloud formation relate to TC intensity change. Observations could be made using either the P-3 aircraft conducting another experiment, or the G- IV during a synoptic surveillance mission.

(14) <u>Hurricane Boundary Layer Entrainment Flux Module:</u> This is a single-aircraft module designed to directly measure turbulent fluxes of momentum and enthalpy near the top of the inflow layer. These fluxes coupled with the energy content measured by the GPS dropsonde data can determine surface fluxes as a residual of the energy budget. The surface turbulent fluxes are also estimated through the bulk aerodynamic parameterization method using the dropsonde and AXBT data.

(15) <u>Offshore Wind Module</u>: This module is designed as a multi-agency (NOAA, Department of Energy, Department of the Interior) supplemental data collection effort to gather hurricane environmental information in the vicinity of proposed offshore wind farms.

OPERATIONS

1. Locations

Starting on 01 June, the N43RF aircraft will be available with two flight crews available for back to back missions. The Gulfstream IV-SP (N49RF) aircraft will be available on approximately 01 July with two flight crews available for back to back missions. In early August, N42RF will become available. Operations for all aircraft will primarily base out of Tampa, Florida and deployments to U.S. coastal locations in the western Gulf of Mexico for suitable Gulf storms. Occasionally, post-mission recovery may be accomplished elsewhere.

2. Field Program Duration

The hurricane field research program will be conducted from 01 June through 31 October 2013.

3. Research Mission Operations

The decision and notification process for hurricane research missions is shown, in flow chart form, in Appendix A (Figs. A-1, A-2, and A-3). The names of those who receive primary notification at each decision or notification point are shown in Figs. A-1, A-2, and A-3, and are also listed in Appendix A. Contacts are also maintained each weekday among the directors of HRD, NHC, EMC, and AOC.

Research operations must consider that the research aircraft are required to be placed in the National Hurricane Operations Plan of the Day (POD) 24 h before a mission. If operational requirements are accepted, the research aircraft must follow the operational constraints described in Section 7.

4. Task Force Configuration

The NOAA P-3 aircraft, equipped as shown in Appendix G, will be available for research missions on a non-interference basis with tasked operational missions from 01 June to 31 October 2013. Also, the G-IV aircraft should be available, on a non-interference basis with tasked operational missions from approximately 01 July to 31 October 2013.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of the 2013 Hurricane Field Program Plan is the responsibility of the Field Program Director, who in turn, reports directly to the HRD director. In the event of deployment, the Field Program Director may assign a ground team manager to assume overall responsibility for essential ground support logistics, site communications, and site personnel who are not actively engaged in flight. Designated lead project scientists are responsible to the Field Program Director or designated assistants. While in flight, lead project scientists are in charge of the scientific aspects of the mission.

5.2 Aircraft Scientific Crews

Tables B-2.1 through B-2.4 (Appendix B) list the NOAA scientific crewmembers needed to conduct the experiments. Actual named assignments may be adjusted on a case-by-case basis. Operations in 2013 will include completion of detailed records by each scientific member while on the aircraft. General checklists of NOAA science-related functions are included in Appendix E.

5.3 Principal Duties of the Scientific Personnel

A list of primary duties for each NOAA scientific personnel position is given in Appendix D.

5.4 HRD Communications

All field program activities are communicated via our web blog and emails. When field activities are occurring, an internal email will be sent out daily to HRD. The internal email will include up-to-date crew, hotel, storm status and schedules. The blog is our main forum where we will provide field operation status, including deployment information of aircraft and personnel for operations outside Miami.

NHC will serve as the communications center for information and will provide interface between AOC, NHC, and CARCAH (Chief, Aerial Reconnaissance Coordinator, All Hurricanes). Personnel who have completed a flight will provide information to the Field Program Director, as required.

6. Data Management

Data management and dissemination will be according to the HRD data policy that can be viewed at:
http://www.aoml.noaa.gov/hrd/data2.html

A brief description of the primary data types and contact information may be found at:
http://www.aoml.noaa.gov/hrd/data/products.html

Raw data are typically available to all of NOAA-sponsored personnel and co-investigators immediately after a flight, subject to technical and quality assurance limitations. Processed data or other data that has undergone further quality control or analyses are normally available to the principal and co-investigators within a period of several months after the end of the Hurricane Field Program.

All requests for NOAA data gathered during the 2013 Hurricane Field Program should be forwarded by email to the associated contact person in the HRD data products description (link above) or in writing to: Director, Hurricane Research Division/AOML, 4301 Rickenbacker Causeway, Miami, Florida 33149.

7. Operational Constraints

NOAA P-3 aircraft are routinely tasked by NHC and/or EMC through CARCAH (Chief, Aerial Reconnaissance Coordinator, All Hurricanes) to perform operational missions that always take precedence over research missions. Research objectives can frequently be met, however, through these operational missions. Occasionally, HRD may request, through NHC and CARCAH, slight modifications to the flight plan on operational missions. These requests must not deter from the basic requirements of the operational flight as determined by NHC and coordinated through CARCAH.

Hurricane research missions are routinely coordinated with hurricane reconnaissance operations. As each research mission is entered into the planned operation, a block of time is reserved for that mission and operational reconnaissance requirements are assigned. A mission, once assigned, *must be flown in the time period allotted and the tasked operational fixes met.* Flight departure times are critical. Scientific equipment or personnel not properly prepared for the flight at the designated pre-take-off time will remain inoperative or be left behind to insure meeting scheduled operational fix requirements. Information on delays to, or cancellations of, research flights must be relayed to CARCAH.

8. Calibration of Aircraft Systems

Calibration of aircraft systems is described in Appendix B (B.1 en-route calibration of aircraft systems). True airspeed (TAS) calibrations are required for each NOAA flight, both to and from station and should be performed as early and as late into each flight as possible (Fig. B-1).

EXPERIMENT AND MODULE DESCRIPTIONS

1a. P-3 Three-Dimensional Doppler Winds Experiment

Principal Investigator(s): John Gamache and Vijay Tallapragada (EMC)

Primary IFEX Goal: 1 - Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation

Program significance: This experiment is a response to the requirement listed as Core Doppler Radar in Section 5.4.2.9 of the National Hurricane Operations Plan. The goal of that particular mission is to gather airborne-Doppler wind measurements that permit an accurate initialization of HWRF, and also provide three-dimensional wind analyses for forecasters.

There are five main goals: 1) to improve understanding of the factors leading to TC intensity and structure changes by examining as much of the life cycle as possible, 2) to provide a comprehensive data set for the initialization (including data assimilation) and validation of numerical hurricane simulations (in particular HWRF), 3) to improve and evaluate technologies for observing TCs, 4) to develop rapid real-time communication of these observations to NCEP, and 5) to contribute to a growing tropical-cyclone database that permits the analysis of statistics of quantities within tropical cyclones of varying intensity.

The ultimate requirement for EMC is to obtain the three-dimensional wind field of Atlantic TCs from airborne Doppler data every 6 h to provide an initialization of HWRF through assimilation every 6 h. The maximum possible rotation of missions is two per day or every 12 h. In hurricanes, coordination will be required between HRD, NCEP, and NESDIS, to effectively collect observations for both the Three- Dimensional Doppler Winds Experiment and the Ocean Winds and Rain Experiment, a NESDIS program designed to improve understanding of satellite microwave surface scatterometery in high-wind conditions over the ocean by collecting surface scatterometery data and Doppler data in the boundary layer of hurricanes.

The highest vertical resolution is needed in the boundary and outflow layers. This is assumed to be where the most vertical resolution is needed in observations to verify the initialization and model. For this reason it is desirable that if sufficient dropwindsondes are available, they should be deployed in the radial penetrations in the Three-Dimensional Doppler Winds experiment to verify that the boundary-layer and surface wind forecasts produced by HWRF resemble those in observations. These observations will also supplement airborne Doppler observations, particularly in sectors of the storm without sufficient precipitation for radar reflectivity. If sufficient dropwindsondes are not available, a combination of SFMR, Advanced Wind and Rain Airborne Profiler (AWRAP), and airborne Doppler data will be used for verification.

Links to IFEX: The P-3 Tail Doppler Radar experiment supports the following NOAA IFEX goals:

Goal 1: Collect observations that span the TC lifecycle in a variety of environments
Goal 2: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment
Goal 3: Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

Mission Descriptions: (The NESDIS Ocean Winds and Rain Experiment will be executed by NESDIS. Specific details regarding these NESDIS missions are not included here.)

Three-Dimensional Doppler Winds: Several different options are possible: i) the lawnmower pattern (Fig. 1a-1); ii) the box-spiral pattern (Figs. 1a-2 and 1a-3); iii) the rotating figure-4 pattern (Fig. 1a-4); iv) the butterfly pattern that consists of 3 penetrations across the storm center at 60-degree angles with respect to each other (Fig. 1a-5); and v) the single figure-4 (Fig. 1a-6). These patterns provide the maximum flexibility in planning, in which the need for dense Doppler-radar coverage must be balanced against the need to sample the entire vortex.

Single-aircraft option only: Temporal resolution (here defined as data collected as close as possible to a 6-h interval) is important, for both initialization and verification of HWRF. This has been verified in communication with EMC. To obtain the maximum temporal resolution feasible, this mission is expected to be a single-P-3 mission, to allow another crew to operate 12 h later, and to continue in a 12-h cycle of single sorties. The type of flight pattern will be determined from the organization, strength and radial extent of the circulation.

Lawnmower pattern: This pattern will be chosen for systems with small, generally asymmetric, weak, newly developed circulations, namely tropical depressions and weak tropical storms. If the system is small enough, lawnmower pattern A (Fig. 1a-1) will be chosen, to permit complete coverage of all reflectors within the developing circulation. Otherwise pattern B will be flown. Pattern B permits a larger area to be sampled, at the expense of some gaps in the Doppler coverage. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at an investigation level at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 12,000 ft. If detailed thermodynamic data from dropwindsondes is desirable, or the distribution of Doppler winds is highly asymmetric, then the preferred level would be 12,000 ft to allow the deepest observation of the thermodynamic and wind structure from the dropwindsondes, while reducing the likelihood of lightning strikes and graupel damage by staying below the melting level. Any orientation of the long and short flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

Box-spiral pattern: As the weak, developing, poorly organized circulations become larger, it will be necessary to spread out the pattern to cover a larger area at the expense of complete Doppler coverage. Pattern A, as shown in Fig. 1a-2, is designed to cover a box 280 nm x 280 nm with radial gaps in the coverage. As long as the circulation is still weak, but covers a larger area, this pattern will be considered; however, lack of symmetric coverage at all radii renders this a less viable option as the system organizes. Pattern B has denser coverage within the outside box, and it will be considered in smaller systems. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

Rotating figure-4 pattern: As the system intensity and/or organization increases, and a circulation center becomes clearly defined, a rotating figure-4 pattern may be preferred (Fig. 1a-4). The advantage of this pattern over the larger versions of the lawnmower pattern is symmetric wind coverage, and the advantage over the box-spiral pattern is good definition of the wind field at all radii within the pattern. This pattern is obviously preferable to the lawnmower pattern in the event there is any operational fix responsibility for the aircraft. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations. See discussion of “lawnmower pattern” regarding flight altitude and use of dropwindsondes.

Butterfly pattern: This pattern (Fig. 1a-5) should be flown in larger, well-organized TCs, generally in hurricanes. As the hurricane circulation becomes larger, it will be necessary to get the full radial coverage at the expense of full azimuthal coverage. As an example, a butterfly pattern out to 100 nm could be flown in 3.3 h, compared to a similar lawnmower coverage that would take 4.8 h. This pattern is obviously preferable to the lawnmower pattern in the event there is any operational fix responsibility for the aircraft. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations. See discussion of “lawnmower pattern” regarding flight altitude and use of dropwindsondes.

Single figure-4 pattern: This pattern (Fig. 1a-6) will be flown in very large circulations, or when little time is available in storm, such as during ferries from one base of operations to another. It still provides wavenumber 0 and 1 coverage with airborne Doppler data, which should be sufficient in strong, organized systems. Radial coverage out to 240 and 300 nm (4 and 5 degrees) is possible in 5.4 and 6.8 h in pattern. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations. See discussion of “lawnmower pattern” regarding flight altitude and use of dropwindsondes.

Three-Dimensional Doppler Winds Experiment Flight Planning Approach: NOAA will conduct a set of flights during several consecutive days, encompassing as much of a particular storm life cycle as possible. This would entail using the two available P-3s on back-to-back flights on a 12-h schedule when the system is at depression, tropical storm, or hurricane strength.

At times when more than one system could be flown, one may take precedence over others depending on factors such as storm strength and location, operational tasking, and aircraft availability. All other things being equal, the target will be an organizing tropical depression or weak tropical storm, to increase the observations available in these systems. One scenario could likely occur that illustrates how the mission planning is determined: an incipient TC, at depression or weak tropical storm stage is within range of an operational base and is expected to develop and remain within range of operational bases for a period of several days. Here, the highest priority would be to start the set of Three-Dimensional Doppler Winds flights, with single-P-3 missions, while the TC is below hurricane strength (preferably starting at depression stage), with continued single-P-3 missions at 12-h intervals until the system is out of range or makes landfall. During the tropical depression or tropical-storm portion of the vortex lifetime, higher azimuthal resolution of the wind field is preferred over radial extent of observations, while in the hurricane portion, the flight plan would be designed to get wavenumber 0 and 1 coverage of the hurricane out to the largest radius possible, rather than the highest time resolution of the eyewall. In all cases maximum spatial coverage is preferred over temporal resolution during one sortie.

P-3 Three-Dimensional Doppler Winds

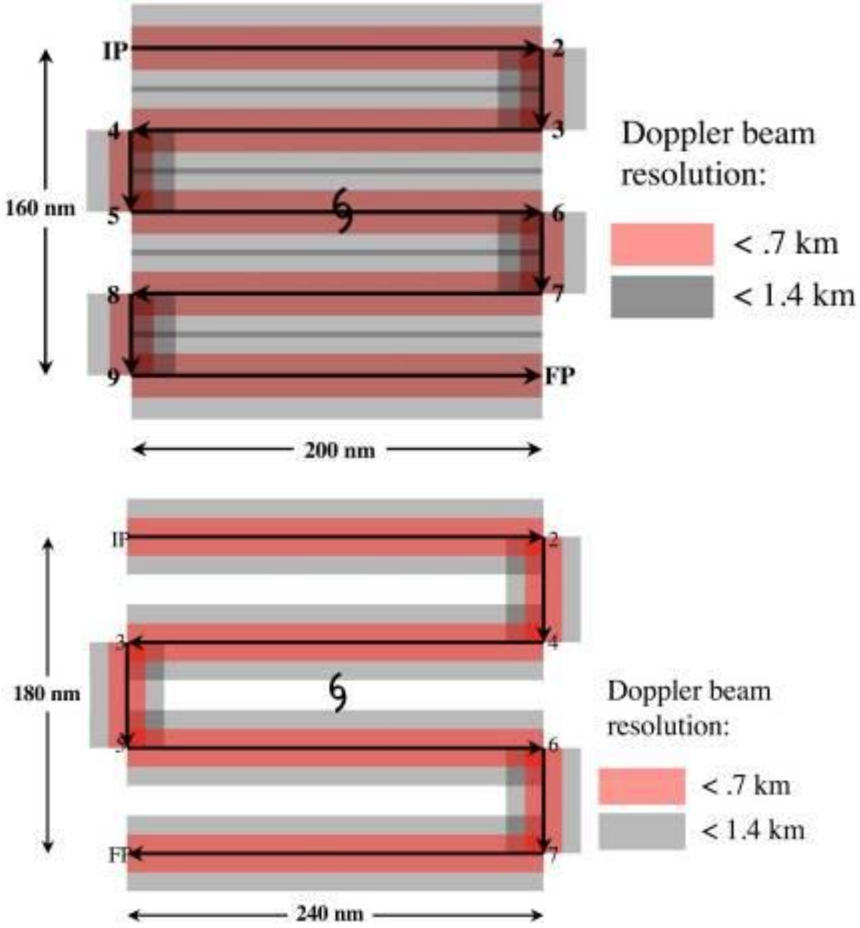


Figure 1a-1: Display of Doppler coverage for A (upper panel) and B (lower panel) lawnmower patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, generally the maximum usable extent of reliable airborne Doppler radar coverage. Total flight distance is 1160 nm for A and 1140 nm for B, and flight times are 4.8 and 4.75 hours, respectively.

Note 1. This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Aircraft flies IP-2-3-4-5-6-7-FP. No attempt should be made to fix a center of circulation unless it is an operational request.
Note 2. Doppler radars should be operated in single-PRF mode, at a PRF of 2100. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 3. Unless specifically requested by the LPS, both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 degrees, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas on the French antenna system.
Note 4. IP can be at any desired heading relative to storm center
Note 5. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 6. If dropwindsondes are not deployed, aircraft can operate at any level below the melting level, with 10,000 ft preferred.
Note 7. Dropwindsondes shown are not a required part of this flight plan and are optional.
Note 8. Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

P-3 Three-Dimensional Doppler Winds

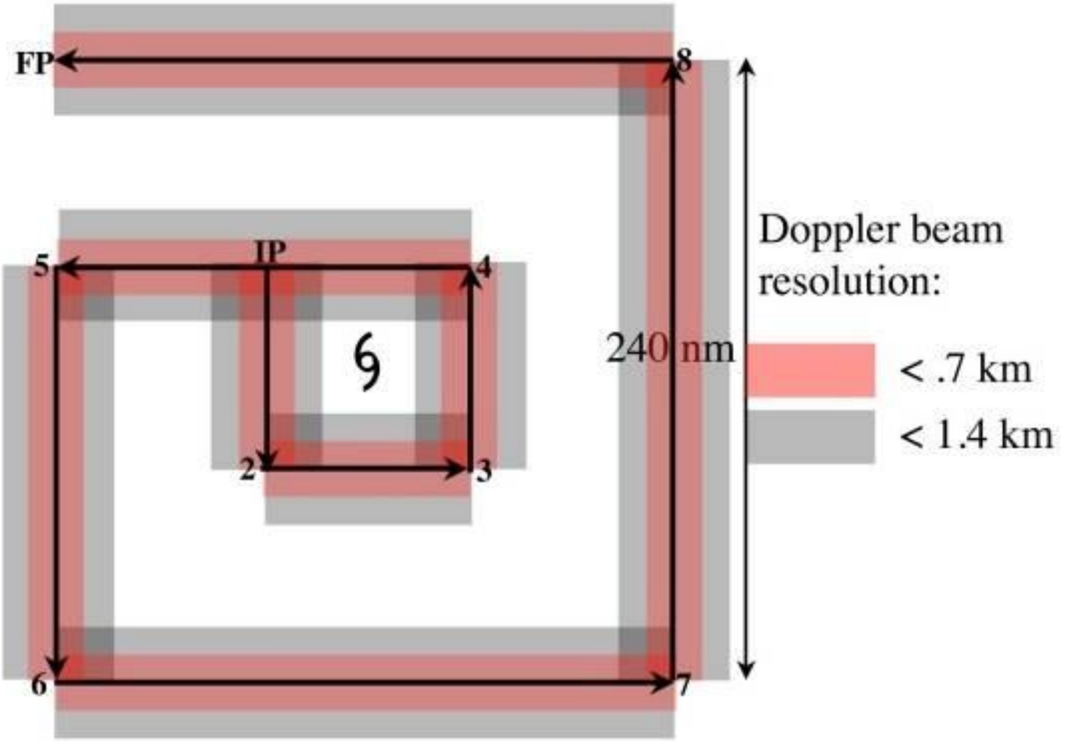


Figure 1a-2: Doppler radar coverage for box-spiral pattern A. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage. Flight distance in pattern above is 1280 nm, and flight time is 5.33 hours.

Note 1. This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Aircraft flies IP-2-3-4-5-6-7-8-FP. No attempt should be made to fix a center of circulation unless requested it is an operational request.
Note 2. Doppler radars should be operated in single-PRF mode, at a PRF of 2100. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 3. Unless specifically requested by the LPS, both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 degrees, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector or continuous scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas in the French antenna system.
Note 4. IP can be at any desired heading relative to storm center
Note 5. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 6. If dropwindsondes are not deployed, aircraft can operate at any level below the melting level, with 10,000 ft preferred.
Note 7. Dropwindsondes shown are not a required part of this flight plan and are optional.
Note 8. Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

P-3 Three-Dimensional Doppler Winds

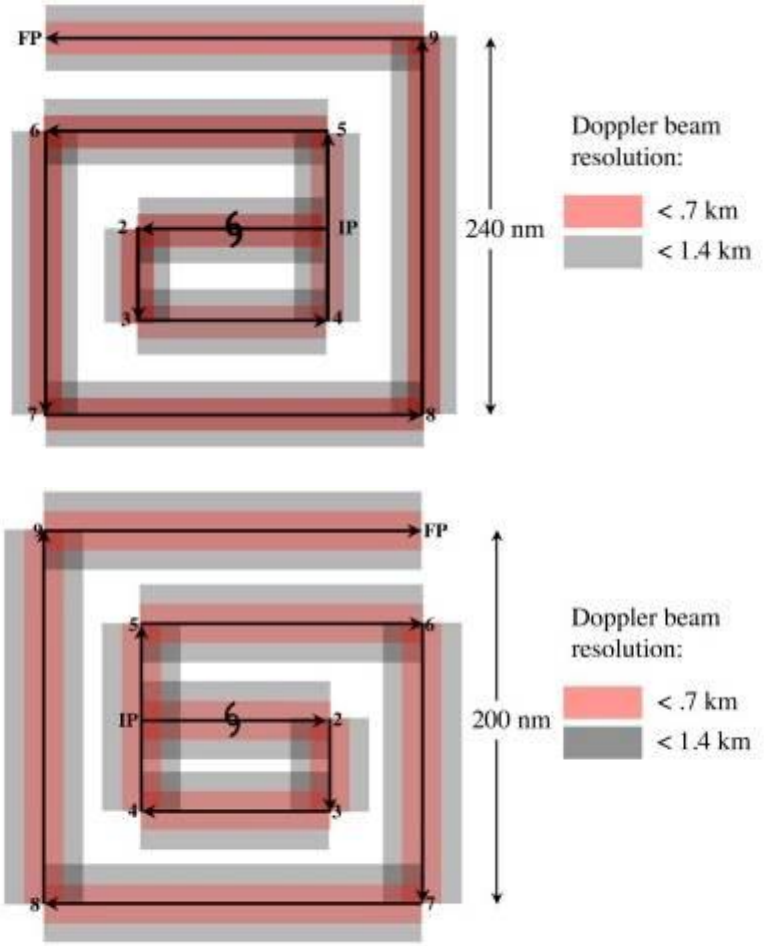


Figure 1a-3: Doppler radar coverage for box-spiral pattern with 200- (top) and 240- (bottom) nm legs. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage. Upper pattern is 1500 nm and uses 6.25 hours, while lower pattern is 1250 nm and uses 5.2 hours.

Note 1. Pattern flown where even coverage is required, particularly in tropical depressions and tropical storms. Doppler radars should be operated in single-PRF mode, at a PRF of 2100, unless in a hurricane—then 2400. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*

Note 2. Both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 degrees, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector or continuous scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas in the French antenna system.

Note 3. IP can be at any desired heading relative to storm center

Note 4. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing.

Note 5. Maximum radius may be decreased or increased within operational constraints.

Note 6. Dropwindsondes shown are not a required part of this flight plan and are optional.

Note 7. Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

Note 8. Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

P-3 Three-Dimensional Doppler Winds

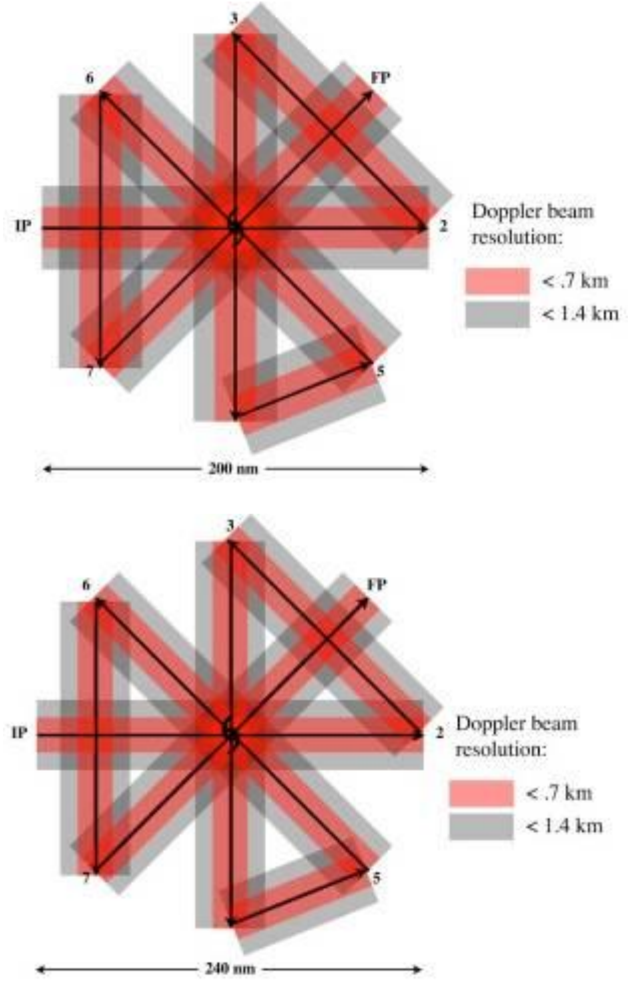


Figure 1a-4: Doppler radar coverage for radial extents of 100 (top) and 120 (bottom) nm of the rotating figure-4 patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

P-3 Three-Dimensional Doppler Winds

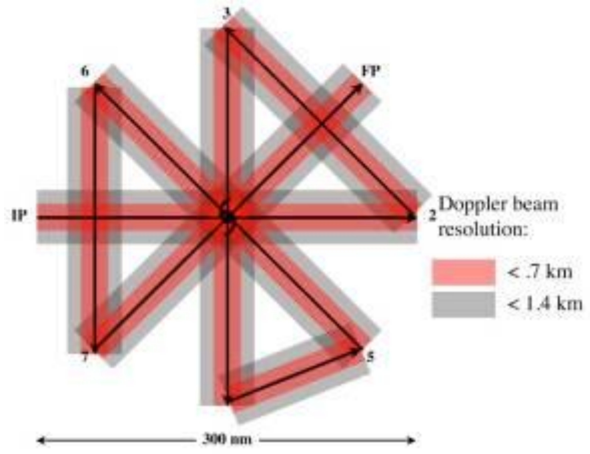


Figure 1a-4 (continued): Doppler radar coverage for 150-nm legs for a rotating figure-4. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

Note 1. This pattern should be flown in strong tropical storms and hurricanes, where the circulation extends from 100 nm to 150 nm from the center. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF for hurricanes, and 2800 for major hurricanes. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*

Note 2. Unless specifically requested by the LPS, both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 degrees, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector or continuous scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas in the French antenna system.

Note 3. IP can be at any desired heading relative to storm center

Note 4. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing

Note 5. Maximum radius may be decreased or increased within operational constraints

Note 6. Dropwindsondes shown are not a required part of this flight plan and are optional.

Note 7. Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

Note 8. Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

P-3 Three-Dimensional Doppler Winds

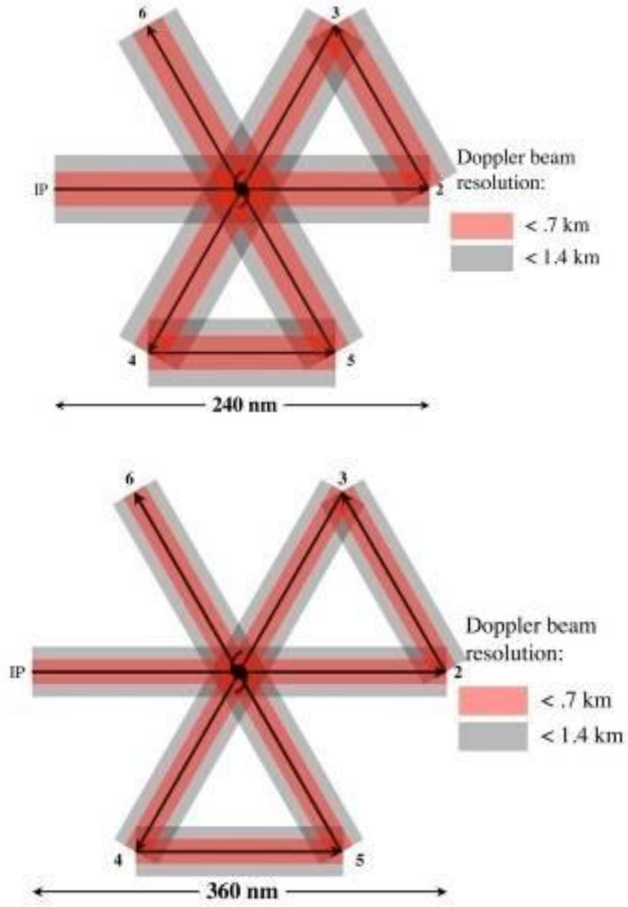


Figure 1a-5: Doppler radar coverage for 120- (top) and 180- (bottom) nm legs for the Butterfly pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage. Flight distances for the patterns with 120 and 180 nm radials legs are 960 and 1440 nm. Corresponding flight durations are 4 and 6 h.

Note 1. This pattern will be flown in large tropical storms, as well as hurricanes. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF for hurricanes, and 2800 for major hurricanes. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*

Note 2. Unless specifically requested by the LPS, both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 degrees, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector or continuous scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas in the French antenna system.

Note 3. IP can be at any desired heading relative to storm center

Note 4. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing

Note 5. Maximum radius may be decreased or increased within operational constraints

Note 6. Dropwindsondes shown are not a required part of this flight plan and are optional.

Note 7. Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

Note 8. Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

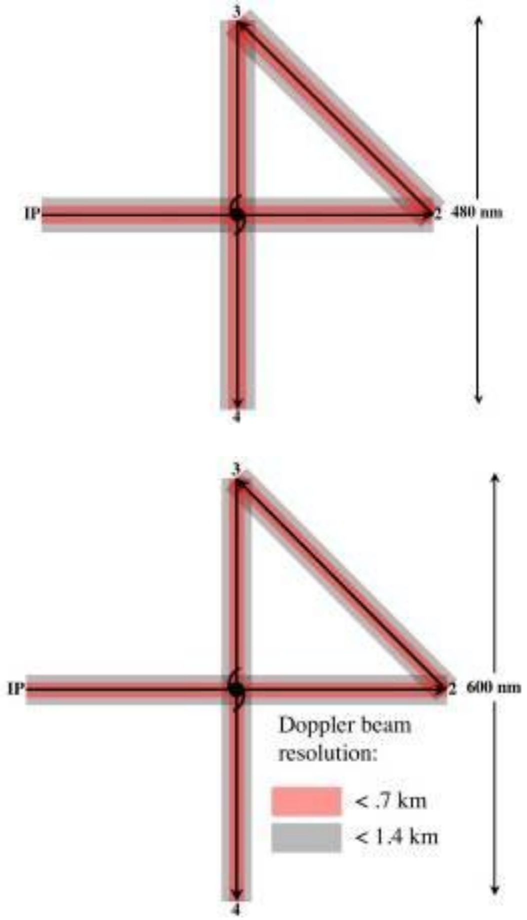


Figure 1a-6: Doppler radar coverage for 300-nm legs for a single figure-4 pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage. Flight distances for radial extents of 240 and 300 nm are 1300 and 1645 nm, respectively. Corresponding flight times are 5.4 and 6.8 h.

Note 1. Pattern for large storms, to obtain as full a radial extent of observations of the full storm circulation as possible. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF for hurricanes and 2800 for major hurricanes. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 2. Both tail Doppler radars should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage. French antenna automatically operates with fore/aft angle of 20 deg, but it should be confirmed, nevertheless that the scanning is F/AST continuous, rather than sector or continuous scanning. Not choosing F/AST scanning will prevent switching between fore and aft antennas in the French antenna system.
Note 3. IP can be at any desired heading relative to storm center
Note 4. To maximize dropwindsonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 5. Maximum radius may be decreased or increased within operational constraints
Note 6. Dropwindsondes shown are not a required part of this flight plan and are optional.
Note 7. Flight pattern should be centered around the 18, 00, 06, or 12 UTC operational model analysis times.
Note 8. Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

1b. G-IV Tail Doppler Radar Experiment

Principal Investigator(s): John Gamache, Peter Dodge, Paul Reasor, Altug Aksoy, and Vijay Tallapragada

Primary IFEX Goal: 1 - Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation.

Program significance: This experiment is a response to the requirement listed as Core Doppler Radar in Section 5.4.2.9 of the National Hurricane Operations Plan. The goal of that particular mission is to gather airborne-Doppler wind measurements that permit an accurate initialization of HWRF, and also provide three-dimensional wind analyses for forecasters. This experiment is similar to the P-3 Three-Dimensional Winds experiment, but employs the G-IV platform and tail Doppler radar.

There are four main goals: 1) to evaluate the G-IV as a platform for observing the cores of TCs, 2) to improve understanding of the factors leading to TC structure and intensity changes, 3) to provide a comprehensive data set for the initialization (including data assimilation) and validation of numerical hurricane simulations (in particular HWRF), and 4) to develop rapid real-time communication of these observations to NCEP.

The ultimate requirement for EMC is to obtain the three-dimensional wind field of Atlantic TCs from airborne Doppler data every 6 h to provide an initialization of HWRF through assimilation every 6 h. In 2013, the maximum possible rotation of missions is two per day or every 12 h. The G-IV platform is currently used by NHC for synoptic surveillance until approximately 36 h prior to TC landfall. In 2013 the flight modules described here are likely to be limited to cases within this landfall window or not of NHC operational interest. In anticipation of future operational use of the G-IV Doppler data, a preliminary flight pattern is introduced which attempts to satisfy the combined need for synoptic surveillance and optimal collection of Doppler data for assimilation. This flight pattern, as well as other proposed G-IV patterns, will be refined through experiments using the Hurricane Ensemble Data Assimilation System (HEDAS) and consultation with NHC.

Following the spring 2012 NOAA acceptance of the G-IV tail Doppler radar, the experiment will focus initially on documenting data coverage in TCs, in particular resolution of the outflow layer (via the central dense overcast). These observations will supplement those collected by the P-3 aircraft, and through HEDAS, their added value in TC initialization will be investigated. Flight patterns will also explore the viability of the G-IV as a substitute for the P-3 aircraft in terms of Doppler radar sampling of the TC core region. Coordinated flights with the P-3 aircraft will be required as part of this assessment.

Links to IFEX: The G-IV Tail Doppler Radar experiment supports the following NOAA IFEX goals:

Goal 1: Collect observations that span the TC lifecycle in a variety of environments

Goal 2: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment

Goal 3: Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

G-IV Three-Dimensional Doppler Winds: Several different options are possible: i) the square-spiral pattern (Figs. 1b-1 and 1b-2); ii) the rotating figure-4 pattern (Fig. 1b-3); iii) the butterfly pattern that consists of 3 penetrations across the storm center at 60-degree angles with respect to each other (Fig. 1b-4); iv) the single figure-4 (Fig. 1b-5); and v) the surveillance/TDR combination pattern (Fig. 1b-6). These patterns provide the maximum flexibility in planning, in which the need for dense date coverage must be balanced against the need to sample the entire vortex.

Square-spiral pattern: As the weak, developing, poorly organized circulations become larger, it will be necessary to spread out the pattern to cover a larger area at the expense of complete Doppler coverage. The pattern, as shown in Figs. 1b-1 and 1b-2, is designed to cover a box 300 nm x 300 nm with radial gaps in the coverage. As long as the circulation is still weak, but covers a larger area, this pattern will be considered; however, lack of symmetric coverage at all radii renders this a less viable option as the system organizes. Fig. 1b-1 (1b-2) shows the option of an outward (inward) spiral from (into) the center. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

Rotating figure-4 pattern: As the system intensity and/or organization increases, and a circulation center becomes clearly defined, a rotating figure-4 pattern may be preferred (Fig. 1b-3). The advantage of this pattern over the square-spiral pattern is good definition of the wind field at all radii within the pattern. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

Butterfly pattern: This pattern (Fig. 1b-4) should be flown in larger, well-organized TCs, generally in hurricanes. As the hurricane circulation becomes larger, it will be necessary to get the full radial coverage at the expense of full Doppler coverage. As an example, a butterfly pattern out to 100 nm could be flown in 3.3 h. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

Single figure-4 pattern: This pattern (Fig. 1b-5) will be flown in very large circulations. It still provides wavenumber 0 and 1 coverage with airborne Doppler data, which should be sufficient in strong, organized systems. Radial coverage out to 240 and 300 nm (4 and 5 degrees) is possible in 5.4 and 6.8 h in pattern. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

Surveillance/TDR combination pattern: This pattern (Fig. 1b-6) will be flown to test the ability of the G-IV platform to satisfy both NHC-tasked surveillance requirements (i.e., sampling the TC environment with GPS dropsondes) and the EMC-tasked requirement for tail Doppler radar sampling of the TC core region. The environmental sampling consists of a cyclonic circumnavigation of the TC at a fixed radius of 150 nm. This is followed by core region sampling using a rotating figure-4 pattern out to 75 nm. The duration of this pattern is approximately 6 h. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

G-IV Tail Doppler Radar Experiment Flight Planning Approach: Ideally, for initial experiments following the NOAA acceptance of the G-IV radar this would entail coordination with a P-3 aircraft conducting a Three-Dimensional Doppler Winds flight when the system is at depression, tropical storm, or hurricane strength. This initial coordination is necessary for 1) comparing and synthesizing storm structure derived from the two radar platforms and 2) the most thorough testing of HEDAS with this new data source. Subsequent flights may relax this requirement for P-3 coordination so as to test the Surveillance/TDR Combination Pattern (Fig. 1b-6). It is not anticipated that the Combination Pattern will be flown during NHC tasking of the G-IV in 2013.

The likely scenarios in which this experiment would be carried out are as follows: 1) at the conclusion of NHC tasking for a landfalling TC, likely coordinated with the P-3 aircraft; 2) prior to NHC tasking for a TC of interest to EMC (priority is coordination with P-3 aircraft); 3) a recurving TC (priority is coordination with P-3 aircraft). Since coordination with the P-3 aircraft is an early requirement, this experiment would have to be weighed against other experiments (e.g., Rapid Intensification) which stagger the P-3 and G-IV flight times.

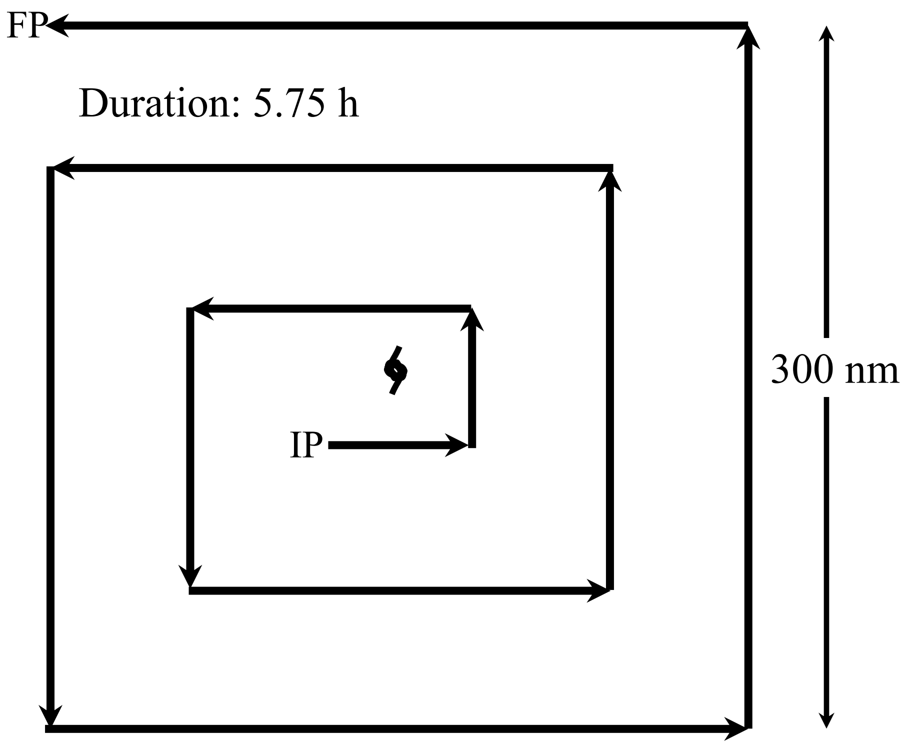


Figure 1b-1: G-IV tail Doppler radar pattern – Square Spiral (outward)

Note 1. G-IV begins 30 nm to south and west of estimated circulation center (with proper rotation starting point can be SE, NE, or NW of center

Note 2. Fly 60 nm due east (due north, due west or due south, for IP SW, NE, and NW of center, respectively)--left turn--60 nm left turn--120 nm--left turn--120 nm--left turn--180 nm--left turn--180 nm--left turn--240 nm--left turn--240 nm--left turn--300 nm--left turn--300 nm--left turn--300 nm

Note 3. Duration: 2100 nm, or 4.75 hour + 1hour for deviations--covers 150 nm (2.5 deg) in each cardinal direction from center

Note 4. Aircraft should operate at its maximum cruising altitude of ~40-45 kft

Note 5. On all legs, deviate to avoid weather deemed to pose possible hazard

Note 6. As flight duration and ATC allow, attempt to sample as much of regions that require deviation

Note 7. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)

Note 8. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

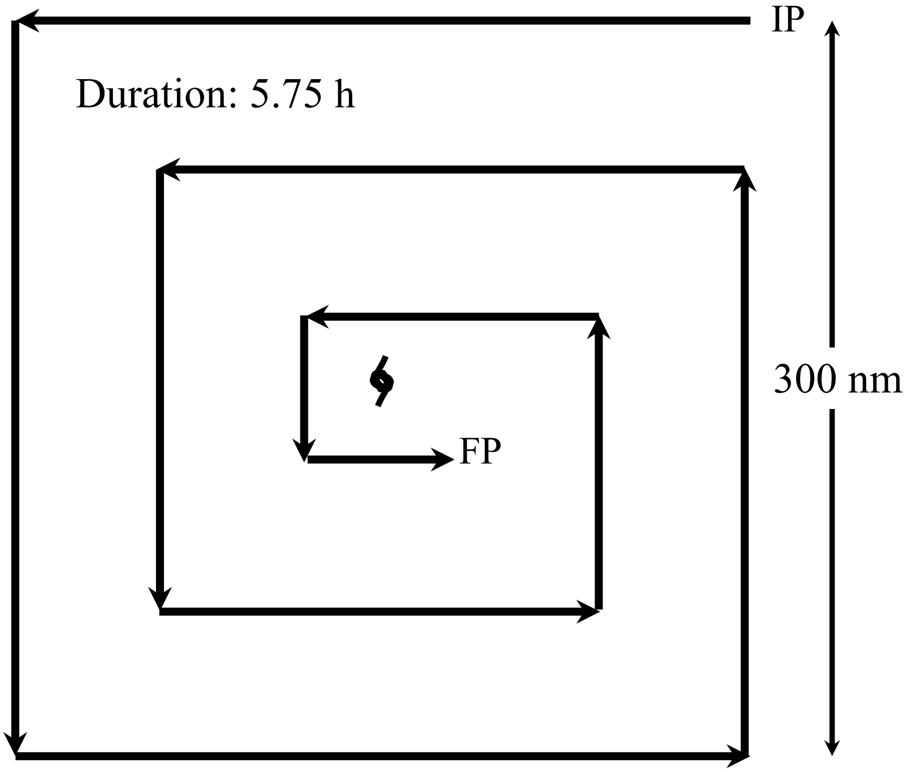


Figure 1b-2: G-IV tail Doppler radar pattern – Square Spiral (inward)

Note 1. G-IV begins 150 nm to north and east of estimated circulation center (with proper rotation starting point can be NE, NW, SW, or SE of center)
Note 2. Fly 300 nm due west (due south, east, north, for IP NW, SW, or SE of center, respectively)--left turn--300 nm--left turn--300 nm--left turn--240 nm--left turn--240 nm--left turn--180 nm--left turn--180 nm--left turn--120 nm--left turn--120 nm--left turn--60 nm--left turn--60 nm
Note 3. Duration: 2100 nm, or 4.75 hour + 1 hour for deviations--covers 150 nm (2.5 deg) in each cardinal direction from center
Note 4. Aircraft should operate at its maximum cruising altitude of ~40-45 kftNote 5. On all legs, deviate to avoid weather deemed to pose possible hazard
Note 6. As flight duration and ATC allow, attempt to sample as much of regions that require deviation
Note 7. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)
Note 8. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

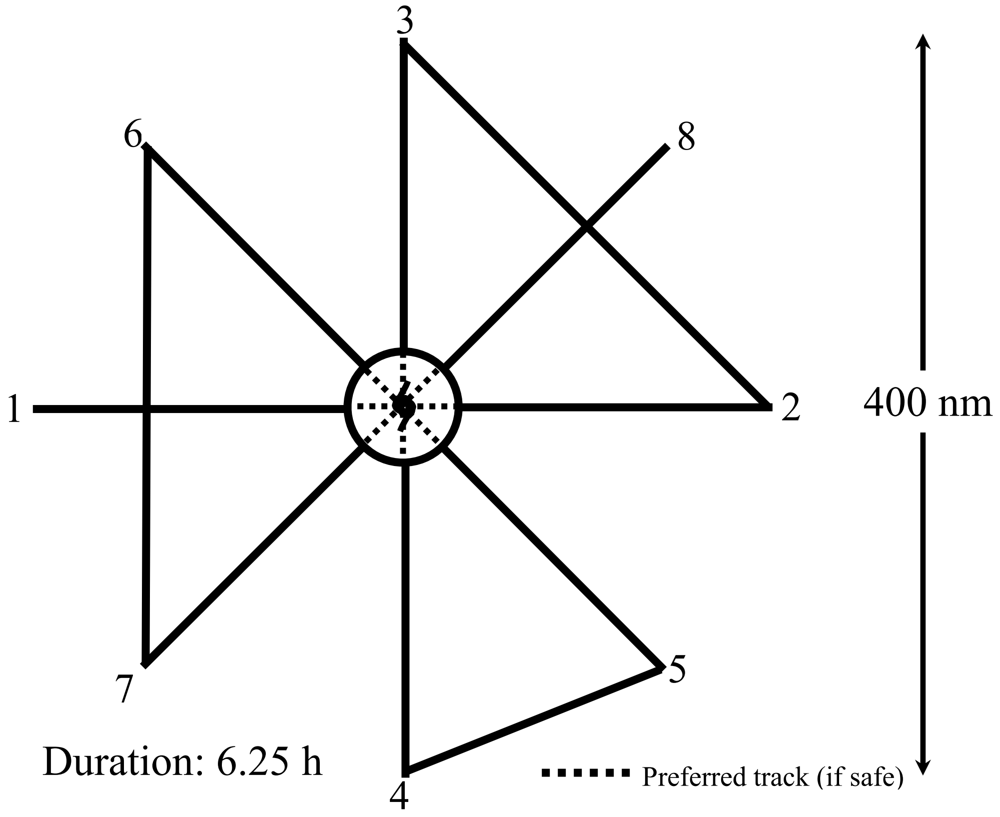


Figure 1b-3: G-IV tail Doppler radar pattern – Rotating Figure-4

Note 1. IP is 200 nm from storm center
Note 2. Fly 1-2, deviating around eyewall if conditions require (eyewall assumed to extend 20 nm from center)--if deviation is required, fly to right of convection if possible. If conditions permit, fly through center of circulation
Note 3. Fly 2-3, deviating around convection if necessary
Note 4. Fly 3-4, as described in segment 1-2
Note 5. Fly 4-5, deviating around convection, if necessary
Note 6. Fly 5-6-7-8 in the same manner as 1-2-3-4
Note 7. Duration: 2317 nm, or 5.25 hours + 1 hour for deviations
Note 8. Aircraft should operate at its maximum cruising altitude of ~40-45 kft
Note 9. As flight duration and ATC allow, attempt to sample as much of regions that require deviations
Note 10. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)
Note 11. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

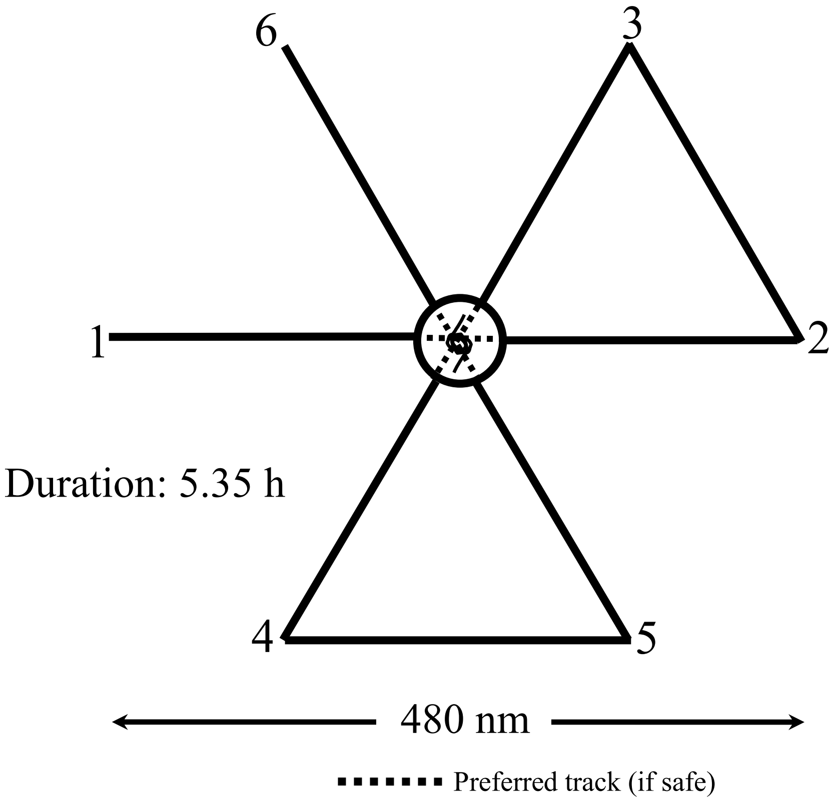


Figure 1b-4: G-IV tail Doppler radar pattern – Butterfly

Note 1. IP is 240 nm from storm center at desired heading from storm center
Note 2. Fly 1-2, deviating around eyewall if conditions require (eyewall assumed to extend 20 nm from center in the figure)--if deviation is required, fly to right of convection if possible. If conditions permit, fly through center of circulation.
Note 3. Fly 2-3, deviating around convection if necessary
Note 4. Fly 3-4-5, as described in segment 1-2
Note 5. Fly 5-6, deviating around convection, if necessary
Note 6. Duration: 1920 nm, or 4.35 hours + 1 hour for deviations
Note 7. Aircraft should operate at its maximum cruising altitude of ~40-45 kft
Note 8. As flight duration and ATC allow, attempt to sample as much of regions missed by deviations
Note 9. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)
Note 10. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

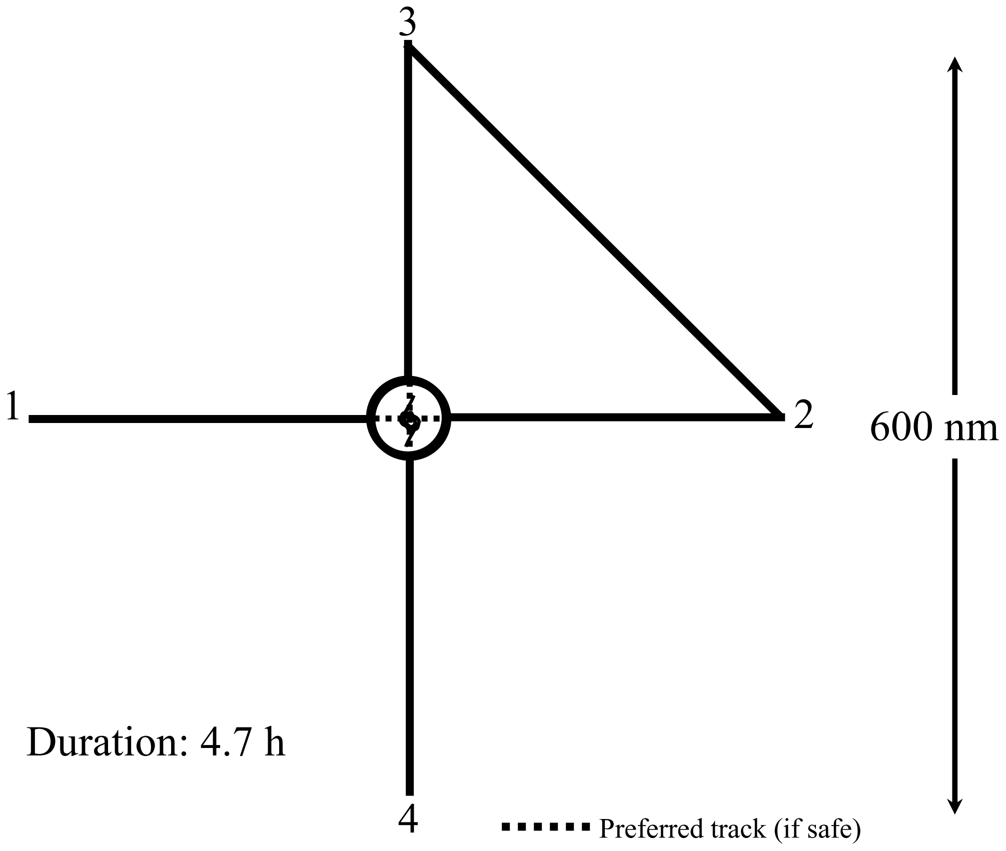


Figure 1b-5: G-IV tail Doppler radar pattern – Single Figure-4

Note 1. IP is 300 nm from storm center
Note 2. Fly 1-2, deviating around eyewall if conditions require (eyewall assumed to extend 20 nm from center in this figure). If deviation is required, fly 1.5 circles around eyewall before continuing to point 2. Otherwise, if conditions permit, fly directly through circulation center.
Note 3. Fly 2-3, deviating around convection if necessary
Note 4. Fly 3-4, as described in segment 1-2; however, if full circle done in first pass, only half circle required
Note 5. Duration: 1624 nm, or 3.7 hours + 1 hour for deviations--pattern could be extended if time allows for even greater radial coverage
Note 6. Aircraft should operate at its maximum cruising altitude of ~40-45 kft
Note 7. As flight duration and ATC allow, attempt to sample as much of regions that require deviations
Note 8. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)
Note 9. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

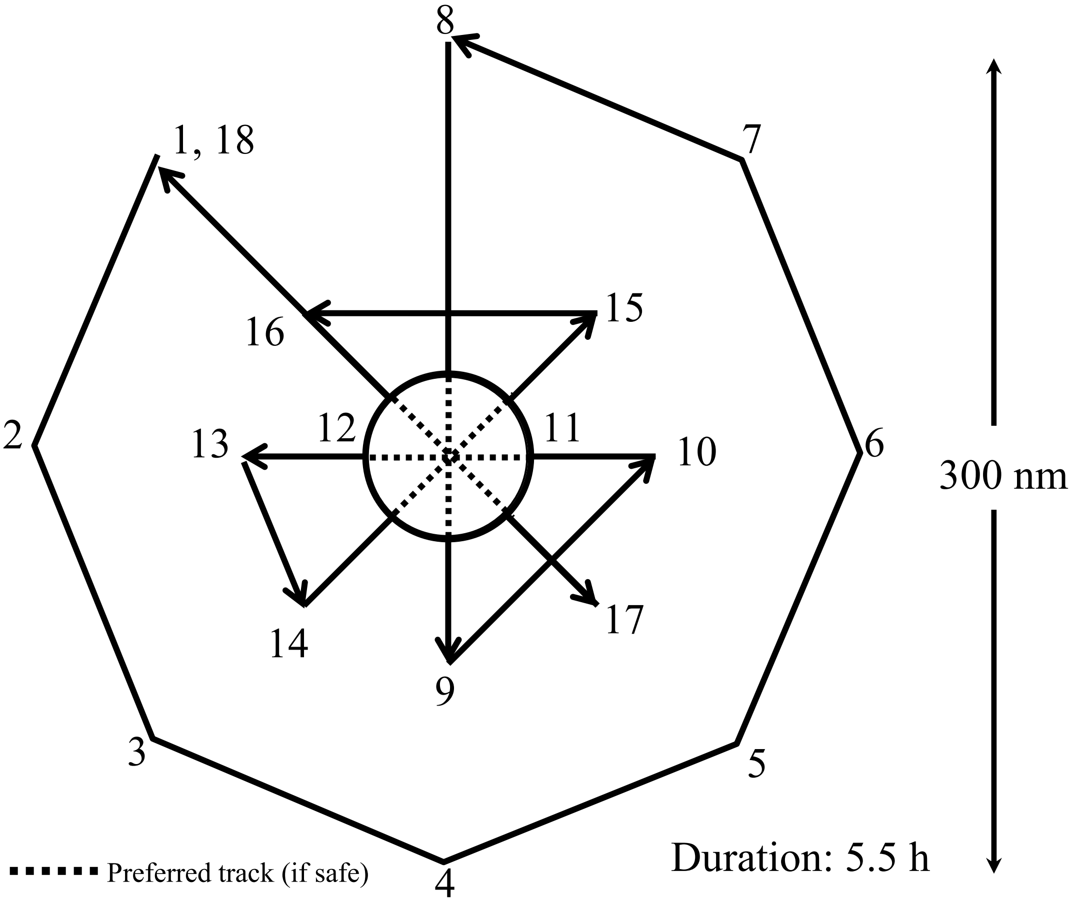


Figure 1b-6: G-IV tail Doppler radar pattern – Surveillance/TDR Combination

Note 1. IP is 150 nm from storm center
Note 2. Fly 1-2-3-4-5-6-7-8-9-10-11-12-11-12-13-14-15-16-17-18, deviating around eyewall if conditions require (eyewall assumed to extend 30 nm from center)--if deviation is required, fly to right of convection if possible. If conditions permit, fly through center of circulation
Note 3. Dropsondes should be launched at all numbered points (except 11 and 12). If the aircraft is able to cross the center, a sonde should be dropped there. Extra sondes may be requested.
Note 4. On-station Duration: ~1933 nm, or about 4.5 hours + 1 hour for deviations
Note 5. Aircraft should operate at its maximum cruising altitude of ~40-45 kft
Note 6. As flight duration and ATC allow, attempt to sample as much of regions that require deviations
Note 7. Tail Doppler radar should be operated at a dual-PRF of 3/2, with the PRFs at 2000 and 3000 (effective Nyquist velocity of 48 m/s)
Note 8. If flying above 40,000 ft, pattern may be flown clockwise, if preferred.

2. HWRF Model Evaluation Experiment

Principal Investigator(s): J. Cione, E. Uhlhorn, S. Gopalakrishnan, V. Tallapragada, R. Lumpkin, R. Rogers, J. Zhang, G. Halliwell, C. Fairall, J. Bao, N. Shay

Primary IFEX Goal: 1 – Collect observations that span the tropical cyclone (TC) lifecycle in a variety of environments and for model initialization and evaluation.

Overarching Objective:

Improve NOAA’s Hurricane Weather Research and Forecasting (HWRF) model performance through a systematic evaluation process, whereby model biases are documented, understood, and ultimately eliminated by implementing accurate observation-based physical parameterizations.

Statement of the problem: Recent experiments related to the use of in-situ observations for improved PBL representation in the HWRF system, increased frequency of physics calls and the subsequent steep-step improvements to structure and intensity predictions illustrate the importance of improving the physical representation of hurricane processes in the modeling system. Additional model comparisons with in-situ observations show that the hurricane near-surface thermodynamic environment in NOAA’s HWRF operational model is generally too warm and too moist. Recent comparisons of the coupled modeling system with observations also suggest that the existing ocean used in HWRF (POM) has a tendency to under-cool. Biases such as these impact how surface fluxes are generated in the model, and as a result, can significantly (and adversely) affect hurricane structure, intensity, and the intensity change process.

What to target: This experiment is designed to obtain high-resolution kinematic thermodynamic and microphysical measurements in convectively active areas of the hurricane environment (both rain-band and inner core). In addition, this experiment will capture areas of strong downdraft activity so as to better assess highly transient, yet critically important physical processes responsible for modifying hurricane boundary layer thermodynamic structure. Finally, this effort will also document the ocean environment from the pre-storm quiescent stage through storm passage with the goal of quantifying ocean response in a storm-centric framework.

Mission Description

The ideal experiment consists of coordinated three-plane missions designed to observe several mechanisms responsible for modulating hurricane boundary layer heat and moisture:

- Air-sea energy exchange
- Transport from convective downdrafts
- Entrainment at the boundary layer top
- Lateral transport from the environment
- Ocean response

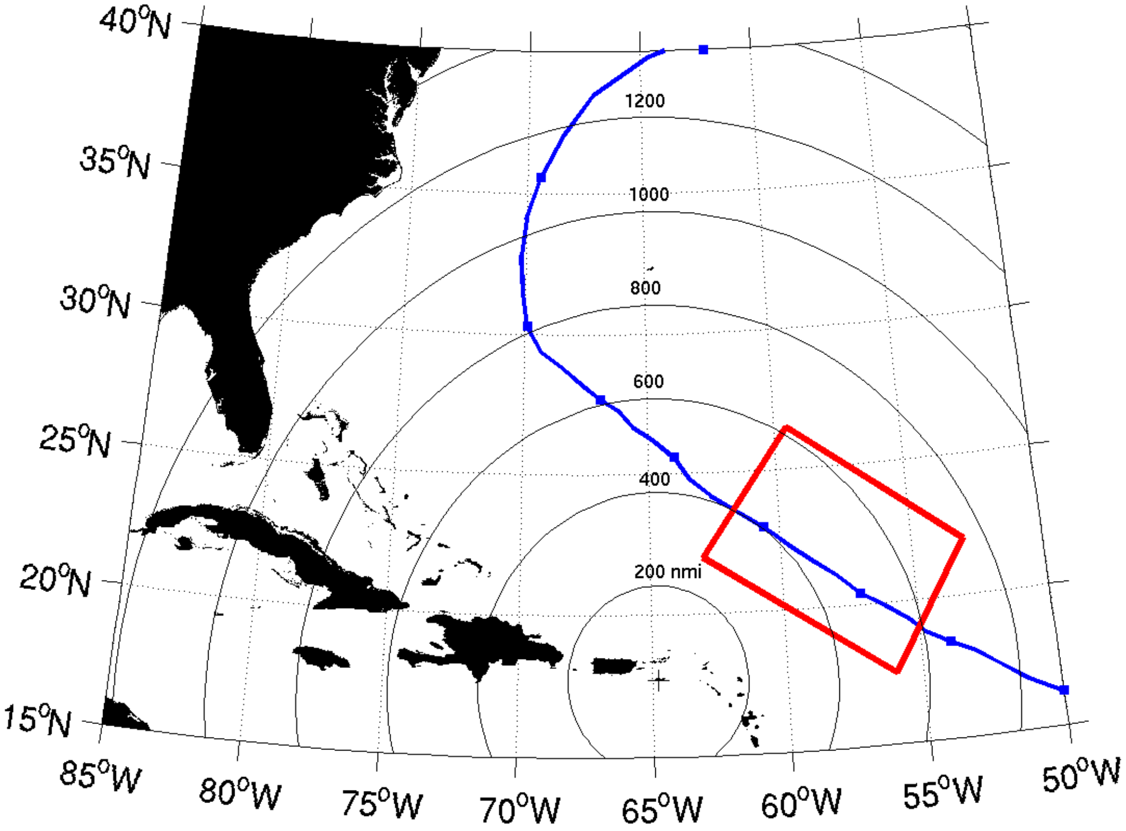


Figure 2-1: Storm track (blue), and observation region (red box), optimally suited for multi-aircraft experiment. Range rings are 200 nmi relative to forward operating base at STX (TISX). Track marks are spaced every 24 hrs.

This multi-aircraft experiment is ideally suited to geographical locales, which limit conflict with other operational requirements, for example, at a forward/eastward-deployed base targeting a storm not imminently threating the U.S. coastline. An optimal geographical situation is shown in Fig. 2-1. It is also worth noting that without such a deployment plan systems not considered to be an immediate threat to make US landfall would likely not be sampled (e.g. Katia 2011).

Each participating aircraft is assigned a “process of responsibility”, whereby the pattern is designed to address specific phenomena and/or processes. Conceptually, this experiment consists of a collection of coordinated modules included in previous years’ Field Program plans. It should also be noted that this experiment will be targeting mature hurricane systems and relies on a 24h cycle of observations (centered roughly on 18Z) with simultaneous utilization of 3 NOAA aircraft (N42RF, N43RF, and N49RF). While several “modular options” exist for this particular experiment, it is important to emphasize that the overall goal is to adequately capture multi-scale interactions within the tropical cyclone environment (i.e. environment/vortex/convective-scale). By doing so, it will be much easier to conduct “budget-oriented” analyses required to accurately evaluate model physical fields and processes.

Capturing structure associated with outer TC environment will be primarily the responsibility of the NOAA GIV aircraft (N49RF). One of the preferred patterns that will be employed is the “starfish” configuration already outlined in several existing HFP experiments (most notably in the RI experiment). Another possible pattern that could be utilized is the circumnavigation flight plan currently described in the shear experiment (proposed for 2013). In either case, the intention for this experiment would be to fly the GIV simultaneously with both P-3 aircraft.

One of the NOAA P-3 aircraft (likely N42RF) will be responsible for capturing storm scale environment (wave number 0/1). Here, the in-storm plan is likely to use a rotating Figure-4 flight pattern (similar to what is currently used for TDR missions). If circumstances dictate, a modified butterfly pattern could be used instead. The exact details of the pattern (e.g. Figure 4, butterfly, specific leg lengths, etc.) will be determined on a flight-by-flight basis.

The second P-3 (likely N43RF) would be tasked to sample pre-determined, high-value areas of interest within specified region(s) of the storm. As previously mentioned, the processes that will be targeted include air sea exchange, vertical/horizontal transport resulting from convective activity (including boundary layer entrainment processes), interactions with the surrounding environment, and ocean response. Additional details associated with these high priority areas are given below.

1) **Air-sea exchange.** At the initiation of the observing period, the pre-storm oceanic environment is sampled to estimate horizontal and vertical ocean structure which is forecasted to respond to TC forcing, ideally 1-2 days prior to the storm's arrival. The observations consist of a field of ocean expendable probes (AXBT, AXCTD, AXCP), and possibly a line a surface drifting probes in coordination with the 53rd WRS. The pre-storm "field" is designed to extend over a significant area to capture a multiple-day event. Refer to "TC-Ocean Interaction Experiment" for details.

   As the TC advances across the previously-sampled region, a series of in-storm missions are executed to observe the storm's evolution. These missions may be carried out in conjunction with other planned experiments, however, one P-3 aircraft is generally assigned the responsibility of observing the overall storm structure, while the other P-3 has a more specific mission to target the localized convective impact (discussed later). The storm-scale P-3 ideally executes a rotated Figure-4 pattern, deploying GPS dropwindsondes and AXBTs in combination to estimated surface fluxes. Refer to "P-3 3D Doppler Winds Experiment" for details.

2) **Convective transport.** The convection-scale P-3 executes one or more "convective-burst module" type patterns associated with outer rain-band structure, deploying a series of GPS dropwindsondes to measure boundary-layer thermodynamic fields to measure the impact of downdrafts for surface fluxes. Refer to the "Convective Burst Module" of GENEX for details.

3) **Entrainment flux.** The same convection-scale P-3 may also be tasked to fly a boundary-layer top entrainment module, consisting of low-level (500 m/1500 ft.) extended legs outside of precipitation to measure the impact of turbulent mixing/shallow convection at the BL top on thermodynamic structure and ultimate surface energy exchange. In addition, the W-band radar for spray flux is ideally on this P-3 to measure outside of precipitation. Refer to "Boundary Layer Entrainment Module" for details.

4) **Transport from the surrounding environment.** Low-level advective transport of moisture from the environment is also responsible for TC boundary-layer moisture. To measure the impact of the environmental moisture source, the G-IV aircraft is tasked with deploying GPS dropwindsondes between 200 and 500 km distance from the storm center. The general flight pattern consists of quasi-radial legs to and from the annulus limits around the storm. Refer to "TC Diurnal Cycle Experiment" for details.

5) **Ocean response.** In anticipation of a coordinated surface drifter deployment, the post-storm ocean current and temperature responses can be observed by drifters for several days after passage. In the absence of drifters, a final, post-storm expendable profiler sampling mission will be required for coupled model evaluation purposes. Refer to "TC-Ocean Interaction Experiment" for details.

3. Doppler Wind Lidar (DWL) SAL Module

Principal Investigator: Jason Dunion

Program Significance:

Installation of a multi-agency (Navy, Army and NASA) pulsed 2-micron coherent-detection Doppler wind profiling lidar system (DWL) onboard NOAA-42 is anticipated prior to the 2013 Atlantic hurricane season. This instrument, referred to as the P3DWL, was flown on board a Navy P3 in 2008 during typhoon research in the western Pacific. The P3DWL includes a compact, packaged, coherent Doppler lidar transceiver and a biaxial scanner that enables scanning above, below and ahead of the aircraft. The transceiver puts out 2 mJ eyesafe pulses at 500 Hz.

The P3DWL will have the capability to detect winds and aerosols both above (up to ~14 km in the presence of high level cirrus) and below (down to ~100 m above the ocean surface) the aircraft flight level (typically 3 -5 km). The vertical resolution of these retrievals will be ~50 m with a horizontal spacing ~2 km for u, v, and w wind profiles. There is an anticipated data void region ~300 m above and below the aircraft. Given the P3DWL's operating wavelength (~2 microns), the instrument requires aerosol scatterers in the size range of ~1+ microns and while measurements within and below optically thin or broken clouds are frequent, there is limited capability in the presence of deep, optically thick convection. Therefore, it is anticipated that the optimal environments for conducting the P-3 DWL module will be in the periphery of the TC inner core, moat regions in between rainbands, the hurricane eye, the ambient tropical environment around the storm, and the Saharan Air Layer. Options for this module will primarily focus on these environments in and around the storm. The P3DWL will require an onboard operator during each mission. When possible, the DWL module could be coordinated with the HRD Convective Burst and HBL Small-Scale Turbulent Processes Modules.

Objectives:

The main objectives of the P-3 DWL SAL Module are to:

- Characterize the suspended Saharan dust and mid-level (~600-800 hPa) easterly jet that are associated with the Saharan Air Layer (SAL) with a particular focus on SAL-TC interactions;
- Observe possible impingement of the SAL's mid-level jet and suspended dust along the edges of the storm's (AEW's) inner core convection (deep convection);

Links to IFEX:

This experiment supports the following NOAA IFEX goals:

Goal 1: Collect observations that span the TC lifecycle in a variety of environments;
Goal 2: Development and refinement of measurement technologies;
Goal 3: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

Mission Description:

This P-3 DWL SAL Module is designed to utilize the WP-3D aircraft [P3DWL, at the maximum allowable flight-level (~12,000-19,000 ft) in the periphery of the storm and GPS dropsonde data]. Although this module is not a standalone experiment, it could be included as a module within any of the following HRD research missions: TC Genesis Experiment, TC Shear Experiment, TC Diurnal Cycle Experiment, Arc Cloud Module, Rapid Intensity Experiment, or as part of operational NHC-EMC-HRD Tail Doppler Radar (TDR) missions. This module will target sampling of the SAL's suspended dust and mid-level jet by the P3DWL and can be conducted between the edges of the storm's (AEW's) inner core convection (deep convection) to points well outside (several hundred kilometers) of the TC environment during the inbound or outbound ferry to/from the storm (no minimum leg lengths are required). For fuel considerations, the outbound ferry is preferable and the optimal flight-level is ~500 mb (~19,000 ft) or as high as possible. The P3DWL should be set to the downward looking and full scan modes. GPS dropsonde sampling along the transect will be used to observe the SAL's thermodynamics and winds as well as to validate the P3DWL's wind retrievals. Drop points should be spaced at ~25-50 nm increments near the region where the SAL is impinging on the storm/AEW and spaced at 50-75 nm increments farther from the storm (Fig. 3-1). GPS dropsonde spacing will determined on a case by case basis at the LPS's discretion.

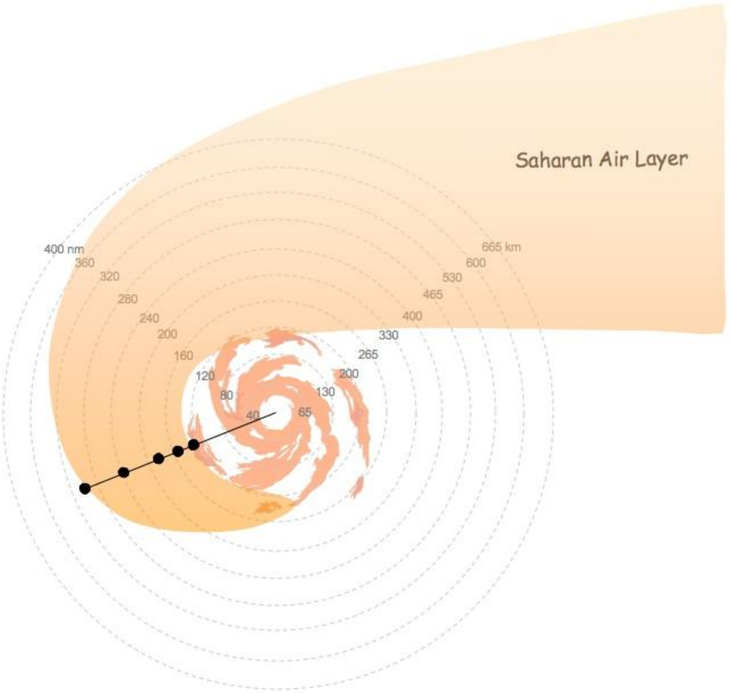


Figure 3-1: Sample WP-3D flight track during the ferry to/from the storm and GPS dropsonde points for the P-3DWL SAL module.

Analysis Strategy

This experiment seeks to observe and characterize the suspended Saharan dust and mid-level easterly jet that are associated with the Saharan Air Layer (with a particular focus on SAL-TC interactions) and to observe possible impingement of the SAL's mid-level jet and suspended dust along the edges of a storm's (AEW's) inner core convection (deep convection). Wind and aerosol information from the P-3DWL will be used to diagnose the 3-dimensional kinematic and aerosol structure of the SAL and to document the evolution of this structure as at various distances from the storm environment. When available, this information will be compared to thermodynamic retrievals from AIRS on the NASA Aqua satellite and 3-dimensional aerosol information from the NASA CALIPSO satellite.

Coordination with Supplemental Aircraft

NASA will be conducting its Hurricane Severe Storm Sentinel (HS3) mission from 20 Aug-24 Sep 2013. This mission will consist of two unmanned Global Hawk (GH) aircraft, flying at approximately 55,000-60,000 ft altitude with mission durations of up to 24-30 h. One GH will focus on flying patterns over the inner-core of TCs, while the other GH will focus on patterns in the environment of TCs. The primary science goals of HS3 are to better understand inner-core and environmental processes important in TC genesis, intensification, and extratropical transition.

When possible, it will be desirable to fly P-3 DWL module legs that are coordinated with the GH aircraft (see Fig. 3-2 for a sample environmental GH flight pattern). For the NOAA P-3, “coordinated” means flying a radial leg where the P-3 and GH are vertically-stacked for at least a portion of the flight leg, when the aircraft are in the periphery of the TC or AEW. The across-track displacement during such coordination should be kept as small as practicable, e.g., no greater than 5-10 km. Given the short nature of this module and likelihood that it would be confined to specific time windows and locations during the P-3 ferry to and from the storm, a stacked multi-aircraft coordination is unlikely. Still, NOAA and HS3 scientists will coordinate flight patterns and real-time aircraft positions via X-Chat and exploit any opportunities that present.

Figure 3-2: Sample flight pattern for the environmental Global Hawk aircraft for Pre-genesis TCs located in proximity to the SAL in the western and central North Atlantic.

4. W-band Radar Sea-Spray Module

Principal Investigator(s): Chris Fairall (ESRL) and Joe Cione (HRD)

HRD Point of Contact: Joe Cione

Links to IFEX Goal 3: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle.

Air–sea exchanges of heat and momentum are important elements in understanding and skillfully predicting hurricane intensity, but the magnitude of the corresponding wind-speed dependent bulk exchange coefficients is uncertain at hurricane force wind speeds. One potentially important aspect of surface flux interactions is the influence of sea spray. Fairall et al. (2009) have developed a parameterization of sea spray that is linked to energy going to breaking waves. This parameterization has seen application in several numerical simulation studies (Bianco et al. 2011; Bao et al. 2011). However, the model contains an adjustable scaling parameter that can be determined by direct field observations of sea spray droplet spectra. Attempts during CBLAST to do these measurements with optical droplet imaging probe (CIP) were not successful because of the impracticality of flying low enough in strong winds (U10>30 m/s). For HFP13 we plan to obtain these measurements using a profile Doppler cloud radar operating at W-band (94 GHz) frequency. The radar has been deployed on ship since 2008 and was recently repackaged for deployment on NOAA P-3 aircraft (Moran et al. 2012).

Profiles of full Doppler spectra from the radar will be recorded. We will also archive the first 3 moments of the spectra (dBZ, mean velocity, Doppler width). Nominal radar operating characteristics (subject to adjustment) will be 3 Hz dwell, 20 m range resolution, 175 range gates. The maximum range will be nominally 3.5 km so sea spray will only be observed when the aircraft is below 3.5 km altitude (11,500 ft). At those setting, the sensitivity threshold of the radar is -33 dBZ at a 1 km range. However, detection of the full droplet spectrum will require a signal of about -23 dBZ at 1 km or **-17.5 dBZ at 3.5 km.** Note that -17 dBZ corresponds to a thin stratus cloud; drizzle is -5 to 5 dBZ, light rain is 15 dBZ. Turbulent

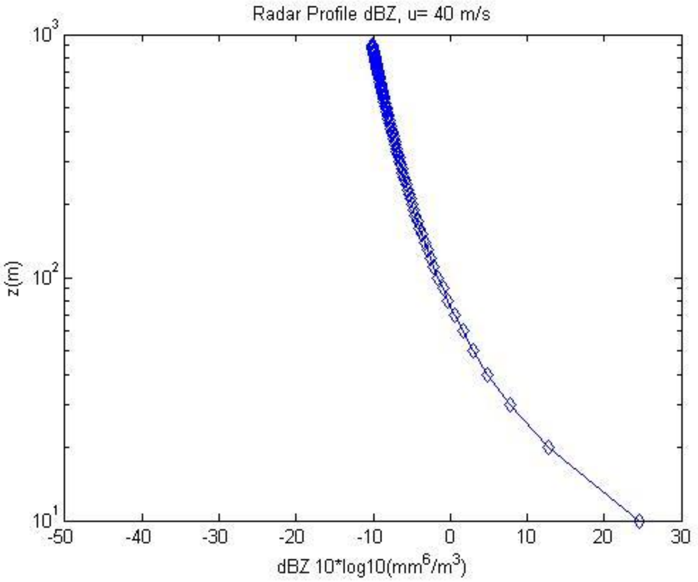


Figure 4-1: Profile of radar backscatter intensity (dBZ) estimated from PSD seaspray model for a 10-m wind speed of 40 m/s.

transport theory allows us to relate the profile of droplet concentration to the surface source strength (Fairall et al. 2009, 2012). Fig. 4-1 shows an example where the profile of radar dBZ is computed using the PSD sea spray model. This suggests that sea spray looks much like drizzle to the radar and that we have about 10 dBZ extra sensitivity to detect sea spray.

The observations of interest here require operation **outside of significant precipitation**. Rain in the line of sight below the aircraft will be indistinguishable from sea spray and will mask the profiles of sea spray that is required to estimate the surface source. Clouds will probably not be a problem, but cloud-free locations are much less likely to have precipitation contamination. So, we request the sea spray module be flown between rain bands (similar to the "Hurricane Boundary Layer Entrainment Flux Module"). It is not necessary to fly in a radial direction; azimuthal direction is acceptable.

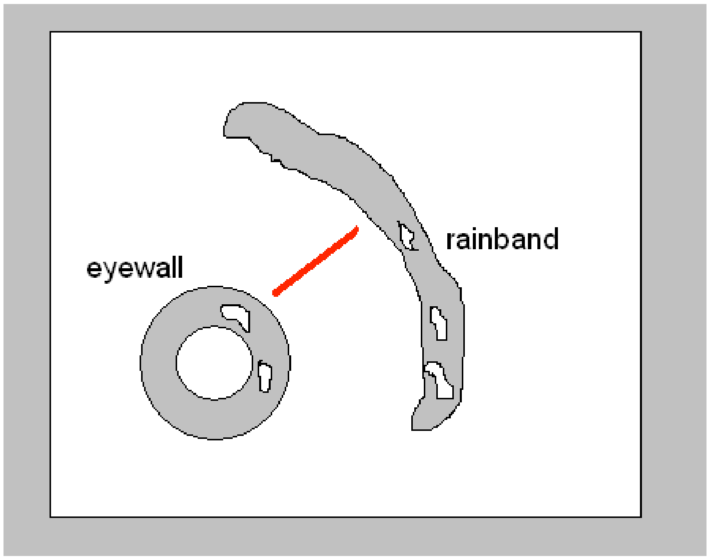


Figure 4-2: Plan view of the preferred location for rain-free region. Red line shows a sample aircraft track, but a track along a fixed radial arc is acceptable too. This figure is borrowed from the Hurricane Boundary Layer Entrainment Flux Module.

Interpretation of the radar profiles will require additional information: 10-m wind speed (SFMR) and high-speed navigational information (IMU) are required. Profiles of wind speed, temperature and humidity (dropsondes) will be useful. Doppler lidar would be very useful.

Bao, J.-W., C. W. Fairall, S. A. Michelson, L. Bianco, 2011: Parameterizations of sea-spray impact on the air-sea momentum and heat fluxes. *Mon. Wea. Rev.*, **139**, 3781–3797, doi: http://dx.doi.org/10.1175/MWR-D-11-00007.1

Bianco, L., J.-W. Bao, C. W. Fairall, and S. A. Michelson, 2011: Impact of sea spray on the surface boundary layer. *Bound.-Layer Meteorol.*,**140** , DOI 10.1007/s10546-011-9617-1.

Fairall, C. W., M. Banner, W. Peirson, R. P. Morison, and W. Asher, 2009: Investigation of the physical scaling of sea spray spume droplet production. *J. Geophys., Res.*, **114**, C10001, doi:10.1029/2008JC004918.

Fairall, C.W., C.J. Zappa, M.L. Banner, R.P. Morison, S. Brumer, X. Yan, and W.L. Peirson, 2012: A Laboratory Study of Sea Spray from Breaking Waves: Part I - Profiles of Droplet Microphysical Properties. Paper 5.1 Proceed. American Meteorological Society, 18th Conference on the Air-Sea Interaction, 9-13 July, 2012, Boston, MA.

Moran, K., S. Pezoa, C. Fairall, T. Ayers, A. Brewer, C. Williams, and S. de Szoeke' 2012: A Motion Stabilized W-band Radar for Shipboard Cloud Observations and Airborne Studies of Sea Spray. *Bound.-Layer Meteor.*, **141**, 3-24, DOI 10.1007/s10546-011-9674-5.

5. NESDIS Ocean Winds and Rain Experiment

Principal Investigator: Paul Chang (NESDIS)

Primary IFEX Goal: 2 Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment

Motivation: This effort aims to improve our understanding of microwave scatterometer retrievals of the ocean surface wind field and to evaluate new remote sensing techniques/technologies. The NOAA/NESDIS/Center for Satellite Applications and Research in conjunction with the University of Massachusetts (Umass) Microwave Remote Sensing Laboratory, the NOAA Hurricane Research Division, and the NOAA Aircraft Operations Center have been conducting flight experiments during hurricane season for the past several years. The Ocean Winds experiment is part of an ongoing field program whose goal is to further our understanding of microwave scatterometer and radiometer retrievals of the ocean surface winds in high wind speed conditions and in the presence of rain for all wind speeds. This knowledge is used to help improve and interpret operational wind retrievals from current and future satellite-based sensors. The hurricane environment provides the adverse atmospheric and ocean surface conditions required.

The Imaging Wind and Rain Airborne Profiler (IWRAP), which is also known as the Advanced Wind and Rain Airborne Profiler (AWRAP), was designed and built by UMass and is the critical sensor for these experiments. IWRAP/AWRAP consists of two dual-polarized, dual-incidence angle radar profilers operating at Ku-band and at C-band, which measure profiles of reflectivity and Doppler velocity of precipitation in addition to the ocean surface backscatter. The Stepped-Frequency Microwave Radiometer (SFMR) and GPS dropsonde system are also essential instrumentation on the NOAA-P3 aircraft for this effort.

The Ocean Winds P-3 flight experiment program has several objectives:

- Calibration and validation of satellite-based ocean surface vector wind (OSVW) sensors such as ASCAT and OSCAT.
- Product improvement and development for satellite-based sensors (ASCAT, OSCAT)
- Testing of new remote sensing technologies for possible future satellite missions (risk reduction) such as the dual-frequency scatterometer concept. A key objective for this year will be the collection of cross-polarized data at C-band to support ESA and EUMETSAT studies for the ASCAT follow- on, which will be part of METOP-SG.
- Advancing our understanding of broader scientific questions such as:
    - Rain processes in tropical cyclones and severe storms: the coincident dual-polarized, dual- frequency, dual-incidence measurements would enable us to improve our understanding of precipitation processes in these moderate to extreme rainfall rate events.
    - Atmospheric boundary layer (ABL) wind fields: the conical scanning sampling geometry and the Doppler capabilities of this system provide a unique source of measurements from which the ABL winds can be derived. The raw data system will enable us to use spectral techniques to retrieve the wind field all the way down to the surface.
    - Analysis of boundary layer rolls: linearly organized coherent structures are prevalent in tropical cyclone boundary layers, consisting of an overturning “roll” circulation in the plane roughly perpendicular to the mean flow direction. IWRAP has been shown to resolve the kilometer-scale roll features, and the vast quantity of data this instrument has already collected offers a unique opportunity to study them.
    - Drag coefficient, Cd: extending the range of wind speeds for which the drag coefficient is known is of paramount importance to further our understanding of the coupling between the wind and surface waves under strong wind forcing, and has many important implications for hurricane and climate modeling. The new raw data capability, which allows us to retrieve wind profiles closer to the ocean surface, can also be exploited to derive drag coefficients by extrapolating the derived wind profiles down to 0 m altitude.

Flight Profiles:

Altitude:

The sensitivity of the IWRAP/AWRAP system defines the preferred flight altitude to be below 10,000 ft to enable the system to still measure the ocean surface in the presence of rain conditions typical of tropical systems. With the Air Force typically flying at 10,000 ft pressure this, we have typically ended up with an operating altitude of 7,000 ft radar. Operating at a constant radar altitude is desired to minimize changes in range and thus measurement footprint on the ground. Higher altitudes would limit the ability of IWRAP/AWRAP consistently see the surface during precipitation, but these altitudes would provide useful data, such as measurements through the melting layer, to study some of the broader scientific questions.

Maneuvers:

Straight and level flight with a nominal pitch offset unique to each P-3 is desired during most flight legs. Constant bank circles of 10-30 degrees have been recently implemented, as a method to obtain measurements at incidence angles greater than the current antenna was design for. These would be inserted along flight legs where the desired environmental conditions were present. Generally it would be a region of no rain and where we might expect the winds to be consistent over a range of about 6-10 miles, about the diameter of a circle. This would not be something we would want to do in a high gradient region where the conditions would change significantly while we did the circle.

Patterns:

Typically an ideal ocean winds flight pattern would include a survey pattern (figure 4 or butterfly) that extended 20-50 nm from the storm center. The actual distance would be dictated by the storm size and safety of flight considerations. Dependent upon what was observed during the survey pattern a racetrack or lawnmower pattern would be setup over a feature of interest such as a rain band or wind band.

Storm types:

The ideal ocean winds storm would typically be a developed hurricane (category 1 and above) where a large range of wind speeds and rain rates would be found. However, data collected within tropical depressions and tropical storms would still provide very useful observations of rain impacts.

6. Small Unmanned Aerial Vehicle Experiment (SUAVE)

Principal Investigator: J. Cione

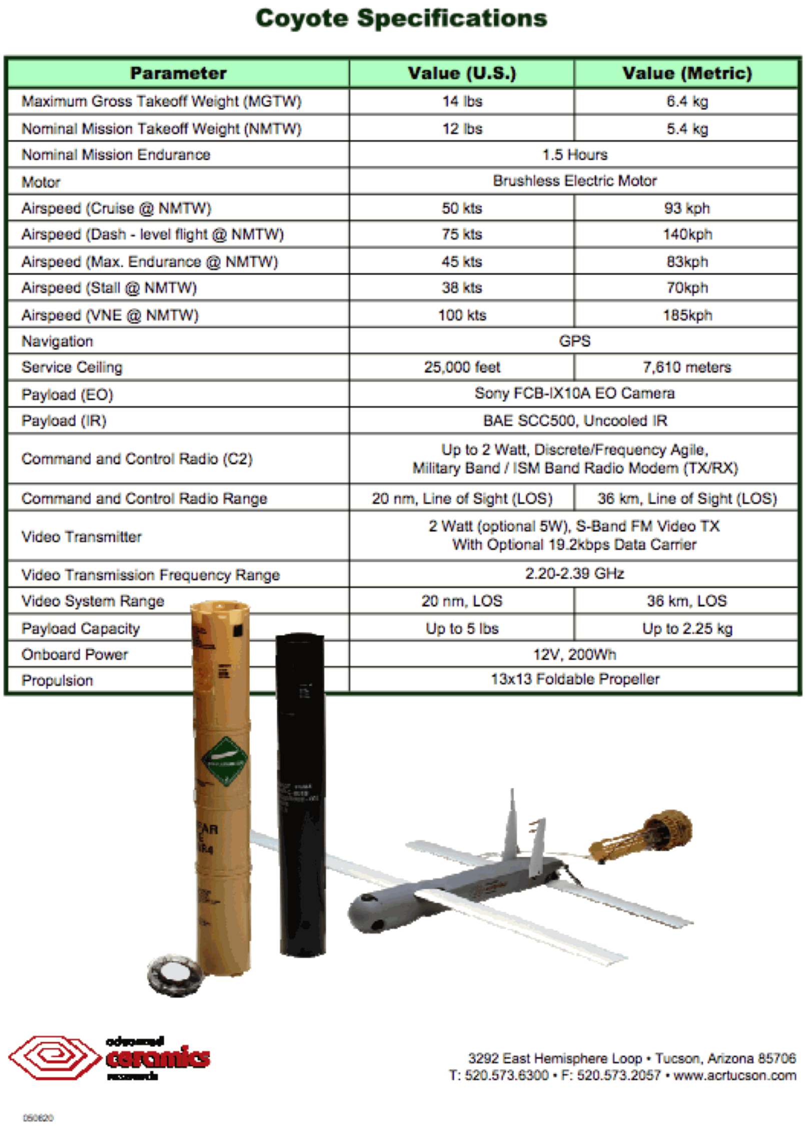
Primary IFEX Goal: 2 - Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment

Why UAS?

The interaction between the ocean and the hurricane is important, complex, and not well handled in current observing systems and models. Specifically, the hurricane depends on the ocean to supply the necessary heat and moisture to form and maintain the system. The detailed process by which a storm ‘draws heat’ from the ocean and ultimately converts it into kinetic energy (i.e. strong winds) is very complex and is currently not well understood. This lack of understanding is primarily due to the limited availability of detailed observations within the storm near the air-sea interface. The amount of heat and moisture extracted from the ocean is a function of wind speed, ocean temperature, atmospheric temperature, pressure and humidity. Accurate measurements of these variables are required, yet exceedingly difficult to obtain due to the severe weather conditions that exist at the ocean surface during a hurricane. A limited array of surface buoys make in-situ measurements in this region spotty at best, while direct measurements at very low altitudes using NOAA and Air Force hurricane hunter manned aircraft is impossible due to the severe safety risks involved. Nevertheless, for scientists to dramatically improve our understanding of this rarely observed region, detailed, continuous observations must be obtained. To this end, an aggressive effort to utilize low level unmanned aerial systems (UAS) designed to penetrate and sample the violent low level hurricane environment would help fill this critical data void. Such improvements in observation and understanding would likely lead to significant advancements in the area of hurricane intensity prediction. Enhancing this predictive capability would in turn reduce the devastating impact hurricanes have on our Nation’s economy and more importantly help save countless lives.

Coyote UAS

Coyote is an aircraft platform that is built by British Aerospace Engineering (BAE) and is currently being used by the US NAVY. The intended deployment vehicle for the Coyote is the P-3 Orion. The Coyote is a small electric-powered unmanned aircraft with 1-3 hour endurance and is capable of carrying a 1-2lb payload. The Coyote can be launched from a P-3 sonobuoy tube in flight, and terrain-permitting, is capable of autonomous landing and recovery. The Coyote is supported by BAE’s integrated control station which is capable of supporting multiple aircraft operations via touch screens that simultaneously show real-time video. This control station can also be incorporated onto the deployment aircraft (i.e. P-3), allowing for in-air command and control after launch. The Coyote, when deployed from NOAA's P-3's within a hurricane environment, provide a unique observation platform from which the low level atmospheric boundary layer environment can be diagnosed in great detail. In many ways, this UAS platform be considered a 'smart GPS dropsonde system' since it is deployed in similar fashion and currently utilizes a comparable meteorological payload (i.e. lightweight sensors for P, T, RH, V) to the one currently used by NOAA on the G-IV and P-3 dropsonde system. Unlike the GPS sonde however, the Coyote UAS can be directed from the NOAA P-3 to specific areas within the storm circulation (both in the horizontal and in the vertical). Also unlike the GPS dropsonde, Coyote observations are continuous in nature and give scientists an extended look into important thermodynamic and kinematic physical processes that regularly occur within the near-surface boundary layer environment. Coyote UAS operations also represent a potentially significant upgrade relative to the more traditional "deploy, launch and recover" low altitude UAS hurricane mission plan used in the past. By leveraging existing NOAA manned aircraft assets, Coyote operations significantly reduces the need for additional manpower. The Coyote concept of operations also reduces overall mission risk since there is no flight ingress/egress. This fact should also help simplify the airspace regulatory approval process. Specifications associated with the Coyote UAS are illustrated in Fig. 6-1.



Coyote Specifications

Parameter	Value (U.S.)	Value (Metric)
Maximum Gross Takeoff Weight (MGTW)	14 lbs	6.4 kg
Nominal Mission Takeoff Weight (NMTW)	12 lbs	5.4 kg
Nominal Mission Endurance	1.5 Hours	
Motor	Brushless Electric Motor	
Airspeed (Cruise @ NMTW)	50 kts	93 kph
Airspeed (Dash - level flight @ NMTW)	75 kts	140kph
Airspeed (Max. Endurance @ NMTW)	45 kts	83kph
Airspeed (Stall @ NMTW)	38 kts	70kph
Airspeed (VNE @ NMTW)	100 kts	185kph
Navigation	GPS	
Service Ceiling	25,000 feet	7,610 meters
Payload (EO)	Sony FCB-IX10A EO Camera	
Payload (IR)	BAE SCC500, Uncooled IR	
Command and Control Radio (C2)	Up to 2 Watt, Discrete/Frequency Agile, Military Band / ISM Band Radio Modem (TX/RX)	
Command and Control Radio Range	20 nm, Line of Sight (LOS)	36 km, Line of Sight (LOS)
Video Transmitter	2 Watt (optional 5W), S-Band FM Video TX With Optional 19.2kbps Data Carrier	
Video Transmission Frequency Range	2.20-2.39 GHz	
Video System Range	20 nm, LOS	36 km, LOS
Payload Capacity	Up to 5 lbs	Up to 2.25 kg
Onboard Power	12V, 200Wh	
Propulsion	13x13 Foldable Propeller	

advanced ceramics research

3292 East Hemisphere Loop • Tucson, Arizona 85706
T: 520.573.6300 • F: 520.573.2057 • www.acrtucson.com

050620

Figure 6-1: Coyote Unmanned Aerial System Specifications

Relevance to NOAA

In recent years, an increasing number of hurricanes have impacted the United States with devastating results, and many experts expect this trend to continue in the years ahead. In the wake of Hurricane Sandy (2012), NOAA is being looked at to provide improved and highly accurate hurricane-related forecasts over a longer time window prior to landfall. NOAA is therefore challenged to develop a program that will require applying the best science and technology available to improve hurricane prediction without placing NOAA personnel at increased risk. UAS are an emerging technology in the civil and research arena capable of responding to this need.

In late February 2006, a meeting was held between NOAA, NASA and DOE partners (including NOAA NCEP and NHC representatives) to discuss the potential for using UAS in hurricanes to take measurements designed to improve intensity forecasts. The group came to a consensus around the need for a UAS demonstration project focused on observing low-level (<200 meters) hurricane winds for the following reasons:

- Hurricane intensity and track forecasts are critical at sea level (where coastal residents live)
- The hurricane's strongest winds are observed within the lowest levels of the atmosphere
- The air-sea interface is where the ocean's energy is directly transferred to the atmosphere
- Ultimately, low-level observations will help improve operational model initialization and verification
- The low-level hurricane environment is too dangerous for manned aircraft

The potential importance of low-level UAS missions in hurricanes is further emphasized by the findings of the Hurricane Intensity Research Working Group established by the NOAA Science Advisory Board. Their recommendation is that:

"Low and Slow" Unmanned Aircraft Systems (UAS) have demonstrated a capacity to operate in hurricane conditions in 2005 and in 2007. Continued resources for low altitude UAS should be allocated in order to assess their ability to provide in situ observations in a critical region where manned aircraft satellite observations are lacking.

This effort is in direct support of NOAA's operational requirements and research needs. Such a project will directly assist NOAA's National Hurricane Center better meet several of its ongoing operational requirements by helping to assess:

The strength and location of the storm's strongest winds

The radius of maximum winds

The storm's minimum sea level pressure *(which in turn may give forecasters advanced warning as it relates to dangerous episodes of rapid intensity change)*

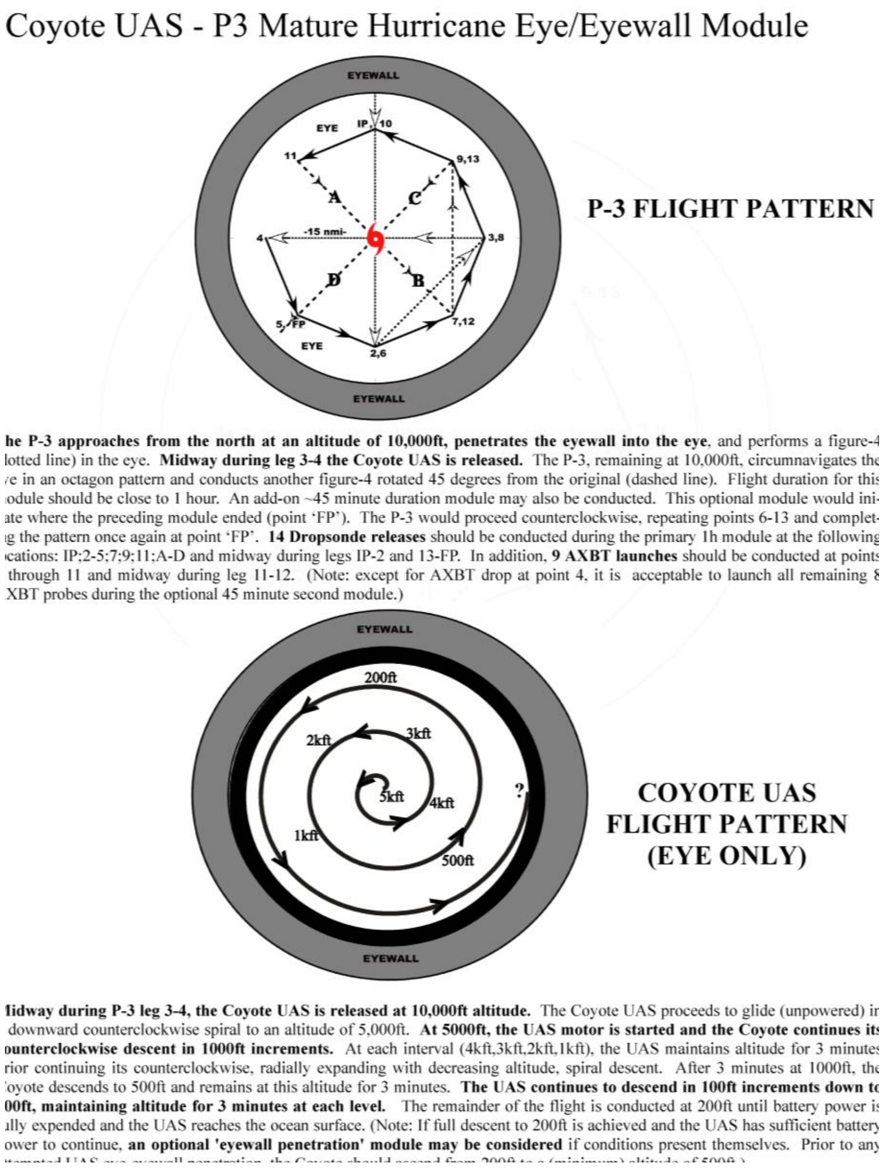
In addition to these NOAA operational requirements, developing the capability to regularly fly low altitude UAS into tropical cyclones will also help advance NOAA research by allowing scientists to sample and analyze a region of the storm that would otherwise be impossible to observe in great detail (due to the severe safety risks involved associated with manned reconnaissance). It is believed that such improvements in basic understanding are likely to improve future numerical forecasts of tropical cyclone intensity change. Reducing the uncertainty associated with tropical cyclone intensity forecasts remains a top priority of the National Hurricane Center. Over time, projects such as this, which explore the utilization of unconventional and innovative technologies in order to more effectively sample critical regions of the storm environment should help reduce this inherent uncertainty.

This HRD field program module is designed to build on the successes and strong momentum from recent UAS missions conducted in 2005 and 2007. Using the experience gained from the Ophelia and Noel UAS experiences. As part of this effort, any UAS data collected will continue to be made available to NOAA's National Hurricane Center in real-time.

Mission Description

The primary objective of this experiment is further demonstrate and utilize the unique capabilities of a low latitude UAS platform in order to better document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. For this purpose, in 2013, we will be using the Coyote UAS. Since the Coyote will be deployed from the manned P-3 aircraft, no UAS-specific forward deployment teams will be required. Furthermore, since the Coyote is launched using existing AXBT launch infrastructure, no special equipment is required beyond a 'ground' control station BAE Coyote operators will have onboard the P-3. In 2013 the Coyote UAS will not be freely launched into the US National airspace. Instead, low altitude UAS deployments in 2013 will be limited to within three locations: 1. Piarco controlled airspace (requiring a Barbados or St Croix deployment); 2. warning areas in the southeastern Gulf of Mexico; and 3. specific warning areas off the U.S. mid-Atlantic coast. For 2013, the target candidate storm is a mature hurricane with a well- defined eye. Furthermore, since the P-3 will have to operate within the eye, daylight missions will be required so as to maintain P-3 visual contact with the eyewall at all times. For 2013, Iridium/satcomm communications between UAS and P-3 are planned. If successfully installed in 2013, this capability will have the dual positive effect of minimizing experimental and safety risks. The immediate focus of this experimental module will be to test the operational capabilities of the Coyote UAS within a hurricane environment. Besides maintaining continuous command and control links with the P-3, these flights will test the accuracy of the new MISTSONDE meteorological payload (vs. observations taken from dropsondes released near the UAS). The UAS will be tested to see if it can maintain altitudes according to command. In addition, the Coyote UAS will attempt to fly at extreme altitudes (as low as 200 ft) in low (eye) and high (eyewall) wind conditions within hurricane environment. The longer term goal for this UAS platform is to assist scientists so they can better document and ultimately improve their understanding of the rarely-observed tropical cyclone boundary layer. To help accomplish this, the UAS will make detailed observations of PTHU at low altitudes within the hurricane eye and eyewall that will then be compared with multiple in-situ and remote-sensing observations obtained from manned aircraft (NOAA P-3 and AFRES C-130, Global Hawk) and select satellite-based platforms. In addition, a primary objective (but not a 2013 requirement) for this effort will be to provide real-time, near-surface wind observations to the National Hurricane Center in direct support of NOAA operational requirements. These unique data will also be used in a ‘post storm’ analysis framework in order to potentially assist in the numerical and NHC verification process.

For this experiment, NOAA P-3 flight altitude will be at 10000ft at all times. Ideally both modules (~1.5h each) would be conducted on the same manned mission. The eye-only module would be conducted first, followed by the eye-eyewall UAS module. The P-3 flight pattern is identical for both eye and eye-eyewall UAS modules. GPS dropsonde and AXBT drop locations are also identical for each UAS module. AXBT and GPS drop locations are explicitly illustrated in the flight plan below. UAS deployment on leg 3-4 is also identical for both modules. UAS operational altitude will be entirely below 5000ft. UAS motor will not be activated until an altitude of 5000ft is met. The UAS will be conducting a controlled, spiral glide (un-powered) descent from 10000ft to 5000ft.



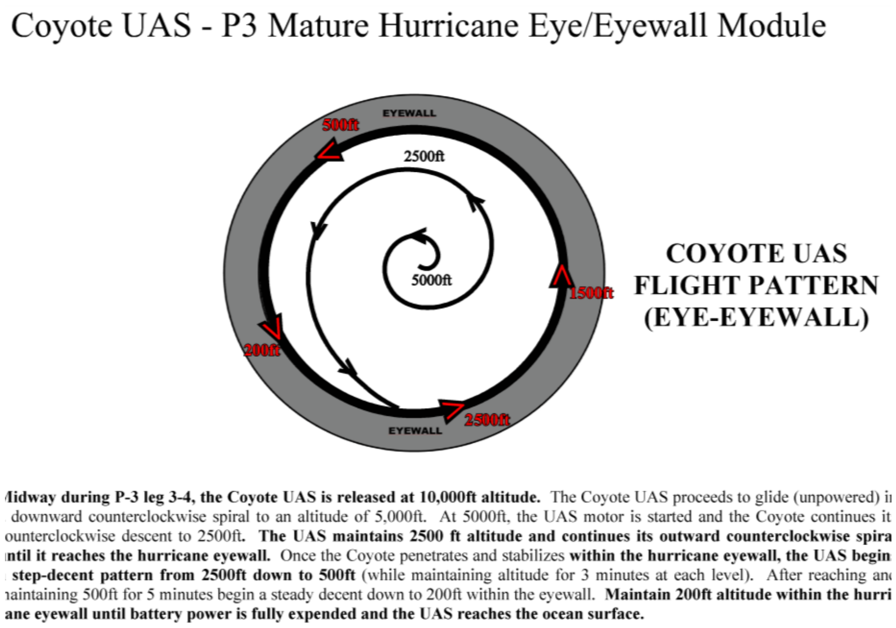
Coyote UAS - P3 Mature Hurricane Eye/Eyewall Module

P-3 FLIGHT PATTERN

he P-3 approaches from the north at an altitude of 10,000ft, penetrates the eyewall into the eye, and performs a figure-4 lotted line) in the eye. **Midway during leg 3-4 the Coyote UAS is released.** The P-3, remaining at 10,000ft, circumnavigates the ve in an octagon pattern and conducts another figure-4 rotated 45 degrees from the original (dashed line). Flight duration for this odule should be close to 1 hour. An add-on ~45 minute duration module may also be conducted. This optional module would initiate where the preceding module ended (point 'FP'). The P-3 would proceed counterclockwise, repeating points 6-13 and completg the pattern once again at point 'FP'. **14 Dropsonde releases** should be conducted during the primary 1h module at the following cations: IP;2-5;7;9;11;A-D and midway during legs IP-2 and 13-FP. In addition, **9 AXBT launches** should be conducted at points through 11 and midway during leg 11-12. (Note: except for AXBT drop at point 4, it is acceptable to launch all remaining XBT probes during the optional 45 minute second module.)

COYOTE UAS
FLIGHT PATTERN
(EYE ONLY)

Iidway during P-3 leg 3-4, the Coyote UAS is released at 10,000ft altitude. The Coyote UAS proceeds to glide (unpowered) in downward counterclockwise spiral to an altitude of 5,000ft. **At 5000ft, the UAS motor is started and the Coyote continues its ounterclockwise descent in 1000ft increments.** At each interval (4kft,3kft,2kft,1kft), the UAS maintains altitude for 3 minutes rior continuing its counterclockwise, radially expanding with decreasing altitude, spiral descent. After 3 minutes at 1000ft, the oyote descends to 500ft and remains at this altitude for 3 minutes. **The UAS continues to descend in 100ft increments down to 00ft, maintaining altitude for 3 minutes at each level.** The remainder of the flight is conducted at 200ft until battery power is ully expended and the UAS reaches the ocean surface. (Note: If full descent to 200ft is achieved and the UAS has sufficient battery ower to continue, **an optional 'eyewall penetration' module may be considered** if conditions present themselves. Prior to any ttempted UAS eye-eyewall penetration, the Coyote should ascend from 200ft to a (minimum) altitude of 500ft.)



Coyote UAS - P3 Mature Hurricane Eye/Eyewall Module

COYOTE UAS
FLIGHT PATTERN
(EYE-EYEWALL)

Iidway during P-3 leg 3-4, the Coyote UAS is released at 10,000ft altitude. The Coyote UAS proceeds to glide (unpowered) in downward counterclockwise spiral to an altitude of 5,000ft. At 5000ft, the UAS motor is started and the Coyote continues it ounterclockwise descent to 2500ft. **The UAS maintains 2500 ft altitude and continues its outward counterclockwise spira ntil it reaches the hurricane eyewall.** Once the Coyote penetrates and stabilizes **within the hurricane eyewall, the UAS begin step-decent pattern from 2500ft down to 500ft** (while maintaining altitude for 3 minutes at each level). After reaching and aintaining 500ft for 5 minutes begin a steady decent down to 200ft within the eyewall. **Maintain 200ft altitude within the hurri ane eyewall until battery power is fully expended and the UAS reaches the ocean surface.**

7. 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)

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 generally have not been carried out in an optimal way to test hypotheses regarding shear-induced modifications of TC structure and their impact on intensity change (see below). It is the purpose of this experiment to sample the TC at distinct phases of its interaction with VWS, and to measure kinematic and thermodynamic fields with the azimuthal and radial coverage necessary to test these hypotheses motivated by recent theoretical and numerical studies.

In addition to enhancing basic understanding of the TC in VWS, 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 2013). Properly representing the flow at greater radial distance 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 the mechanisms for shear-induced intensity change 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 of the vortex, 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 of TCs in VWS, 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 the coupling between vertical layers, and 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 displacements between the upper- and lower-level circulations, 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 (2013) have recently clarified the dependence of resilience on the vortex profile outside the core, suggesting that in cloudy vortices, like the TC, changes in the profile outside the core alter the vortex-Rossby wave guide there and, ultimately, the evolution of vortex tilt.

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

1) **Structure evolution:** The vertically-tilted vortex structure which develops following a significant increase in VWS is governed by balance-dynamics theory. (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 2013). To test this hypothesis, the core-region kinematic structure of the vortex will be sampled out to approximately 4xRMW with Doppler radar at specific times relative to the VWS evolution. The thermodynamic structure will be sampled with flight-level instruments and closely-spaced dropsondes.)

2) **Convective asymmetry:** Eyewall convective asymmetry is organized by shear-forced, balanced mesoscale ascent. (In both numerical and observational studies, 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. To test this hypothesis, the core kinematic and precipitation structures will be sampled with Doppler radar during a period when VWS is the dominant forcing of low-wavenumber asymmetry. The thermodynamic structure will be sampled with flight-level instruments and closely-spaced dropsondes. Satellite observations of convective activity should also be archived during the periods of observation.)

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 the thermodynamic properties of the inflow layer has not been demonstrated in the observational context. To test this hypothesis, the core-region kinematic structure of the vortex (e.g., the tilt asymmetry) must be sampled out to approximately 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. The thermodynamic structure of the inflow layer will be sampled with closely-spaced dropsondes. The near-core thermodynamic structure of the lower to middle troposphere will be 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. To test this hypothesis, the moist envelope will be defined using P-3 flight-level and P-3/G-IV dropsonde data within and surrounding the eyewall out to 8xRMW, before and after the shear increase. Similarly, the low- to mid-level storm-relative horizontal flow topology outside the core will be 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 R1** 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.

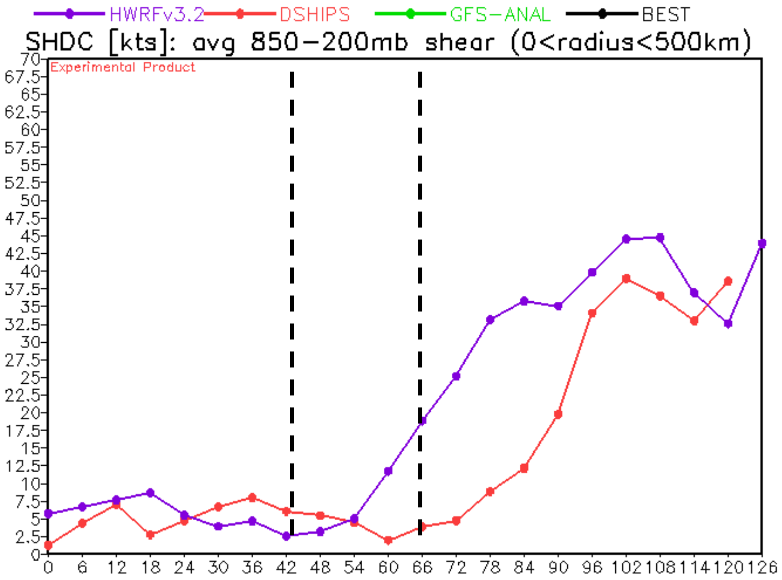


Figure R1

Pre-shear sampling:

The TC must be sampled just prior to the shear increase (at 54 h in this case) to obtain the pre-shear vortex and environmental structure. **Figure R2** shows that the TC exhibits a vertically-aligned vorticity structure through the tropospheric depth at this time.

Mission 1: A G-IV aircraft performs storm-relative environmental TDR and dropsonde sampling (**Fig. 7-1**) through clockwise octagonal circumnavigation, starting at 8xRMW, moving inward to 6xRMW, and finishing at 4xRMW (for an 18-nm RMW, the rings are at radii of 144 nm, 108 nm, and 72 nm, respectively). A coordinated P-3 aircraft performs a single Figure-4 pattern (orientation chosen for efficiency) with TDR to obtain the TC core structure (**Fig. 7-2**). 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.

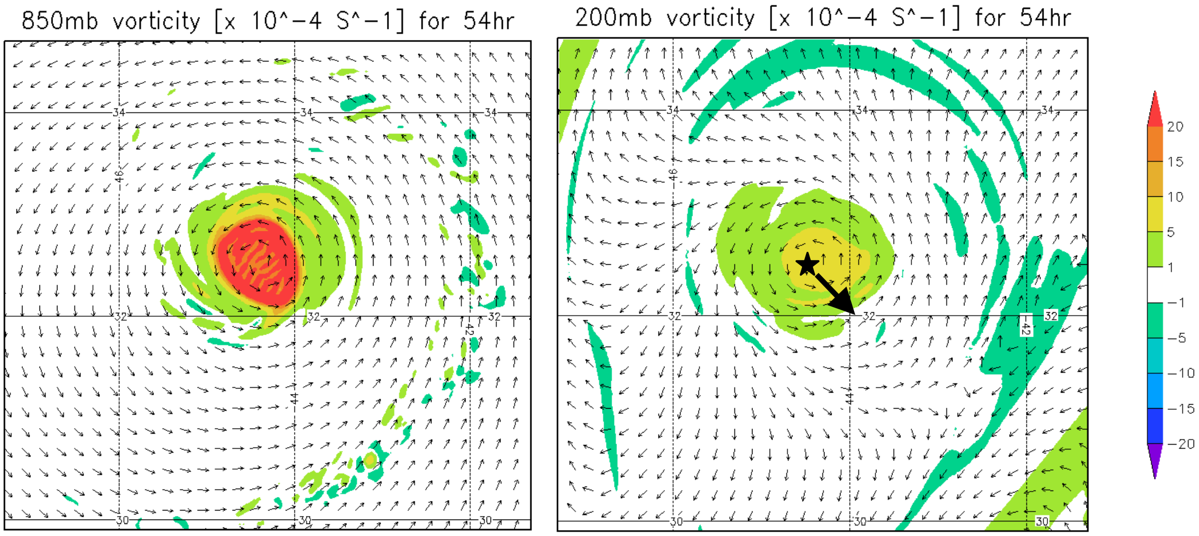


Figure R2

Threshold shear and large tilt sampling:

The TC's kinematic structure will respond 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**, we recommend that time series of forecast shear from a number of different sources (e.g., SHIPS, HWRF coarse grid, etc.) 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 R3** illustrates this convective asymmetry at the time the shear threshold is reached (and the core begins to tilt). In this example, the second P-3 mission would commence approximately 12 h after the first to sample the storm.

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. 7-3**). 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.

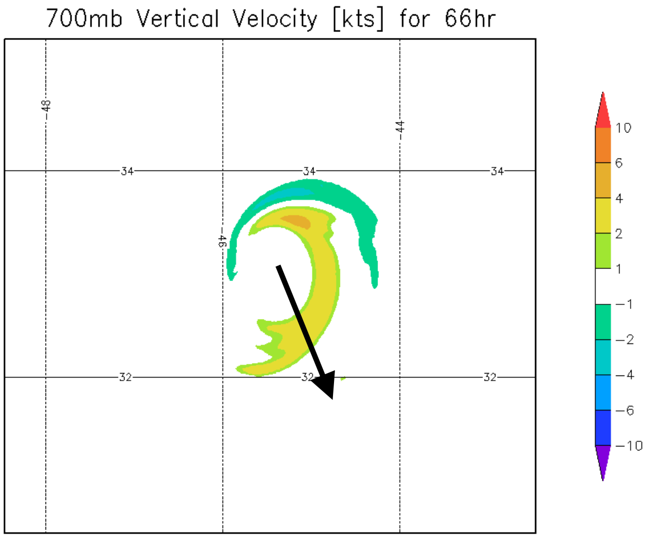


Figure R3

Figure R4 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. 7-4**). The first inbound leg should be oriented along the shear vector (if available resources suggest a tilt left of shear, then the pattern should be rotated with first inbound leg along the tilt 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. 7-1**) through clockwise octagonal circumnavigation, starting at 8xRMW, moving inward to 6xRMW, and finishing at 4xRMW (for an 18-nm RMW, the rings are radii of 144 nm, 108 nm, and 72 nm, respectively). 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, 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 is sought.

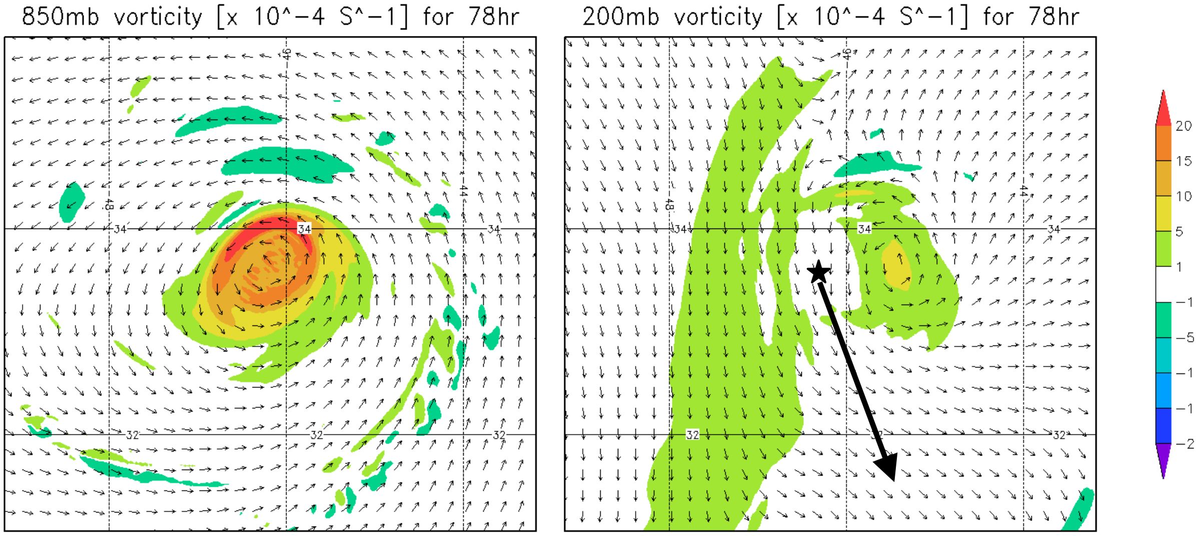


Figure R4

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 being examined here, 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 R5**). 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.

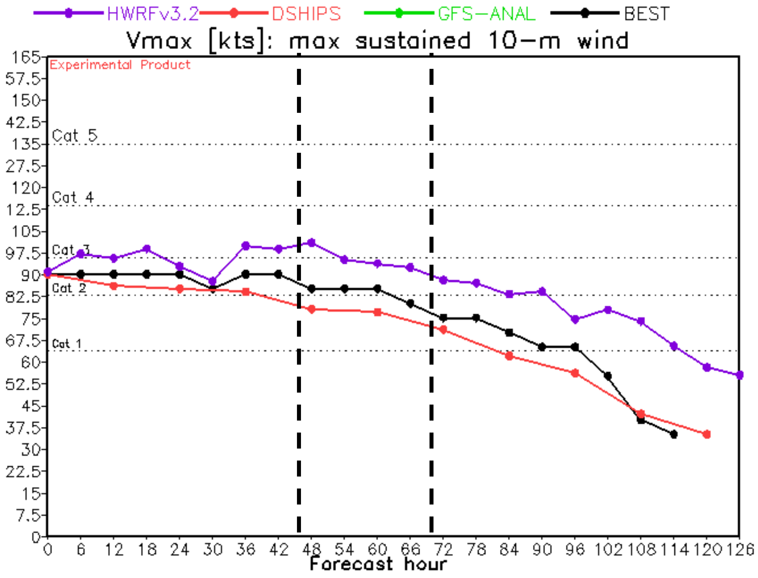


Figure R5

Analysis Strategy:

The basic analysis will follow 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). This 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 8xRMW 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 will 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 8xRMW, and 3D θ_e analyses below P-3 flight level within 4xRMW and below G-IV flight level between 4xRMW and 8xRMW. 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 will 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 will 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 will proceed 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. 7-6**). 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. 7-6**. 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. 7-7**). 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. 7-8**). 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.

References:

Bender, M. A., 1997: The effect of relative flow on the asymmetric structure in the interior of hurricanes. *J. Atmos. Sci.*, **54**, 703–724.

Black, M. L., J. F. Gamache, F. D. Marks, C. E. Samsury, and H. E. Willoughby, 2002: Eastern Pacific Hurricanes Jimena of 1991 and Olivia of 1994: The effect of vertical shear on structure and intensity. *Mon. Wea. Rev.*, **130**, 2291–2312.

Braun, S. A., M. T. Montgomery, and Z. Pu, 2006: High-resolution simulation of Hurricane Bonnie (1998). Part I: The organization of eyewall vertical motion. *J. Atmos. Sci.*, **63**, 19–42.

Davis, C. A., S. C. Jones, and M. Riemer, 2008: Hurricane vortex dynamics during Atlantic extratropical transition. *J. Atmos. Sci.*, **65**, 714–736.

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.*, **53**, 2076–2088.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.

Eastin, M. D., W. M. Gray, and P. G. Black, 2005: Buoyancy of convective vertical motions in the inner core of intense hurricanes. Part II: Case studies. *Mon. Wea. Rev.*, 133, 209–227.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–605.

Emanuel, K. A., 1991: The theory of hurricanes. *Annu. Rev. Fluid Mech.*, **23**, 179–196.

Frank, W. M. and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.*, **129**, 2249–2269.

Gray, W. M., 1968: Global view of the origin of tropical disturbances. *Mon. Wea. Rev.*, **96**, 669-700.

Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc.*, **121**, 821–851.

Jones, S. C., 2000: The evolution of vortices in vertical shear. III: Baroclinic vortices. *Quart. J. Roy. Meteor. Soc.*, **126**, 3161–3185.

Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting*, **18**, 1093–1108.

Molinari, J., D. Vollaro, K. L. Corbosiero, 2004: Tropical cyclone formation in a sheared environment: A case study. *J. Atmos. Sci.*, **61**, 2493-2509.

Molinari, J., P. Dodge, D. Vollaro, K. L. Corbosiero, F. D. Marks Jr., 2006: Mesoscale aspects of the downshear reformation of a tropical cyclone. *J. Atmos. Sci.*, **63**, 341-354.

Reasor, P. D., M. T. Montgomery, F. D. Marks Jr., and J. F. Gamache, 2000: Low-wavenumber structure and evolution of the hurricane inner core observed by airborne dual-Doppler radar. *Mon. Wea. Rev.*, **128**, 1653-1680.

Reasor, P. D., M. T. Montgomery, and L. D. Grasso, 2004: A new look at the problem of tropical cyclones in vertical shear flow: Vortex resiliency. *J. Atmos. Sci.*, **61**, 3–22.

Reasor, P. D., M. Eastin, and J. F. Gamache, 2009: Rapidly intensifying Hurricane Guillermo (1997). Part I: Low-wavenumber structure and evolution. *Mon. Wea. Rev.*, **137**, 603–631.

Reasor, P. D., and M. D. Eastin, 2012: Rapidly intensifying Hurricane Guillermo (1997). Part II: Resilience in shear. *Mon. Wea. Rev.*, **140**, 425–444.

Reasor, P. D., R. Rogers, and S. Lorsolo, 2013: Environmental flow impacts on tropical cyclone structure diagnosed from airborne Doppler radar composites. *Mon. Wea. Rev.*,in press.

Reasor, P. D., and M. T. Montgomery, 2013: Does the tropical cyclone's response to vertical wind shear depend on the near-core tangential wind profile? *J. Atmos. Sci.*, in review.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2010: A new paradigm for intensity modification of tropical cyclones: thermodynamic impact of vertical wind shear on the inflow layer. *Atmos. Chem. Phys.*, **10**, 3163–3188.

Riemer, M., and M. T. Montgomery, 2011: Simple kinematic models for the environmental interaction of tropical cyclones in vertical wind shear. *Atmos. Chem. Phys.*, **11**, 9395–9414.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmos. Chem. Phys.*, **13**, 327–346.

Rogers, R., and Coauthors, 2006: The Intensity Forecasting Experiment: A NOAA Multiyear Field Program for Improving Tropical Cyclone Intensity Forecasts. *Bull. Amer. Meteor. Soc.*, **87**, 1523–1537.

Rogers, R., P. Reasor, and S. Lorsolo, 2013: Airborne Doppler observations of the inner-core structural differences between intensifying and steady-state tropical cyclones. *Mon. Wea. Rev.*, in press.

Simpson, R. H. and H. Riehl, 1958: Mid-tropospheric ventilation as a constraint on hurricane development and maintenance. *Proc. Tech. Conf. on Hurricanes*, Miami, FL, Amer. Meteor. Soc., D4.1-D4.10.

Tang, B., K. Emanuel, 2012: Sensitivity of tropical cyclone intensity to ventilation in an axisymmetric model. *J. Atmos. Sci.*, **69**, 2394–2413.

Wang, Y., M. Montgomery, and B. Wang, 2004: How much vertical shear can a well-developed tropical cyclone resist? Preprints, *26th Conference on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 100-101.

Wong, M. L. M. and J. C. L. Chan, 2004: Tropical cyclone intensity in vertical wind shear. *J. Atmos. Sci.*, **61**, 1859–1876.

Zhang, J. A., and E. Uhlhorn, 2012: Hurricane sea surface inflow angle and an observation-based parametric model. *Mon. Wea. Rev*., **140**, 3587-3605.

Zhang, J. A., R. F. Rogers, P. D. Reasor, E. W. Uhlhorn, and F. D. Marks Jr., 2013: Asymmetric hurricane boundary layer structure in relation to the environmental vertical wind shear from dropsonde composites. *Mon. Wea. Rev.*, in press.

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.

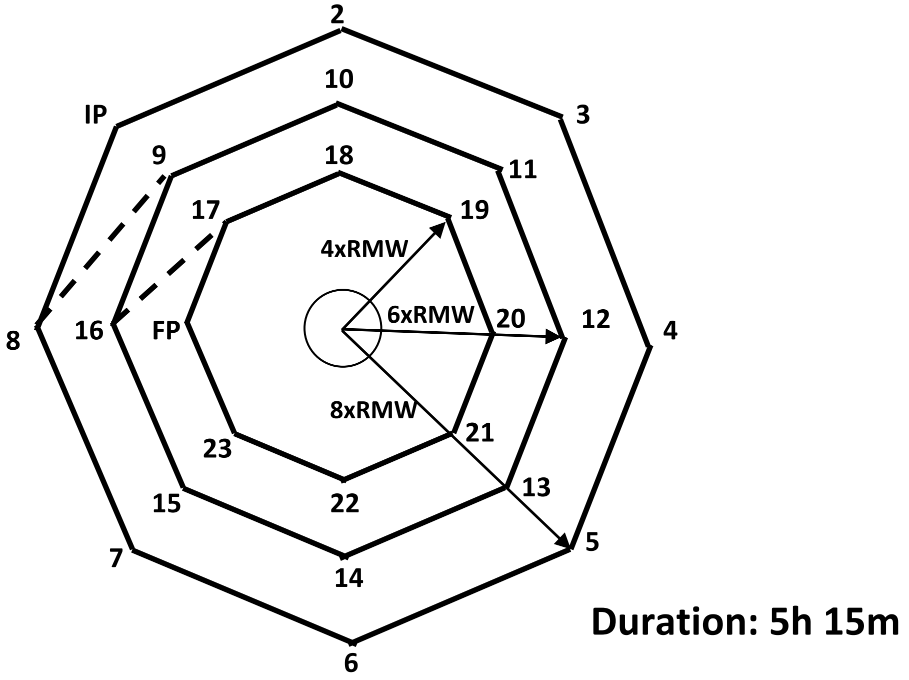


Figure 7-1: G-IV pre-shear outer-core survey pattern

- Altitude: 40-45 kft
- Expendables: Deploy dropsondes at all turn points. No more than 24 GPS drops needed.
- Pattern: The pattern is flown with respect to the surface storm center. Three concentric octagons are flown clockwise at decreasing radii of 8xRMW, 6xRMW, and 4xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 144 nm. Dashed lines show transitions between rings.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

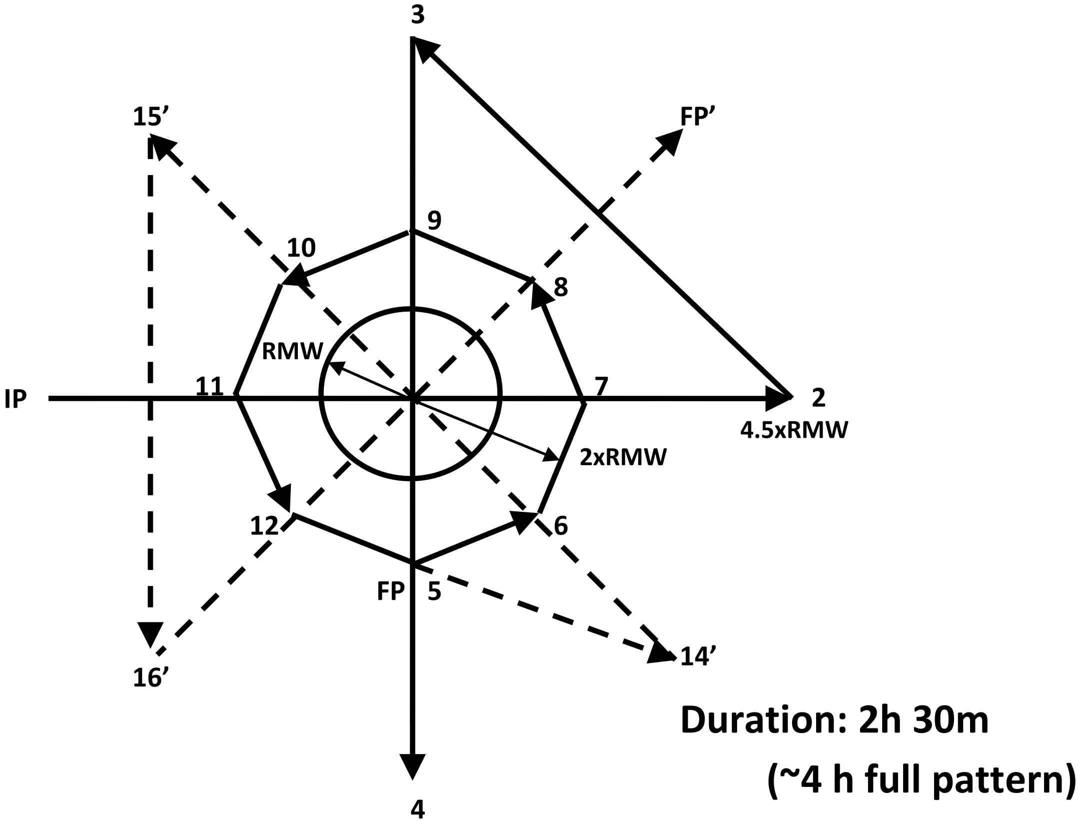
Tropical Cyclone in Shear Experiment

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: Before a significant increase in environmental vertical wind shear. The P-3 should be coordinated with the corresponding G-IV mission.



Duration: 2h 30m
(~4 h full pattern)

Figure 7-2: 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) and mid points of octagonal flight pattern legs. No more than 42 drops needed (25 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. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 81 nm. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. 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 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.

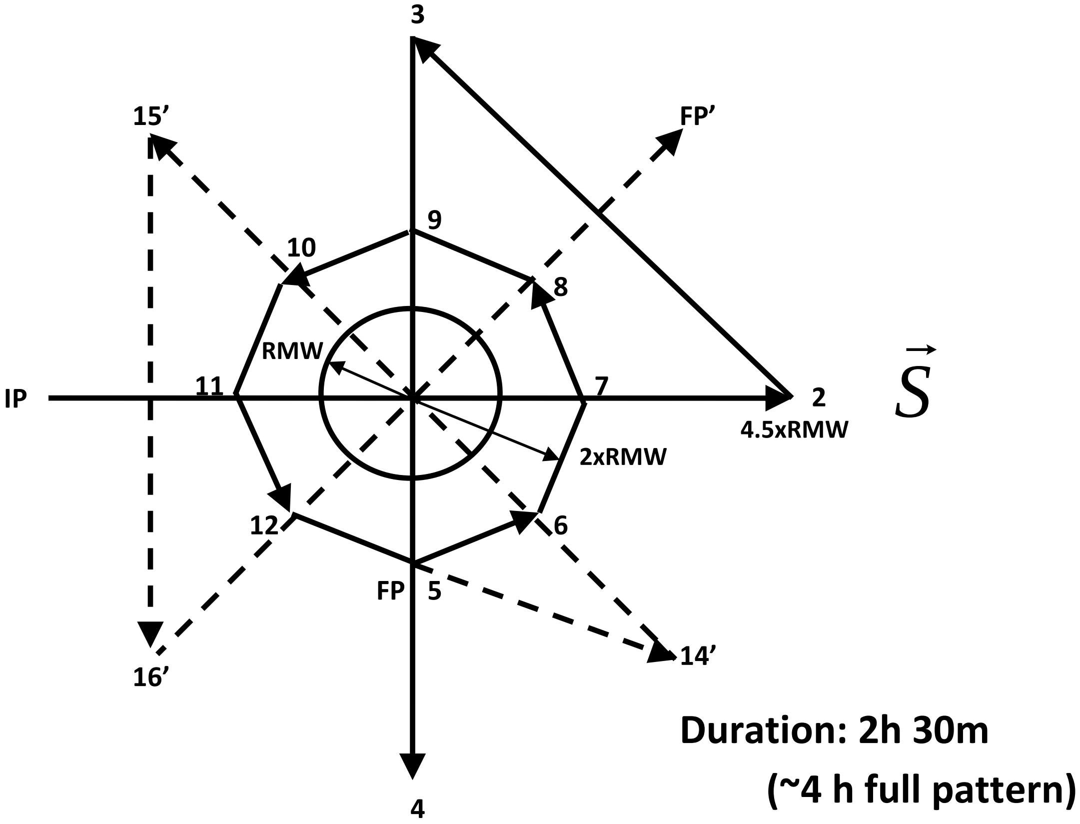


Figure 7-3: P-3 “threshold shear” core-region survey pattern

- 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 42 drops needed (25 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. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 81 nm. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. 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.

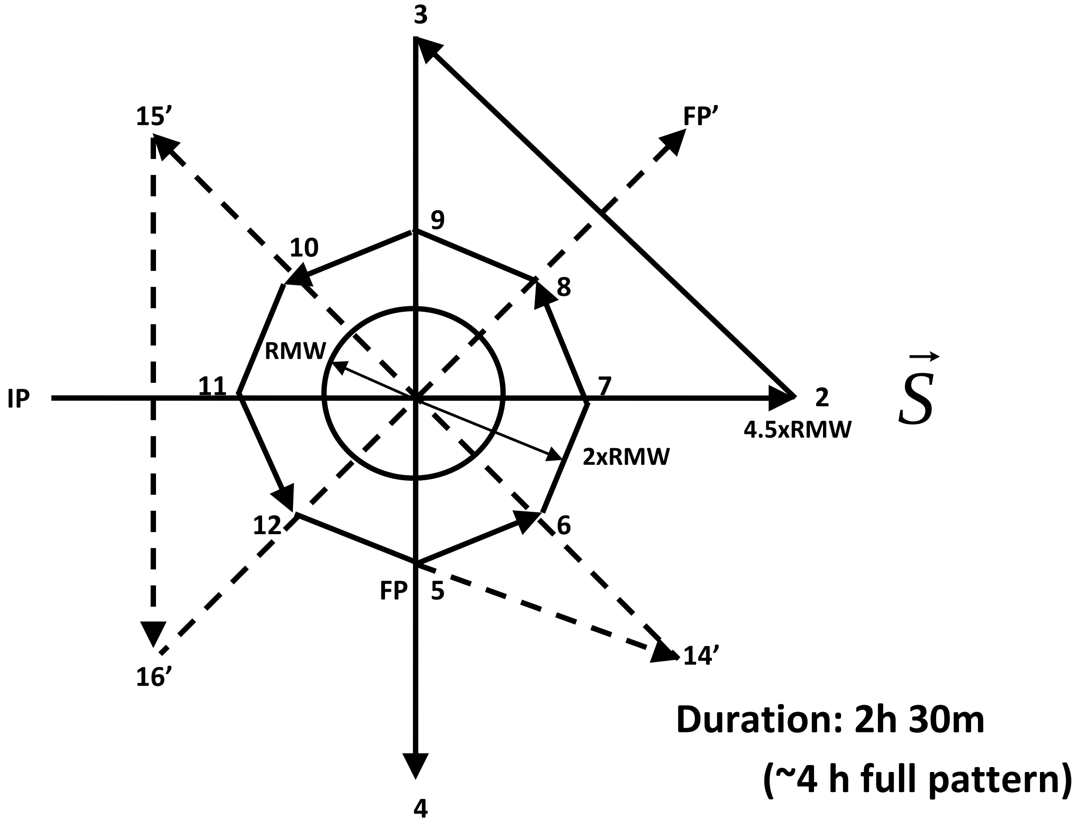


Figure 7-4: P-3 “large tilt” core-region survey pattern

- 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 42 drops needed (25 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. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 81 nm. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. 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).

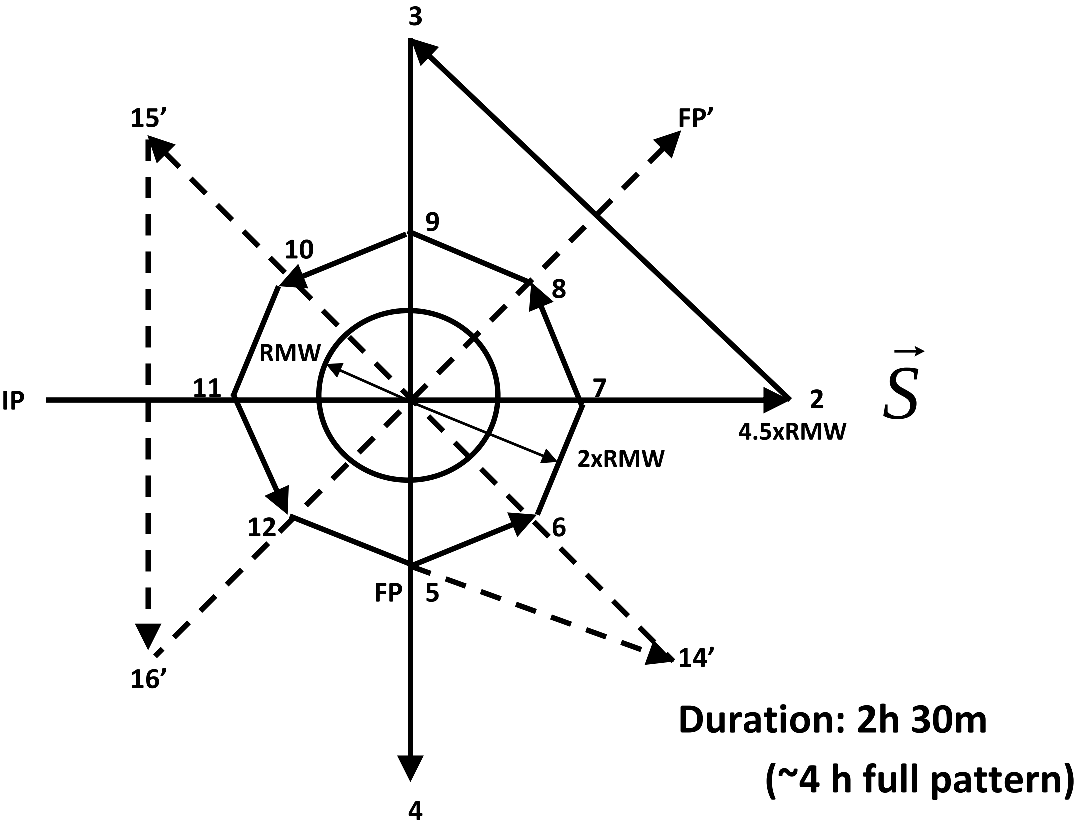


Figure 7-5: P-3 "realignment and recovery" core-region survey pattern

- 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 42 drops needed (25 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. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 81 nm. The aircraft then turns inbound and performs a counter-clockwise octagonal circumnavigation at a radius of 2xRMW. 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.

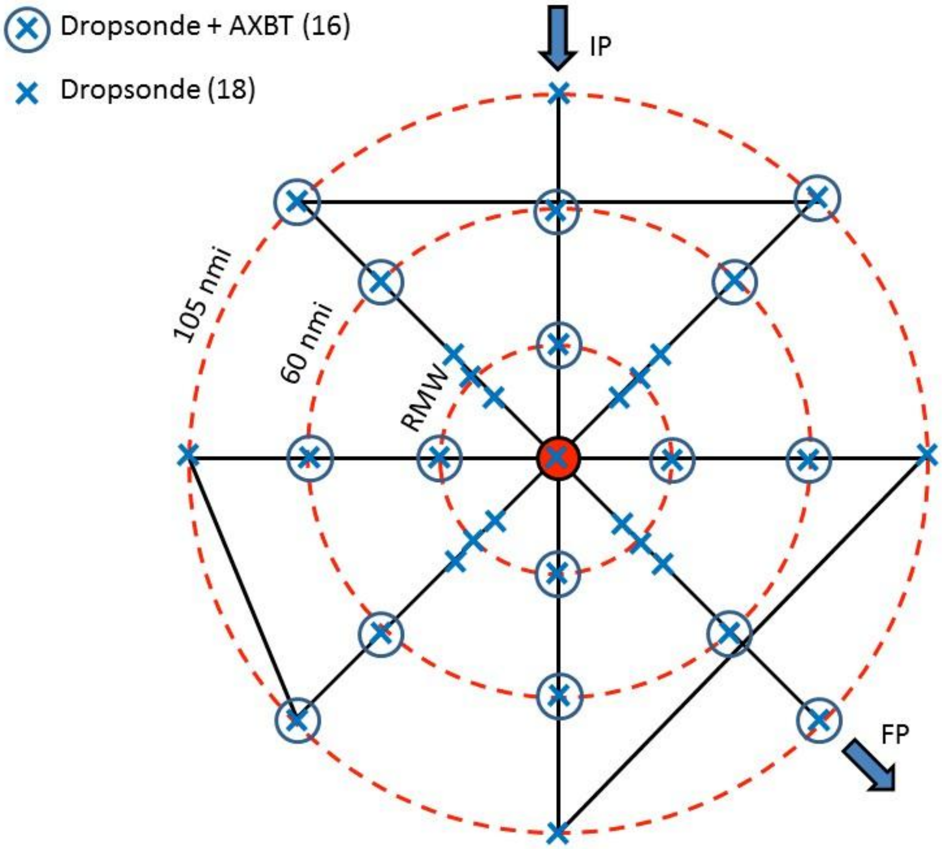


Figure 7-6: Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/Figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. 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.

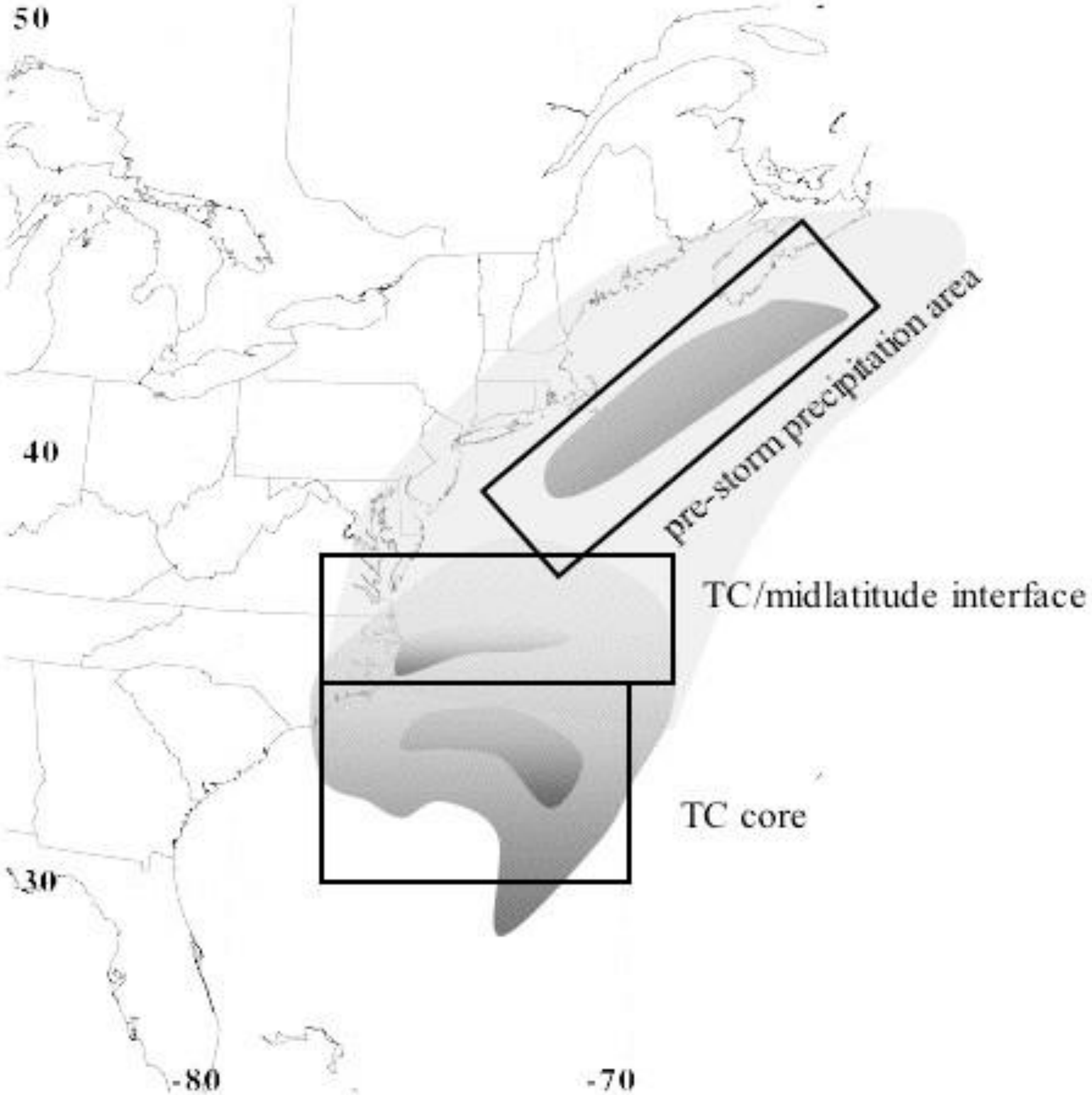


Figure 7-7: Extra-tropical transition module. Schematic of Tropical Cyclone undergoing extra-tropical transition.

Tropical Cyclone in Shear Experiment

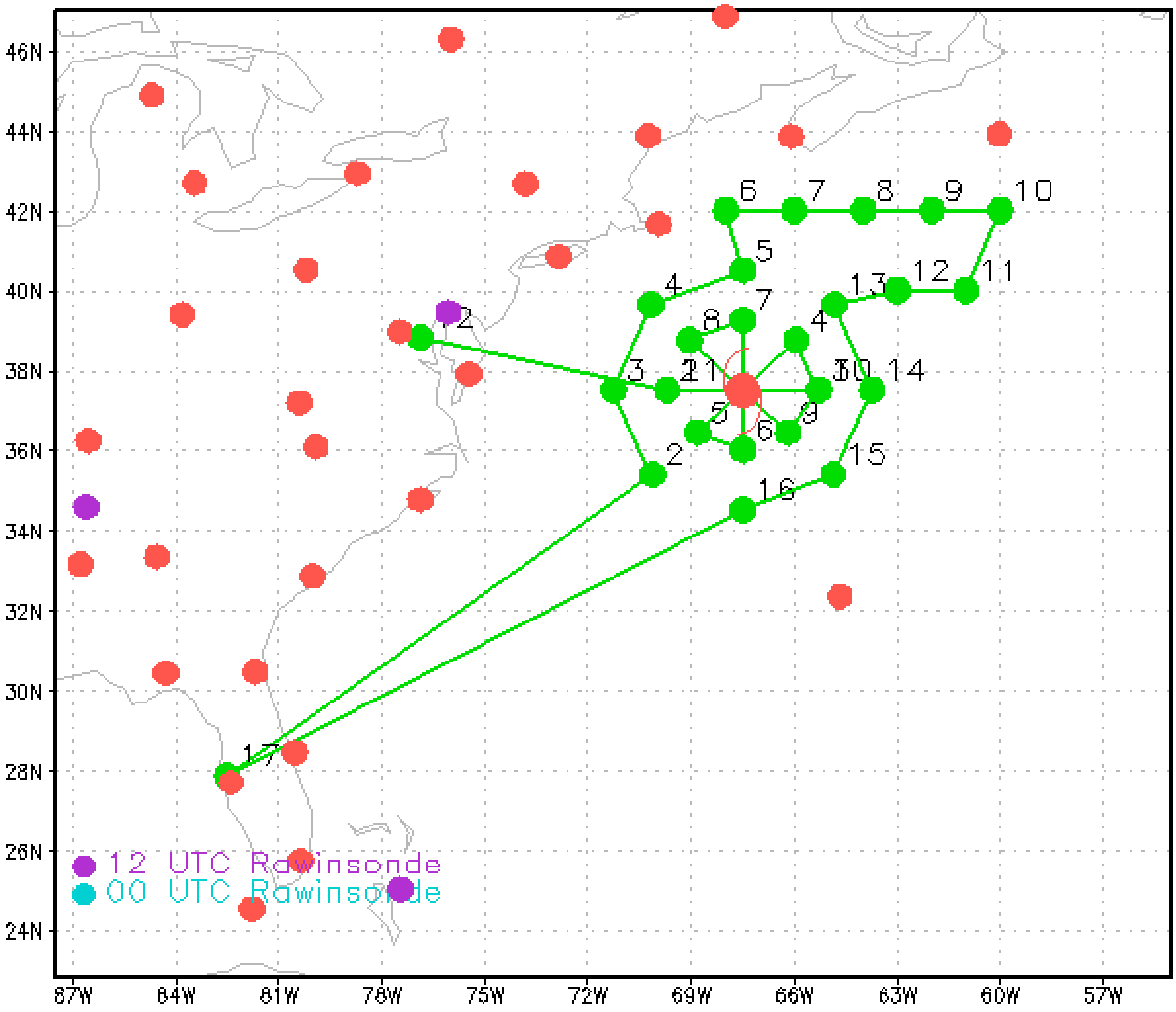


Figure 7-8: Extra-tropical transition module. Proposed flight tracks for G-IV and P3 aircraft.

8. TC Diurnal Cycle Experiment

Principal Investigator: Jason Dunion

Program Significance:

Numerous studies have documented the existence of diurnal maxima and minima associated with tropical convection. However, predicting the timing and extent of this variability remains a difficult challenge. Recent research using GOES satellite imagery has identified a robust signal of tropical cyclone diurnal pulsing. These pulses can be tracked using new GOES infrared satellite image differencing and may represent an unrealized, yet fundamental process of mature TCs. The new satellite imagery reveals "cool rings" in the infrared that begin forming in the storm's inner core near local sunset each day. Similar to ripples that form after a pebble is thrown into a pond, the cool ring, or pulse, continues to away from the storm overnight, reaching areas several hundred km from the storm center by the following afternoon. There appear to be significant structural changes and disruptions to a storm [as indicated by GOES IR and microwave (37 and 85 GHz) satellite imagery] as this pulse moves out from the inner core each day and the timing/propagation of these cool rings also appears to be remarkably predictable. The goal of this experiment is to sample the thermodynamic and kinematic environment of these diurnal pulses at various stages of their life cycles, including their initial formation and subsequent evolution, and to observe any corresponding fluctuations in TC structure and intensity during these events.

Objectives:

To employ both NOAA P-3 and G-IV aircraft to collect kinematic and thermodynamic observations both within the inner-core (i.e., radius < 200 km) and in the surrounding large-scale environment (i.e., 200 km < radius < 600 km) for systems that have exhibited signs of diurnal pulsing in the previous 24 hours. Satellite imagery available from the experimental UW-CIMSS/HRD Diurnal Pulsing web page and a recently developed conceptual clock that describes the timing and position of TC diurnal pulses at various stages of their life cycle will be used to monitor storms and identify optimal aircraft sampling strategies and takeoff times.

Hypotheses:

- Although the exact nature of diurnal pulses is not yet clear, new GOES IR satellite imagery and recent model simulations indicate a diurnal process that is likely being driven by rapid changes in incoming shortwave radiation (resulting in rapid cooling at the CDO level) around sunset each day;
- Rawinsonde data from Caribbean stations suggests that are two necessary conditions needed to initiate TC diurnal pulsing: a cirrus canopy over an area of deep convection and rapid cooling of the cloud tops (i.e. sunset). These conditions appear create large (~4-7 C) temperature inversions at the cloud top level that may help trigger diurnal pulse formation;
- Diurnal pulses may be signatures of outwardly propagating gravity waves, harmonic oscillations of the CDO as it warms (cools) during the day (night), a response to changes in inertial stability in the upper-levels of the storm, or temperature responses that lead to previously documented anvil expansion.
- Diurnal pulses appear to stimulate outward propagation of mass from the inner core as seen in GOES IR imagery (i.e. upper-levels) and 37/85 GHz microwave imagery (i.e. low to mid-levels);
- The aforementioned multi-scale TC Diurnal Pulsing Experiment datasets can be used to improve our understanding of this recently discovered phenomenon and test its observability in model simulations

Links to IFEX goals:

- **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

Mission Description:

The experimental UW-CIMSS/HRD Diurnal Pulsing web page will be used to monitor the development and propagation of TC diurnal pulses and associated cool ring propagation for storms of interest. Additionally, the timing and propagation of the diurnal pulses appears to be remarkably predictable: after its initial formation in the inner core region, it propagates outward at ~10 m s^{-1} and reaches peripheral radii (e.g. 200-500 km) at very specific times of day (local time). Therefore, a conceptual clock describing the evolution of this phenomenon has been developed. Figure 8-1 shows a conceptual 24-hr clock that predicts the approximate times that the pulse passes various radii. This conceptual clock will be used in concert with the UW-CIMSS/HRD real-time diurnal pulsing imagery to plan aircraft sampling strategies and takeoff times.

The P-3 aircraft will dispense GPS dropsondes and collect Doppler radar data while flying a rotating figure-4 pattern (see sample pattern shown in Fig. 8-2) in the inner-core with leg lengths of ~200 km at the maximum safe altitude (~8k-12k feet) for avoiding graupel. The GPS dropsondes should be dispensed on each leg with a spacing of ~50 km to provide adequate coverage for sampling the radial gradients of kinematics and thermodynamics. The GPS dropsonde sampling density should be increased to ~20 km just ahead of, within, and behind the diurnal pulse that will be identified in real-time using the UW-CIMSS/HRD Diurnal Pulsing satellite imagery. Since the diurnal pulse begins forming around local sunset (~1800-2030 LST) and typically passes the 200 km radius at ~0400-0800 LST the following morning, optimal P-3 sampling will occur from ~2000-0400 LST so that the aircraft can adequately sample the formation (just after sunset) and early-stage (inner core out to 200 km) propagation of the cool ring. The P-3 may also fly an arc cloud module or convective burst module as opportunities present. The execution of these optional modules will be at the discretion of the LPS.

The NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) GPS dropsonde drop points will be based on a star pattern selected using real-time information from the UW-CIMSS/HRD diurnal pulsing satellite imagery (Fig. 8-3). The flight pattern will consist of several radial runs toward and away from the storm that will allow for sampling of radial gradients of winds and thermodynamics. GPS dropsondes will be deployed at the turn points in the pattern as well as at mid-points along each leg in the pattern. Additional GPS dropsondes will be deployed just ahead of, within, and behind the diurnal pulse cool ring (Fig. 8-3, yellow to pink shading) and will be determined by the LPS during the mission. Since the diurnal pulse typically passes the TC outer radii (e.g. 300-400 km) later in the morning and early afternoon local time, the optimal G-IV sampling will occur slightly later than the optimal P-3 sampling. The diurnal cycle conceptual clock (Fig. 8-1) indicates that the cool ring passes the 300 (400) km radius at ~0800-1200 LST (~1200-1500 LST). Therefore, the optimal G-IV sampling will occur from ~0800-1500 LST and will target the later stages of the diurnal cycle cool ring evolution. The G-IV may also fly an arc cloud module as opportunities present. The execution of this optional module will be at the discretion of the LPS.

When possible, TC Diurnal Cycle Experiment missions will be coordinated with the HRD Tropical Cyclone Genesis Experiment (GenEx), TC Shear Experiment, and Rapid Intensity Experiment (RAPX). This coordination will involve the WP-3D and G-IV and will be executed on a case-by-case basis.

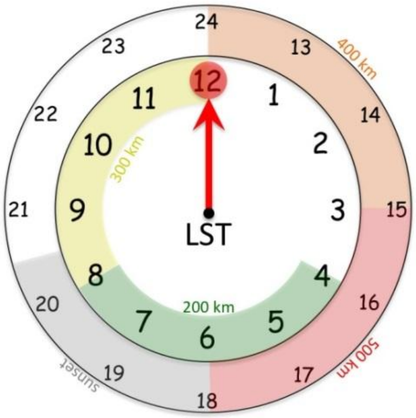


Figure 8-1: Conceptual 24-hr TC diurnal pulsing clock that outlines the lifecycle of cool rings propagating from the TC inner core. For example, the pulse forms at local sunset (~1800-2030 LST, gray shading) and begins to propagate away form the inner core, passing the 200 km radius at ~0400-0800 LST (green shading) the following morning. It eventually reaches the 400 km radius at ~1200-1500 LST (orange shading) in the early afternoon.

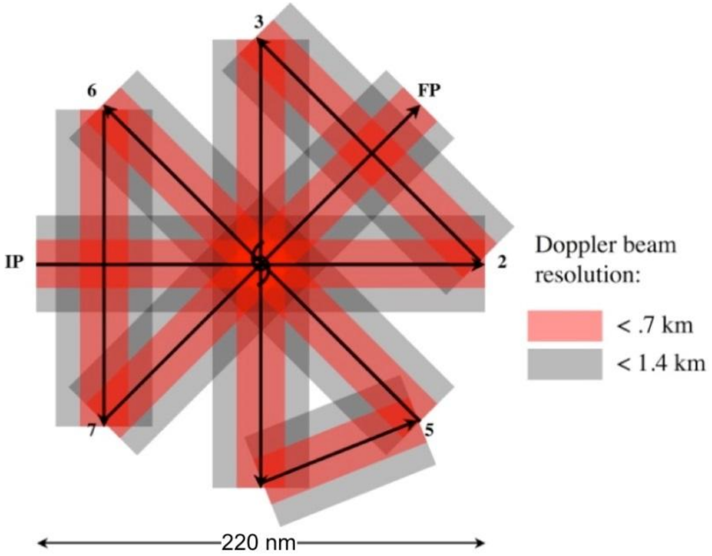


Figure 8-2: Sample rotated figure-4 flight pattern for TC Diurnal Cycle Experiment mission. The red shading denotes locations where vertical spacing of Doppler beam < 0.7 km, grey shading where vertical spacing < 1.4 km. GPS dropsondes should be released at all turn points (past the turn after the aircraft has leveled), at midpoints of inbound/outbound legs, and at center point between IP/2 and 5/6.

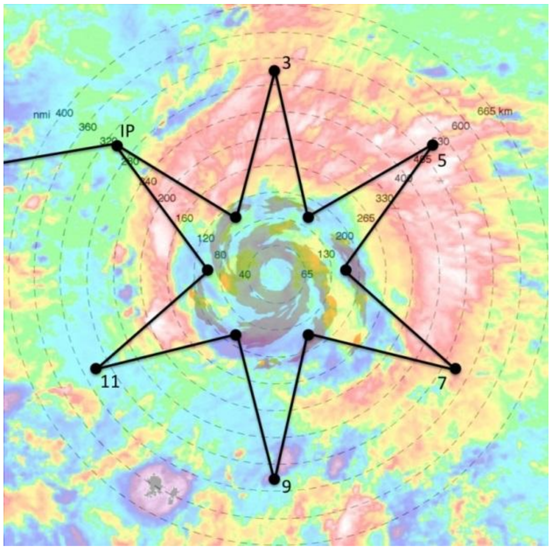


Figure 8-3: Sample G-IV star pattern for the TC Diurnal Cycle Experiment. The endpoints of the pattern will be ~400 km from the storm center, but could be adjusted inward or outward depending in the exact position of the outwardly propagating diurnal pulse cool ring. The pattern is overlaid on a sample GOES IR diurnal pulsing image. The yellow to pink shading indicates a cool ring propagating away from the storm during this time and shows its typical evolution at ~1500 LST when it has reached the ~400 km radius.

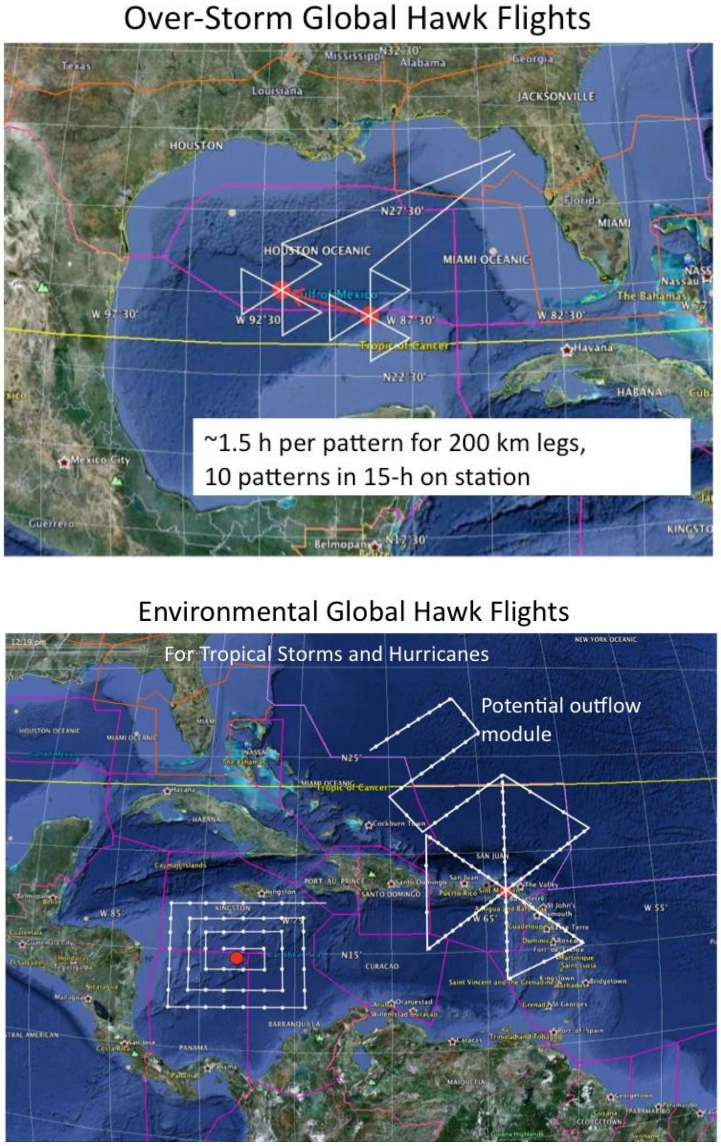
Analysis Strategy

This experiment seeks to observe the formation and evolution of TC diurnal pulsing. Specifically, GPS dropsonde and radar observations will be used to analyze both the inner-core and environmental kinematics and thermodynamics that may lead to the formation of diurnal pulsing and to document the kinematics and thermodynamics that are associated with TC diurnal pulses at various stages of their evolution.

Coordination with Supplemental Aircraft

NASA will be conducting its Hurricane Severe Storm Sentinel (HS3) mission from 20 Aug – 24 Sep 2013. This mission will consist of two unmanned Global Hawk (GH) aircraft, flying at approximately 55,000-60,000 ft altitude with mission durations of up to 24-30 h. One GH will focus on flying patterns over the inner-core of TCs, while the other GH will focus on patterns in the environment of TCs. The primary science goals of HS3 are to better understand inner-core and environmental processes important in TC genesis, intensification, and extratropical transition.

When possible, it will be desirable to fly P-3 and G-IV patterns that are coordinated with the GH aircraft (see Fig. 8-4 for sample GH flight patterns). For the NOAA P-3, “coordinated” means flying radial penetrations where the P-3 and GH are vertically-stacked for at least a portion of the flight leg, preferably when the aircraft are approaching the center of the TC. The across-track displacement during such coordination should be kept as small as practicable, e.g., no greater than 5-10 km. In practice, the NOAA P-3 will likely fly its planned figure-4/butterfly/rotating figure-4 patterns as indicated in Fig. 8-2. The inner-core GH can fly patterns that are similar in geometry to the NOAA P-3 patterns (Fig. 8-4). To achieve coordination, the inner-core GH would align its legs such that the GH will be stacked with the P-3. The G-IV pattern could either be designed/timed to supplement simultaneous coverage by the GH environmental aircraft or could supplement storm environment coverage on days when the GH environmental aircraft is not flying the storm.


Over-Storm Global Hawk Flights

Environmental Global Hawk Flights

Figure 8-4: Sample flight pattern for the (top) over-storm and (bottom) environmental Global Hawk aircraft for TCs located in the Gulf of Mexico, Caribbean, and western North Atlantic.

9. TC-Ocean Interaction Experiment

Principal Investigator(s): Rick Lumpkin (PhOD), Luca Centurioni (SIO), and Nick Shay (U. Miami/RSMAS)

HRD Point of Contact: Eric Uhlhorn

Primary IFEX Goal: 3 - Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

Significance and Goals:
This program broadly addresses the role of the ocean and air-sea interaction in controlling TC intensity by making detailed measurements of these processes in storms during the 2013 season. Specific science goals are in two categories:

Goal: To observe and improve our understanding of the upper-ocean response to the near-surface wind structure during TC passages. Specific objectives are:

1. The oceanic response of the Loop Current (LC) to TC forcing; and,
2. Influence of the ocean response on the atmospheric boundary layer and intensity.

In addition, these ocean datasets fulfill needs for initializing and evaluating ocean components of coupled TC forecast systems at EMC and elsewhere.

Rationale:
Ocean effects on storm intensity. Upper ocean properties and dynamics undoubtedly play a key role in determining TC intensity. Modeling studies show that the effect of the ocean varies widely depending on storm size and speed and the preexisting ocean temperature and density structure. The overarching goal of these studies is to provide data on TC-ocean interaction with enough detail to rigorously test coupled TC models, specifically:

- Measure the two-dimensional SST cooling, air temperature, humidity and wind fields beneath the storm and thereby deduce the effect of the ocean cooling on ocean enthalpy flux to the storm.
- Measure the three-dimensional temperature, salinity and velocity structure of the ocean beneath the storm and use this to deduce the mechanisms and rates of ocean cooling.
- Conduct the above measurements at several points along the storm evolution therefore investigating the role of pre-existing ocean variability.
- Use these data to test the accuracy of the oceanic components coupled models.

Ocean boundary layer and air-sea flux parameterizations. TC intensity is highly sensitive to air-sea fluxes. Recent improvement in flux parameterizations has led to significant improvements in the accuracy of TC simulations. These parameterizations, however, are based on a relatively small number of direct flux measurements. The overriding goal of these studies is to make additional flux measurements under a sufficiently wide range of conditions to improve flux parameterizations, specifically:

- Measure the air-sea fluxes of enthalpy and momentum using ocean-side budget and covariance measurements and thereby verify and improve parameterizations of these fluxes.
- Measure the air-sea fluxes of oxygen and nitrogen using ocean-side budget and covariance measurements and use these to verify newly developed gas flux parameterizations.
- Measure profiles of ocean boundary layer turbulence, its energy, dissipation rate and skewness and use these to investigate the unique properties of hurricane boundary layers.
- Conduct the above flux and turbulence measurements in all four quadrants of a TC so as investigate a wide range of wind and wave conditions.

The variability of the Gulf of Mexico Loop Current system and associated eddies have been shown to exert an influence on TC intensity. This has particular relevance for forecasting landfalling hurricanes, as many

TCs in the Gulf of Mexico make landfall on the U.S. coastline. To help better understand the LC variability and improve predictions for coupled model forecasts, upper-ocean temperature and salinity fields in the vicinity of the LC will be sampled using expendable ocean profilers (see Fig. 9-1).

Pre- and post-storm expendable profiler surveys

Flight description:

Feature-dependent survey. Each survey consists of deploying 60-80 expendable probes, with take-off and recovery at KMCF. Pre-storm missions are to be flown one to three days prior to the TC's passage in the LC (Fig. 9-1). Post-storm missions are to be flown one to three days after storm passage, over the same area as the pre-storm survey. Since the number of deployed expendables exceeds the number of external sonobuoy launch tubes, profilers must be launched via the free-fall chute inside the cabin. Therefore the flight is conducted un-pressurized at a safe altitude. In-storm missions, when the TC is passing directly over the observation region, will typically be coordinated with other operational or research missions (e.g. Doppler Winds missions). These flights will require 10-20 AXBTs deployed for measuring sea surface temperatures within the storm.

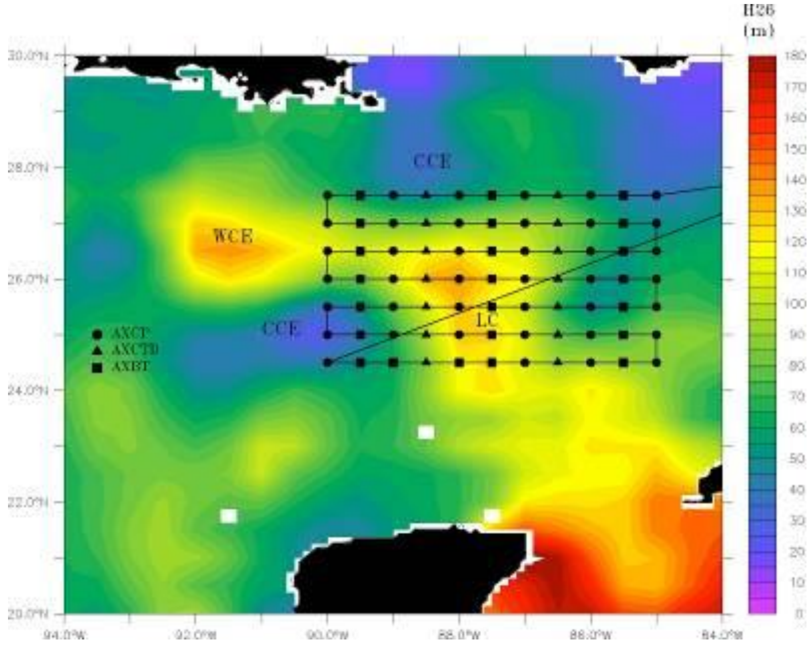


Figure 9-1: Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at KMCF.

Track-dependent survey. For situations that arise in which a TC is forecast to travel outside of the immediate Loop Current region, a pre- and post-storm ocean survey focused on the official track forecast is necessary. The pre-storm mission consists of deploying AXBTs/AXCTDs on a regularly spaced grid, considering the uncertainty associated with the track forecast. A follow-on post-storm mission would then be executed in the same general area as the pre-storm grid, possibly adjusting for the actual storm motion. Figure 9-2 shows a scenario for a pre-storm survey, centered on the 48 hour forecast position. This sampling strategy covers the historical "cone of uncertainty" for this forecast period.

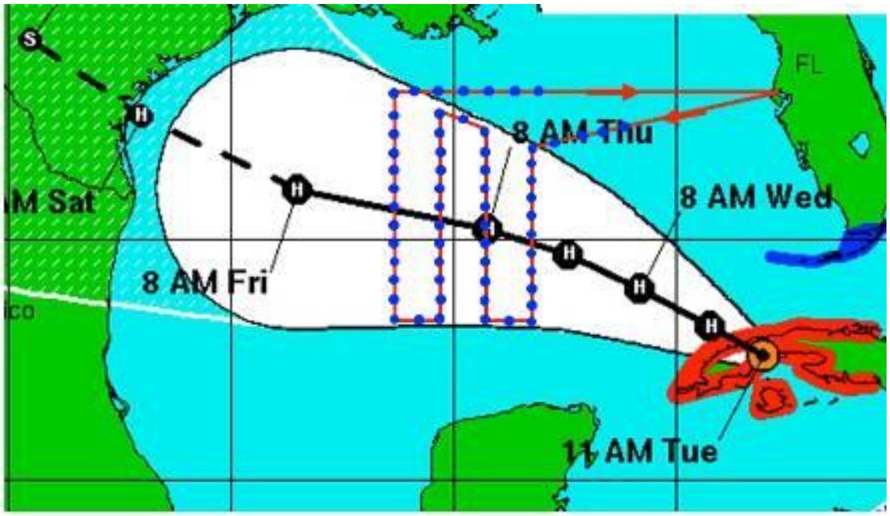


Figure 9-2: Track-dependent AXBT/AXCTD ocean survey. As for the Loop Current survey, a total of 60-80 probes would be deployed on a grid (blue dots).

Coordinated float/drifter deployment overflights:

Measurements will be made using arrays of drifters deployed by AFRC WC-130J aircraft in a manner similar to that used in the 2003 and 2004 CBLAST program. Additional deployments have since refined the instruments and the deployment strategies. MiniMet drifters measure SST, sea level air pressure and wind velocity. Thermistor chain Autonomous Drifting Ocean Station (ADOS) drifters add ocean temperature measurements to 150m. All drifter data are reported in real time through the Global Telecommunications System (GTS) of the World Weather Watch. An additional stream of real-time, quality controlled data is also provided by a server located at the Scripps Institution of Oceanography.

If resources are available from other Principal Investigators, flux Lagrangian floats will measure temperature, salinity, oxygen and nitrogen profiles to 200 m, boundary layer evolution and covariance fluxes of most of these quantities, wind speed and scalar surface wave spectra, while E-M APEX Lagrangian floats will measure temperature, salinity and velocity profiles to 200m. Float profile data will be reported in real time on GTS.

This drifter effort is supported by the Global Drifter Program. The HRD contribution consists of coordination with the operational components of the NHC and the 53rd AFRC squadron and P-3 survey flights over the array with SFMR and SRA wave measurements and dropwindsondes. If the deployments occur in the Gulf of Mexico, Loop Current area, this work will be coordinated with P-3 deployments of AXBTs, AXCTDs and AXCPs to obtain a more complete picture of the ocean response to storms in this complex region.

Coordination and Communications:
Alerts **-** Alerts of possible deployments will be sent to the 53rd AWRO up to 5 days before deployment, with a copy to CARCAH, in order to help with preparations. Luca Centurioni (SIO) and Rick Lumpkin (PhOD) will be the primary point of contact for coordination with the 53rd WRS and CARCAH.

Flights:
Coordinated drifter deployments would nominally consist of 2 flights, the first deployment mission by AFRC WC-130J and the second overflight by NOAA WP-3D. An option for follow-on missions would depend upon available resources.

Day 1- WC-130J Float and drifter array deployment- Figure 9-3 shows a possible nominal deployment pattern for the float and drifter array. It consists of two lines, A and B, set across the storm path with 8 and 4 elements respectively. The line length is chosen to be long enough to span the storm and anticipate the errors in forecast track. The element spacing is chosen to be approximately the RMW. In case of large uncertainties of the forecast track a single 10 node line is deployed instead. The thermistor chain drifters (ADOS) are deployed near the center of the array to maximize their likelihood of seeing the maximum wind speeds and ocean response. The Minimet drifters are deployed in the outer regions of the storm to obtain a full section of storm pressure and wind speeds. The drifter array is skewed one element to the right of the track in order to sample the stronger ocean response on the right side (cold wake).

Day 2. P-3 In-storm mission- Figure 9-4 shows the nominal P-3 flight path and dropwindsonde locations during the storm passage over the float and drifter array. The survey should ideally be timed so that it occurs as the storm is passing over the drifter array.

The survey includes legs that follow the elements of float/drifter line 'A' at the start and near the end. The survey anticipates that the floats and drifters will have moved from their initial position since deployment and will move relative to the storm during the survey. Waypoints 1-6 and 13-18 will therefore be determined from the real-time positions of the array elements. Each line uses 10 dropwindsondes, one at each end of the line; and two at each of the 4 floats, the double deployments are done to increase the odds of getting a 10m data.

The rest of the survey consists of 8 radial lines from the storm center. Dropwindsondes are deployed at the eye, at half R_{max}, at R_{max}, at twice R_{max} and at the end of the line, for a total of 36 releases. AXBTs are deployed from the sonobuoy launch tubes at the eye, at R_{max} and at 2 R_{max}. This AXBT array is focused at the storm core where the strongest air-sea fluxes occur; the buoy array will fill in the SST field in the outer parts of the storm. In this particular example, the final two radials have been moved after the second float survey to avoid upwind transits. For other float drift patterns, this order might be reversed.

It is highly desirable that this survey be combined with an SRA surface wave survey because high quality surface wave measurements are essential to properly interpret and parameterize the air-sea fluxes and boundary layer dynamics, and so that intercomparisons between the float wave measurements and the SRA wave measurements can be made.

Extended Mission Description:
If the storm remains strong and its track remains over water, a second or possibly third oceanographic array may be deployed, particularly if the predicted track lies over a warm ocean feature predicted to cause storm intensification (Fig. 9-5). The extended arrays will consist entirely of thermistor chain and minimet drifters, with 7-10 elements in a single line. As with the main mission, the spacing and length of the line will be set by the size of the storm and the uncertainty in the forecast track.

Mission timing and coordination will be similar to that described above. P-3 overflights would be highly desirable.

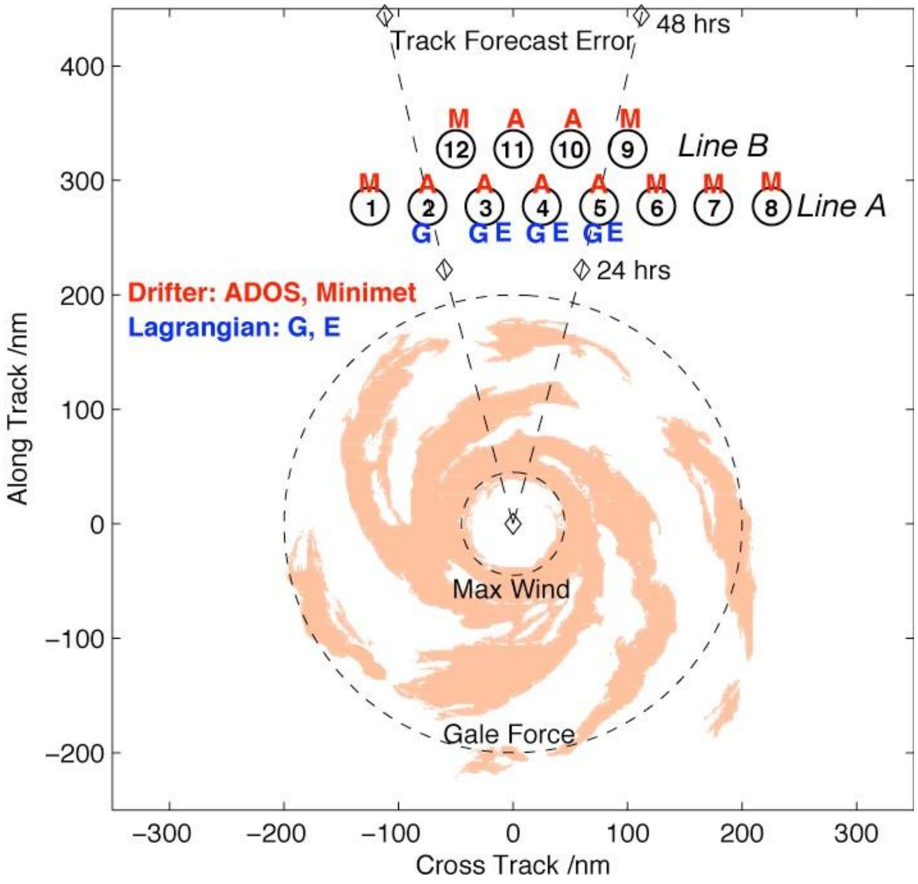
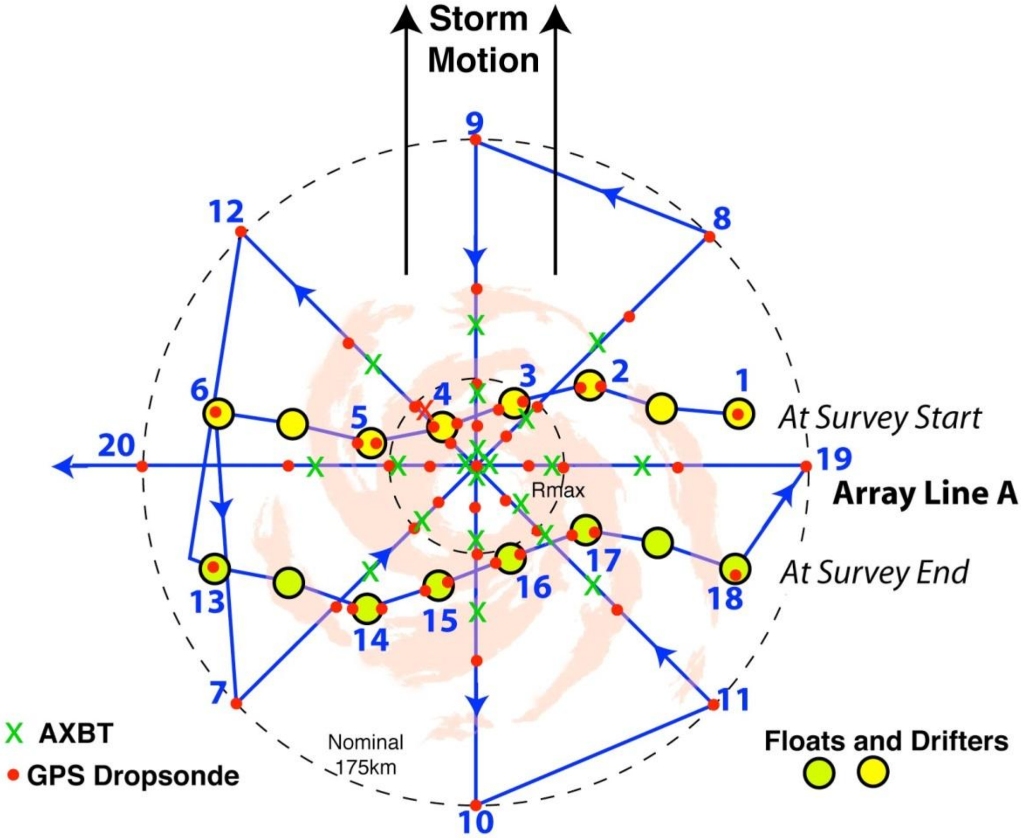


Figure 9-3: Drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of ADOS thermistor chain (A) and minimet (M) drifters. Gas (G) and EM (E) Lagrangian floats could be added if available. Three items are deployed at locations 3, 4 and 5, two items at location 3 and one item elsewhere.



Notes:
4 diameter lines through eye each with
9 dropsondes. At eye, 0.5 Rmax, Rmax, 2 Rmax, Line end.
5 AXBT. At eye, Rmax, 2 Rmax
2 float array lines each with
10 dropsondes. 2 at each of 4 floats, 2 Line ends.
Total: 56 dropsondes, 20 AXBT

Figure 9-4: P-3 pattern over float and drifter array. The array has been distorted since its deployment on the previous day and moves relative to the storm during the survey. The pattern includes two legs along the array (waypoints 1-6 and 13-18) and an 8 radial line survey. Dropwindsondes are deployed along all legs, with double deployments at the floats. AXBTs are deployed in the storm core.

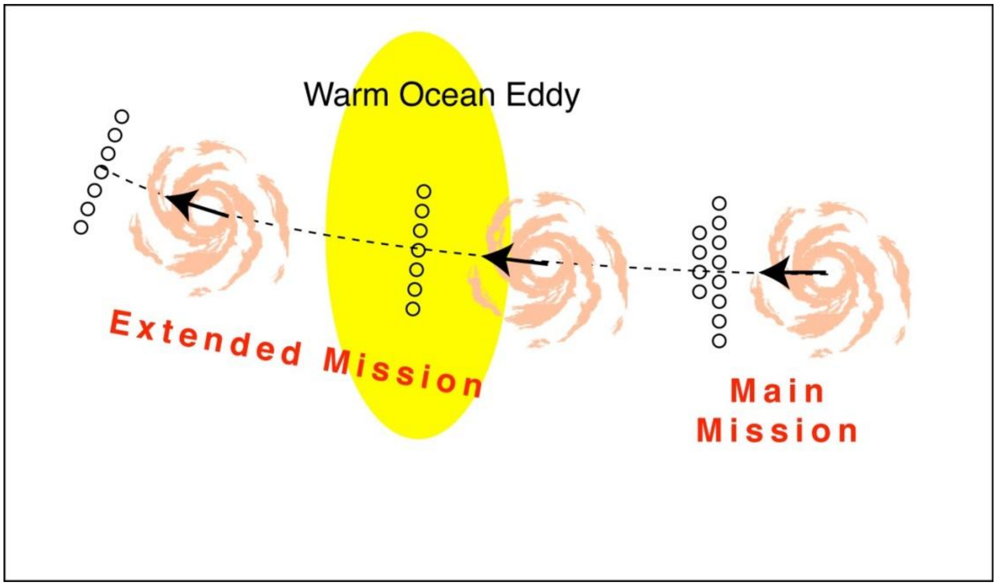


Figure 9-5: Extended Mission. Two additional drifter arrays will be deployed along the storm track.

10. Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Motivation:

While forecasts of TC track have shown significant improvements in recent years (Aberson 2001), corresponding improvements in forecasts of TC intensity have been much slower (DeMaria and Gross 2003). The lack of improvement in intensity forecasting is the result of deficiencies in the numerical models (e.g., resolution limitation and parameterization inadequacies), deficiencies in the observations, and deficiencies in basic understanding of the physical processes involved. The problem becomes even more acute for forecasting tropical cyclogenesis. While global models have shown some skill in recent years in predicting tropical cyclogenesis, understanding of the physical processes involved remains limited, largely because observing genesis events is a difficult task. However, a key aspect of IFEX (Rogers et al. 2006) is the collection of observations during all portions of a TC lifecycle, particularly on the early lifecycle stages. This emphasis on the early stages of the lifecycle will provide an opportunity to observe several genesis events and improve understanding of this key process, leading to better predictions of tropical cyclogenesis, organization, and intensification.

Since both tropical cyclogenesis and TC intensity change can be defined by changes in low- and mid-level vorticity, knowledge of the processes that play a significant role in genesis will also advance understanding of intensity change. A better understanding of the processes that lead to an increase in low- and mid-level cyclonic vorticity will also allow NHC to better monitor and forecast tropical cyclogenesis and intensity change, improvements that would be especially valuable for those events that threaten coastal areas. Data obtained by aircraft investigating potential genesis events will positively impact operations and research in other ways as well. The collection of three-dimensional data at all stages in a TC lifecycle is one of the key requirements for NCEP as a part of IFEX. Such data will provide information that will guide the development of error covariances important in the development of data assimilation schemes for models (i.e., HWRF) that will be used in these environments. They will also provide important datasets for evaluating the performance of HWRF. In addition to improving the understanding and forecasting of tropical cyclogenesis and intensity change, the proposed experiment will yield useful insight into the structure, growth and ultimately the predictability of the systems responsible for almost all of the weather-related destruction in the tropical Atlantic and East Pacific. Investigation of systems that fail to complete the genesis process will also result in a better understanding and prediction of easterly disturbances in general so that distinction can be better made between developing and non-developing tropical disturbances.

Background:

Tropical cyclogenesis can be viewed as a rapid increase of low-level cyclonic vorticity organized on the mesoscale within a region of enhanced convective activity. Numerous hypotheses have been advanced in the literature to explain how this vorticity develops and amplifies. One of the key aspects differentiating these hypotheses centers on whether the lower-tropospheric cyclonic vorticity begins in the mid-levels and develops downward to the surface or begins in the lower troposphere and builds upward to the middle troposphere – the so-called top-down vs. bottom-up mechanisms. Prominent top-down theories include one study which showed observations of multiple midlevel vortices prior to genesis in the West Pacific (Ritchie et al. 1997) that led them to view the genesis process as a stochastic one whereby chance merger and axisymmetrization of these midlevel vortices leads to growth of the circulation to the surface by increasing the Rossby-Prandtl-Burger penetration depth of potential vorticity anomalies associated with the vortices. Another study supporting the top-down approach showed observations of genesis in the East Pacific (Bister and Emanuel 1997) and hypothesized that downdrafts driven by evaporational cooling advected the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production.

The set of hypotheses supporting the bottom-up approach generally describes the genesis process as being driven by low-level convergence that increases cyclonic vorticity near the surface through vortex stretching. One such bottom-up hypothesis emphasizes the role of a parent midlevel vortex in axisymmetrizing nearby low-level convectively generated cyclonic vorticity, called vortical hot towers, that leads to the spin-up of the surface circulation (e.g., Montgomery and Enagonio 1998; Davis and Bosart 2001; Hendricks et al 2004). A similar hypothesis was advanced by Rogers and Fritsch (2001) and Chen and Frank (1993) who emphasized the role of the midlevel vortex and high midlevel humidity in providing a favorably reduced local Rossby radius of deformation to retain the heating from convective bursts and spin up low-level vorticity through low-level stretching caused by the convective heating. The importance of convective heating and divergence profiles for the development of low-level vorticity has been shown in the Doppler radar observations of Tropical Storm Dolly by Reasor et al. (2005) and Hurricane Ophelia by Houze et al. (2009) and in numerical simulations of the genesis of Tropical Storm Gert by Braun et al. (2010) and the rapid intensification of Hurricane Dennis in Rogers (2010). Another set of genesis theories focuses on the reduction of the lower tropospheric effective static stability to low values in the core of incipient cyclones. Suppression of convectively induced downdrafts is one means of accomplishing this (Emanuel 1995; Raymond, Lopez-Carrillo, and Lopez Cavazos 1998). Eliminating low-level outflows produced by the downdrafts allows the inflow of updraft air to spin up the low-level circulation, leading to the development of the warm-core characteristic of the TC.

With the bottom-up paradigm in mind, the sensitivity of the convective and low-level vorticity evolution to background rotation has been examined in idealized numerical simulations by Wissmeier and Smith (2011). Kilroy and Smith (2012) looked additionally at the impact of dry air (motivated by soundings from the 2010 PREDICT genesis experiment) on the development of convection and vorticity. Drier air aloft did not yield stronger convectively induced downdrafts in their simulations, but they did find that the depth through which vertical vorticity is enhanced is more limited with the introduction of dry air. They attributed the shallower vorticity development to reduced vertical penetration of the updrafts, which in turn was caused by enhanced updraft detrainment. Bell and Montgomery (2010) provided observational documentation of vertically sheared vortical convection during the pre-depression disturbance phase – future numerical studies are needed to systematically determine the impact of vertical wind shear on the bottom-up development for environments with different background rotation and moisture structure.

Finally, it has been shown in Dunkerton, Montgomery and Wang (2009, DMW09) and Wang, Montgomery and Dunkerton (2009, WMD09) that genesis tends to occur near the intersection of a tropical wave critical surface and the precursor parent wave’s axis, which is the center of a “pouch”. This “marsupial” paradigm suggests that the critical layer of a tropical easterly wave is important to tropical storm formation because 1) wave breaking or roll-up of the cyclonic vorticity near the critical surface in the lower troposphere provides a favored region for the aggregation of vorticity seedlings and TC formation; 2) the wave critical layer is a region of closed circulation, where air is repeatedly moistened by convection and protected from dry air intrusion; and 3) the parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave.

Hypotheses:

With the above background in mind, the following hypotheses will be tested by data collected and analyzed here:

1. <u>Tropical cyclogenesis is primarily a bottom-up process that requires a broad area of convective processes in concert with stratiform precipitation</u>
   This hypothesis will be tested by documenting the development of low-level vorticity in the presence of a midlevel vortex center, and vice versa, as well as by documenting the interactions between low- and mid-level vortices in pre-genesis environments. The sensitivity of this development to the environment (e.g., background rotation, vertical wind shear, and moisture gradients) will be examined. It will also consider the precipitation structures within the developing circulation and how these structures (convective vs. stratiform) evolve over time.

2. The interaction of an incipient vortex with the Saharan Air Layer (SAL) overall is detrimental for tropical cyclogenesis.
   Key tasks in testing this hypothesis involve collecting temperature, humidity, pressure, and wind measurements across multiple scales, i.e., within the core and near environment of an incipient vortex. These measurements will be key to assessing the importance of pre-existing vorticity and broad areas of high humidity on the maintenance of deep convection in the incipient vortex and determining the importance of their spatial and temporal distribution in tropical cyclogenesis. Another important question to address is the importance of downdraft suppression in limiting boundary layer stabilization. A final, and key, task is to examine hypotheses relating humidity and static stability profiles to downdraft morphology and the vortex response to convective heating, in particular in the presence of dry air and lower-tropospheric shear typically associated with SAL interactions.

3. As stated in DMW08 and WMD09, genesis tends to occur near the intersection of a tropical wave critical surface and the precursor parent wave's axis, which is the center of a "pouch".
   The objective of marsupial tracking is to track the wave pouch (rather than the diabatic vortices inside the pouch) and estimate its propagation speed and predict the genesis location, which can be used to provide useful guidance for flight planning during IFEX.

Links to IFEX:

It supports the following NOAA IFEX goals:

- **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;

Experiment Description:

The physical processes that are important in tropical cyclogenesis span a wide spectrum of temporal and spatial scales, with time scales ranging from minutes to days and space scales ranging from mm to hundreds of km. Furthermore, many of the processes are highly nonlinear and transient. For these reasons, an experimental approach that combines observations and numerical modeling is required to adequately address the questions posed above. What is discussed here is the observational component of GenEx. When possible, GenEx missions will be coordinated with SALEX. This coordination will involve the P-3 and/or G-IV and be executed on a case-by-case basis.

Recent observations from airborne Doppler radar have identified important processes on the mesoscale that contribute to tropical cyclogenesis. For example, results obtained from a P-3 aircraft investigation of Dolly in 1996 (Reasor et al. 2005) indicate its genesis was strongly influenced by persistent, deep convection in the form of mesoscale convective systems (MCSs) that developed in association with an easterly wave over the Caribbean. Within this deep convection an eye-like feature formed, after which time the system was declared a depression. The initial development of the low-level circulation in both Dolly (1996) and Guillermo (1991) occurred in the presence of multiple midlevel vortices. The close proximity of the low- and mid-level vorticity maxima (often within 50-100 km horizontally) observed in these two genesis cases supports a further examination of the aforementioned vortex merger ideas. To adequately diagnose the role of these vortices, it is vital that they be sampled in their entirety (which will invariably depend on the distribution of precipitation scatterers) and with a temporal resolution that allows time continuity of the vortices to be established when possible.

In addition to the wind and rainfall measurements provided by the Doppler radars, measurements of temperature and moisture are vital to address the thermodynamic issues described above. Dropwindsondes released in a regular grid will enable the determination of thermodynamic fields in the vicinity of the incipient system, as well as enable the calculation of mean divergence and vorticity fields around the system, important in determining the strength and depth of the downdrafts (provided time aliasing is minimized). The dropwindsondes should be released from as high an altitude as possible to provide observations of mid-level humidity and wind speeds where scatterers are not present. The tail radars on the P-3s will also enable a determination of the presence of saturation when scatterers are observed.

This may be executed with the P-3 alone, but optimally it will involve the participation of the NOAA G-IV aircraft as well. Flights will occur into incipient tropical disturbances over the western Caribbean Sea, Gulf of Mexico, and tropical Atlantic Ocean. For these missions the P-3's may be based in Tampa, St. Croix, or Barbados. The systems flown here will primarily be incipient systems. To minimize the potential of land interactions, no system will be targeted that has the potential of making landfall within 48 h of the beginning of the first flight. Also, no system will be targeted that does not have the likelihood of being a viable target for at least three consecutive P-3 missions (i.e., 24 h), with four P-3 missions or more being considered optimal.

The primary mission will require the P-3 flying back-to-back missions. It will fly mesoscale survey patterns designed to document any suspected low- and mid-level vortices and sample any changes in the low- and mid-level thermodynamic fields associated with the incipient systems. Crucial to a complete understanding of the genesis process is the collection of observations with high temporal and spatial resolution. In anticipation of future operational missions required at synoptic times (12 and 00 UTC) as the incipient system intensifies, the staggered P-3 missions are designed to commence on station at 12 and 00 UTC, meaning that takeoff would be around 09 and 21 UTC, respectively. If it is not possible to fly the P-3 at 12-h staggering, then 24-h staggering will be performed. If available, the G-IV aircraft would fly simultaneously at upper levels (42,000 ft or 175 hPa).

The main aircraft for the mesoscale flights will be the P-3. Doppler radar observations, dropwindsondes, and flight-level observations obtained during these flights will help locate low- and mid-level vortices and help document their structures and life cycles. Primary aspects will be to observe the complete life cycle and interaction of low- and mid-level vortices, understand how these vortices are influenced by the diurnal cycle of convection and their interaction with the environmental flow, and observe the evolution of the thermodynamic fields as the incipient system evolves. The location of persistent areas of deep convection and candidate vortices will be determined using high-resolution visible and infrared GOES-winds produced available online, supplemented by satellite microwave imagery when available. Additionally, favorable environments for deep convection and vortex development, such as those described in the Introduction, will be identified using water vapor loops, model analysis fields enhanced by satellite wind measurements, and possibly ASCAT imagery, also available online.

Staggered missions with the P-3 aircraft will begin with the aircraft flying one of two survey patterns at max 12,000 ft (4 km). The primary purpose of these patterns will be to collect F/AST Doppler radar and dropwindsonde data in the area of deep convection in order to map the evolution of the three-dimensional wind and thermodynamic structure of the deep convection and incipient vortex. Two possible patterns can be flown, with the decision of which pattern determined by the degree of organization of the system. For incipient systems that are relatively disorganized, a lawnmower pattern is flown (Fig. 10-1) along the axis of an easterly wave. Leg lengths will be 150-200 nm (250-300 km), with some variability dependent on the size of the system and the time available on station. The pattern will be centered approximately on any discernible circulation or wave axis, if identifiable, or in the absence of such features, on a dominant area of convective activity. Priority will be placed, however, on centering the pattern on the mesoscale circulation pattern (i.e., the pouch), and *not* targeted at transient convective activity.

As a system becomes better organized, a second survey pattern is flown (Fig. 10-2), consisting of a square-spiral centered on a broad low- or mid-level circulation center. If multiple mesoscale convective systems exist embedded within a parent circulation, the pattern will be centered on the parent circulation. Dropwindsondes are released at regular intervals to create a near uniform grid covering the circulation and including any MCSs, if possible. The spacing between the outer spiral and the inner box pattern is nominally set for 60 nm (111 km), but it can be varied to ensure optimal representation of the convective and mesoscale features.

Once a persistent low-level vortex is identified, subsequent missions will include a rotating figure-4 pattern (Fig. 10-3) centered on the vortex. Flight legs will be 60-120 nm (111-225 km) to allow for the collection of data with high temporal and spatial resolution in the vicinity of the vortex center. The length of these flight legs is designed to completely include the low-level vortex and convection associated with it. Depending on the leg lengths and the time available on station, the pattern may consist of higher azimuthal resolution. The tail radar will operate in F/AST mode during the entirety of these patterns.

If available, the G-IV will fly a synoptic pattern at maximum altitude to observe the troposphere with dropwindsondes in the pre-genesis and incipient tropical disturbance environment. The most likely scenario calls for the G-IV to fly a star pattern to sample and possible interaction of the system with a SAL (e.g. as depicted in Fig. 10-5).

The possible availability of multiple aircraft leads to several different scenarios. A summary of the potential combinations of aircraft during genesis follows:

Option 1 (Optimal experiment):

The optimal experiment is when the P-3 aircraft will fly in the tropical Atlantic, Gulf of Mexico, or western Caribbean basins, either lawnmower or square-spiral survey patterns to locate low- and mid-level vortices (Figs. 10-1 or 10-2). These flights will be flown in coordination with the G-IV aircraft, providing synoptic-scale measurements of upper- and lower-tropospheric observations around the incipient disturbance (Fig. 10-5b and SALEX description). Once a persistent mid-level vortex is located, the P-3 will fly either rotating figure-4 (Fig. 10-3) or square-spiral patterns. The lesser experiment is only with the P-3.

NASA will be conducting their Hurricane Severe Storm Sentinel (HS3) mission from Sept. 1 – Oct. 5. This mission will consist of two unmanned Global Hawk (GH) aircraft, flying at approximately 60,000 ft altitude with mission durations of up to 30 h. One GH will focus on flying patterns over the inner-core of tropical cyclones, while the other GH will focus on patterns in the environment of TC's. The primary science goals of HS3 are to better understand inner-core and environmental processes important in TC genesis, intensification, and extratropical transition.

When possible, it will be desirable to fly patterns with the NOAA aircraft that are coordinated with the GH aircraft. For the NOAA P-3, "coordinated" means flying legs where the P-3 and GH are vertically-stacked for at least a portion of the flight leg. Both the inner-core and environmental GH can fly patterns that are similar in geometry to the NOAA P-3 patterns, including lawnmower (Fig. 10-6), square-spiral (Fig. 10-7), and figure-4 type patterns (Fig. 10-8). The across-track displacement during such coordination should be kept as small as practicable, e.g., no greater than 5-10 km. In practice, the NOAA P-3 will likely fly its patterns as indicated in Fig. 10-3. To achieve coordination the inner-core GH would align its legs such that the GH will be stacked with the P-3. It is likely that not all of these aircraft will be flying simultaneously; rather, efforts will be made to have an aircraft either in the inner core or the environment at all times.

Convective Burst Module:

This is a stand-alone module that takes one hour or less to complete. Execution is dependent on system attributes, aircraft fuel and weight restrictions, and proximity to operations base. The objectives are to obtain quantitative description of the kinematic, thermodynamic, and electrical properties of intense convective systems (bursts) and the nearby environment to examine their role in the cyclogenesis process. It can be flown separately within a mission designed to study local areas of convection or at the end of one of the survey patterns. Once a local area of intense convection is identified, the P-3 will transit at altitude (12,000 ft.) to the nearest point just outside of the convective cores and fly a circumnavigation of the convective area (Fig. 10-4). The circumnavigation will consist of a series of straight legs just outside of the main convection. The tail radar should be operated in F/AST sector scan and regularly spaced dropwindsondes (10-20 km apart) will be released during this time. While flying parallel to the leading convective line, dropwinsonde deployment should occur as close to the leading line as is safely possible. Once the circumnavigation is completed, and the P-3 is near the original IP, two straight-line crossings of the convective area should be performed with the P-3 avoiding the strongest cores, as necessary for safety considerations. The P-3 should fly at a constant altitude of 12,000 ft – radar or pressure altitude is fine. If time permits, the P-3 should descend to the lowest safe altitude and perform another circumnavigation (or partial one) of the convective burst. No dropwindsondes will be released during the low-level run.

Pouch Module:

This is a two-plane mission coordinated between the P-3 and G-IV, designed to monitor a potentially developing tropical wave. The P-3 will fly a survey pattern (diamond or square-spiral) within the pouch, as diagnosed by examining tropical wave-relative lower-tropospheric flow (Fig. 10-5b). If there is an organized area of deep convection present within the pouch, the P-3 will break off from the survey pattern to perform a convective burst module. Priority is placed on performing at least one convective burst module, even at the expense of completing the survey pattern if time is limited. The G-IV will fly a star pattern with triangular legs that extend to the edge of the pouch in each quadrant of the storm. On the inbound legs the G-IV will extend inward to the edge of the cold cloud shield, as safety permits, and fly a leg tangential to the system before extending back outward for the next triangular portion of the pattern. Dropsondes from the P-3 will be launched at each turn point in the pattern plus the midpoints of the legs, provided there is no overlap with previous drop locations. Dropsondes from the G-IV will be launched at all turn points and the midpoints of the radial legs.

Analysis strategy:

As discussed above, airborne Doppler, dropwindsonde, and flight-level data will be critical datasets for the documenting of the evolution of the wind, temperature, and humidity field during this experiment. Analyses of the three-dimensional wind field from the Doppler radar will identify circulation at multiple altitudes (where scatterers are present), while the dropsonde data will measure the temperature and humidity fields in the lower troposphere. Flight-level data will also be useful for measuring winds, temperature, and moisture. As a circulation center becomes defined, decomposition of the variables into symmetric and asymmetric components will be performed to document the vortex evolution. Precipitating areas will be partitioned into convective and stratiform regions, and statistics (e.g., CFADs) of vertical velocity and reflectivity will be calculated for these regions from the Doppler data to document the evolution of convective-scale features during the genesis process. Data from multiple aircraft can be included to create a synthesis of measurements spanning multiple scales and the entire lifecycle.

In addition to testing the hypotheses stated above, this multiscale, near-continuous dataset will prove valuable in evaluating high-resolution model simulations (i.e., HWRF) of tropical cyclogenesis.

References:

Aberson, S. D., 2001: The ensemble of tropical cyclone track forecasting models in the North Atlantic basin (1976–2000). *Bull. Amer. Meteor. Soc*., **82**, 1895–1904.

Bell, M. M., and M. T. Montgomery: Sheared deep vortical convection in pre-depression Hagupit during TCS08. *Geophys. Res. Lett.*, **37**, L06802.

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev*.,**125**, 2662–2682.

Braun, S.A., M.T. Montgomery, K.J. Mallen, and P.D. Reasor, 2010: Simulation and Interpretation of the Genesis of Tropical Storm Gert (2005) as Part of the NASA Tropical Cloud Systems and Processes Experiment. *J. Atmos. Sci*., **67**, 999-1025.

Chen, S. S., and W. M. Frank, 1993: A numerical study of the genesis of extratropical convective mesovortices. Part I: Evolution and dynamics. *J. Atmos. Sci*.,**50**, 2401–2426.

Davis, C.A., and L.F. Bosart, 2001: Numerical Simulations of the Genesis of Hurricane Diana (1984). Part I: Control Simulation. *Mon. Wea. Rev*., **129**, 1859-1881.

DeMaria, M., and J. M. Gross, 2003: Evolution of tropical cyclone forecast models. Hurricane! Coping with Disaster, R. Simpson, Ed., Amer. Geophys. Union, 103–126.

Dunkerton, T. J., M. T. Montgomery, and Z. Wang, 2009: Tropical cyclogenesis in a tropical wave critical layer: Easterly waves. *Atmospheric Chemistry and Physics*, **9**, 5587-5646. (www.atmos-chem-phys.net/9/5587/2009/)

Emanuel, K.A., 1995: The Behavior of a Simple Hurricane Model Using a Convective Scheme Based on Subcloud-Layer Entropy Equilibrium. *J. Atmos. Sci*., **52**, 3960-3968.

Houze, R.A., Jr., W.-C. Lee, and M.M. Bell, 2009: Convective Contribution to the Genesis of Hurricane Ophelia (2005). *Mon. Wea. Rev*., **137**, 2778-2800.

Montgomery, M. T., and J. Enagonio, 1998: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci*.,**55**, 3176–3207.

Hendricks, E.A., M.T. Montgomery, and C.A. Davis, 2004: The Role of “Vortical” Hot Towers in the Formation of Tropical Cyclone Diana (1984). *J. Atmos. Sci*., **61**, 1209-1232.

Kilroy, G., and R. K. Smith, 2012: A numerical study of rotating convection during tropical cyclogenesis. *Quart. J. Roy. Meteor. Soc.*, doi: 10.1002/qj.2022.

Raymond, D. J., C. López-Carrillo, and L. López Cavazos. 1998. Case-studies of developing east Pacific easterly waves. *Quart. J. Roy. Meteor. Soc*., **124**, 2005–2034.

Reasor, P.D., M.T. Montgomery, and L.F. Bosart, 2005: Mesoscale Observations of the Genesis of Hurricane Dolly (1996), *J. Atmos. Sci*., **62**, 3151-3171.

Ritchie, E. A., and G. J. Holland, 1997: Scale interactions during the formation of Typhoon Irving. *Mon. Wea. Rev*.,**125**, 1377–1396.

Rogers, R.F., and J.M. Fritsch, 2001: Surface Cyclogenesis from Convectively Driven Amplification of Midlevel Mesoscale Convective Vortices, *Mon. Wea. Rev*., **129**, 605-637.

Rogers, R.F., S. Aberson, M.Black, P. Black, J. Cione, P. Dodge, J. Gamache, J. Kaplan, M. Powell, J. Dunion, E. Uhlhorn, N. Shay, and N. Surgi, 2006: The Intensity Forecasting Experiment: A NOAA Multiyear Field Program for Improving Tropical Cyclone Intensity Forecasts, *Bull. Amer. Meteor. Soc*., **87**, 1523-1537.

Rogers, R.F., 2010: Convective-Scale Structure and Evolution during a High-Resolution Simulation of Tropical Cyclone Rapid Intensification, *J. Atmos. Sci*., **67**, 44-70.

Wang, Z., M. T. Montgomery, and T. J. Dunkerton, 2010a: Genesis of pre-hurricane Felix (2007). Part I: The role of the easterly wave critical layer. *J. Atmos. Sci*., **67**, , 1711-1729.

Wissmeier, U., and R. K. Smith, 2011: Tropical cyclone convection: the effects of ambient vertical vorticity. *Quart. J. Roy. Meteor. Soc.*, **137**, 845–857.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical wave or organized area that has shown a history of persistent deep convection (convection may not be active at time of takeoff).

When to Target: When system is early in its development into a tropical depression.

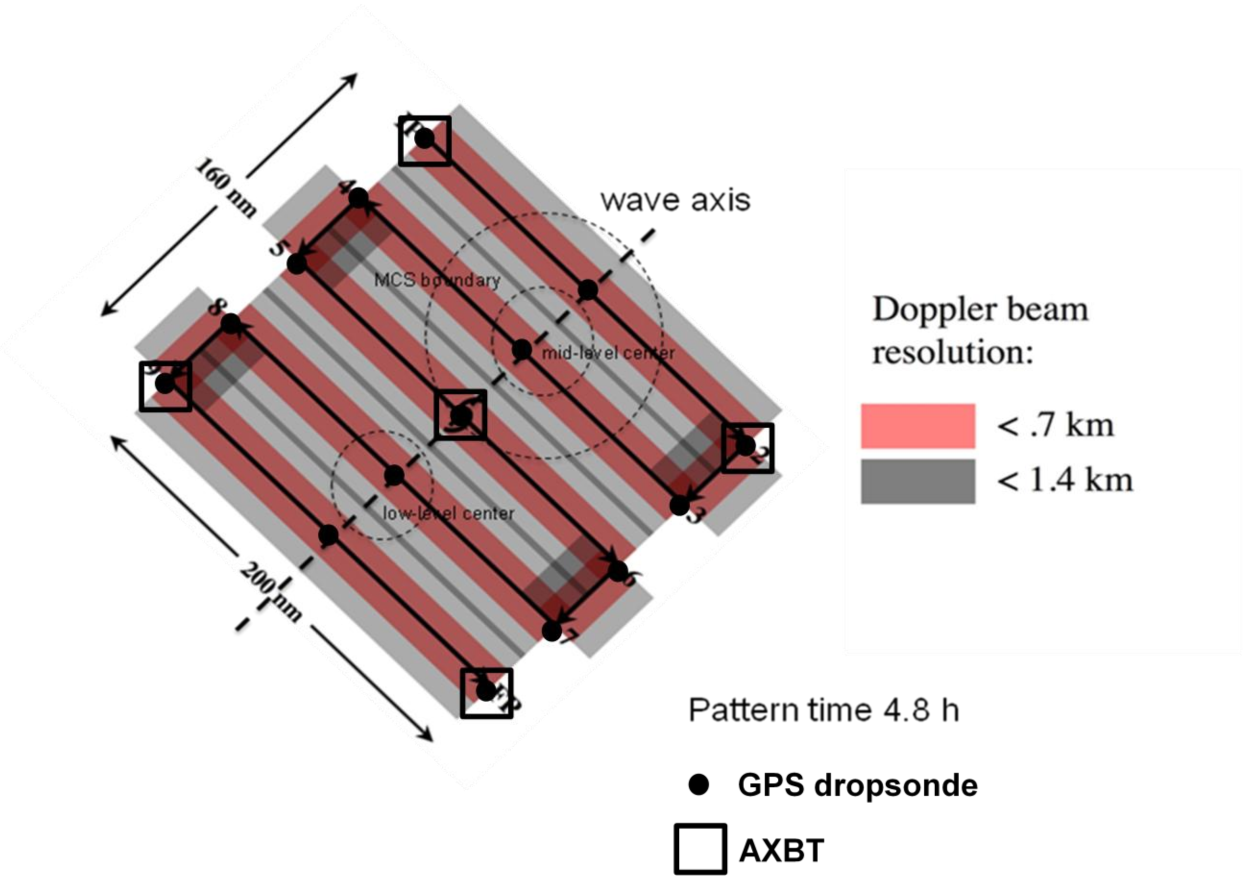


Figure 10-1: P-3 Pre-genesis early organization vortex survey pattern – Lawnmower pattern.

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Deploy dropwindsondes at all turn points and midway along long legs. If available, deploy AXBT's at outer corners and center of pattern, coincident with dropsondes. No more than 24 GPS drops, 8 AXBT's needed.
- Pattern: The pattern is flown with respect to the wave axis, typically inclined at 30-40° from N, or relative to circulation or vorticity centers. Length of pattern (axis parallel to wave axis) should cover both low- and mid-level vortices, leg lengths range from 150 – 200 nm (275-375 km). Leg lengths and separation distance can vary, depending on storm size and ferry time.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical wave or organized area that has shown a history of persistent deep convection (convection may not be active at time of takeoff).

When to Target: When system is later in its development into a tropical depression.

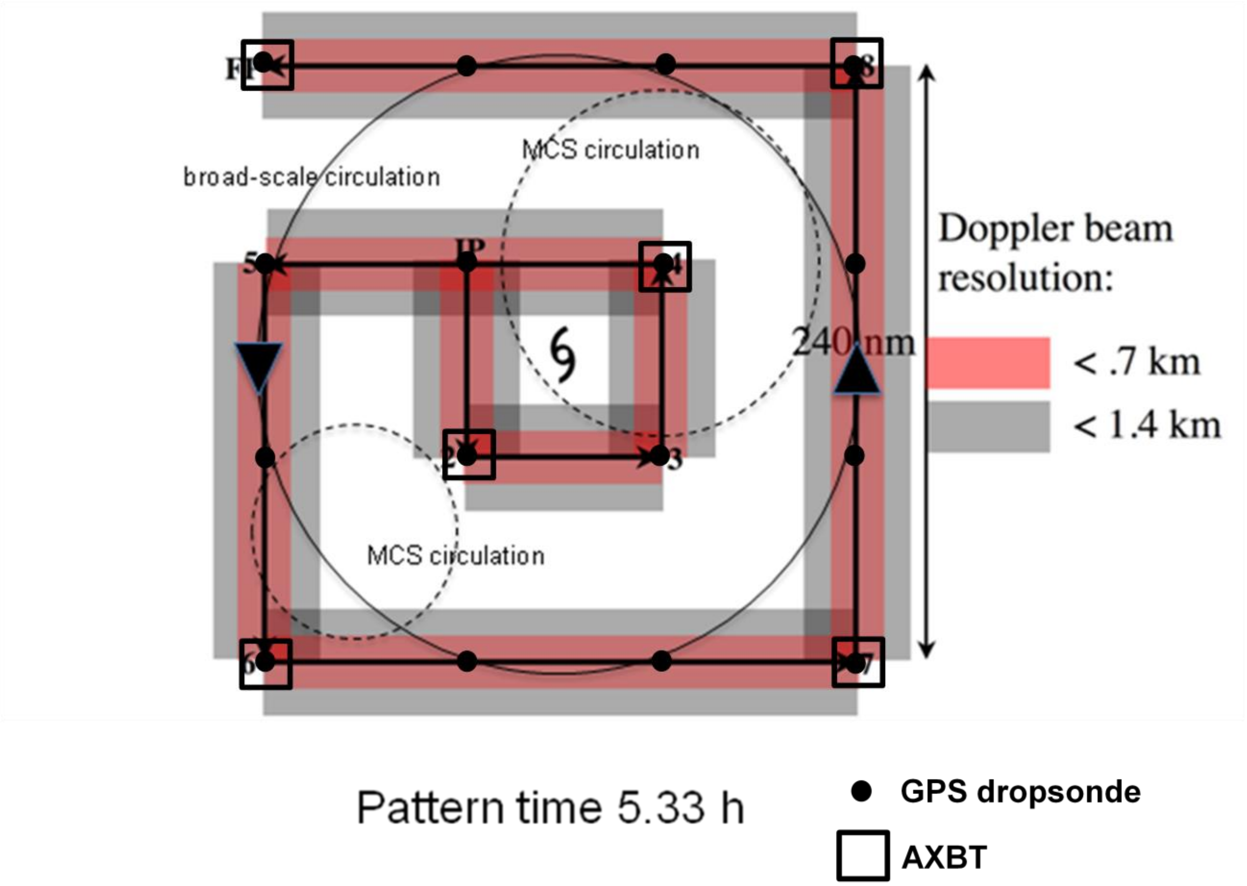


Figure 10-2: P-3 Pre-genesis late organization vortex survey pattern – Square-spiral pattern.

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Release dropwindsondes at all numbered points. Releases at intermediate points can be omitted if dropwindsonde supply is insufficient. If available release AXBT's at outer corner locations and at two corner locations in inner square, coincident with dropwindsondes. No more than 24 GPS drops, 8 AXBT's needed.
- Pattern: The spacing between the outer spiral and inner box (nominally set to 60 nm (111 km)) can be increased or decreased depending on the size of the disturbance and ferry time.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

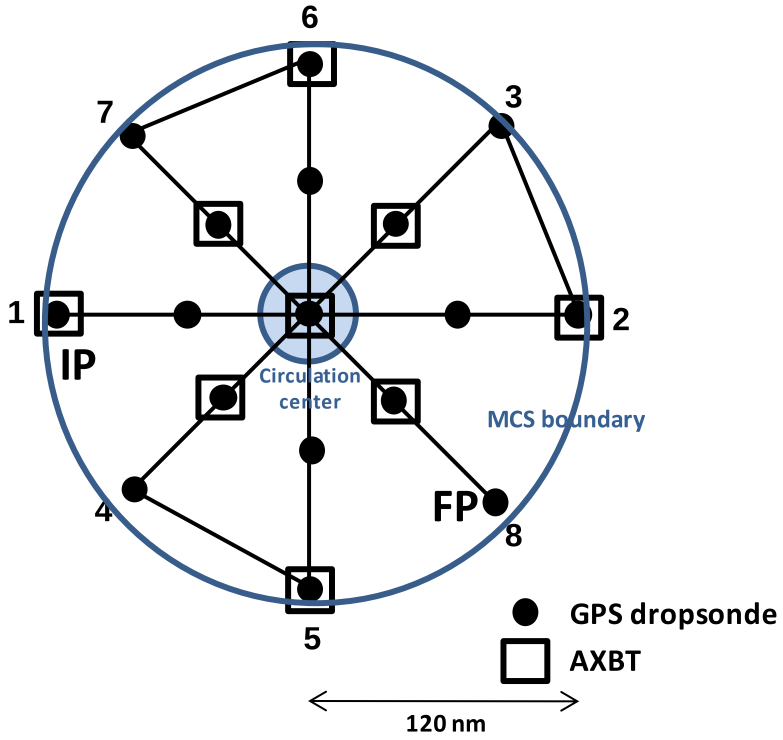
Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical depression or tropical storm (convection likely to be active at time of takeoff).

When to Target: During tropical depression stage, or if the tropical storm is in the early stage of its development.



Pattern time: ~5.0 h

Figure 10-3: P-3 Post-genesis rotating figure-4 pattern.

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Release dropsondes at turn points, midpoint of radial legs, and on the first and last center pass. If available, drop AXBT's at points 1, 2, 5, and 6, at midpoints of leg 3-4 (both inbound and outbound), at midpoints of leg 7-8 (both inbound and outbound), and on first center pass. All AXBT's should be released coincident with dropsondes.
- Pattern: Fly 1-2-3-4-5-6-7-8 at 12,000 ft altitude, 60-120 nm (111-225 km) leg length. The pattern may be entered along any compass heading.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: An area of vigorous, deep convection occurring within the circulation of a developing tropical disturbance.

When to Target: When deep convection is identified either by radar or satellite during the execution of a GenEx pattern.

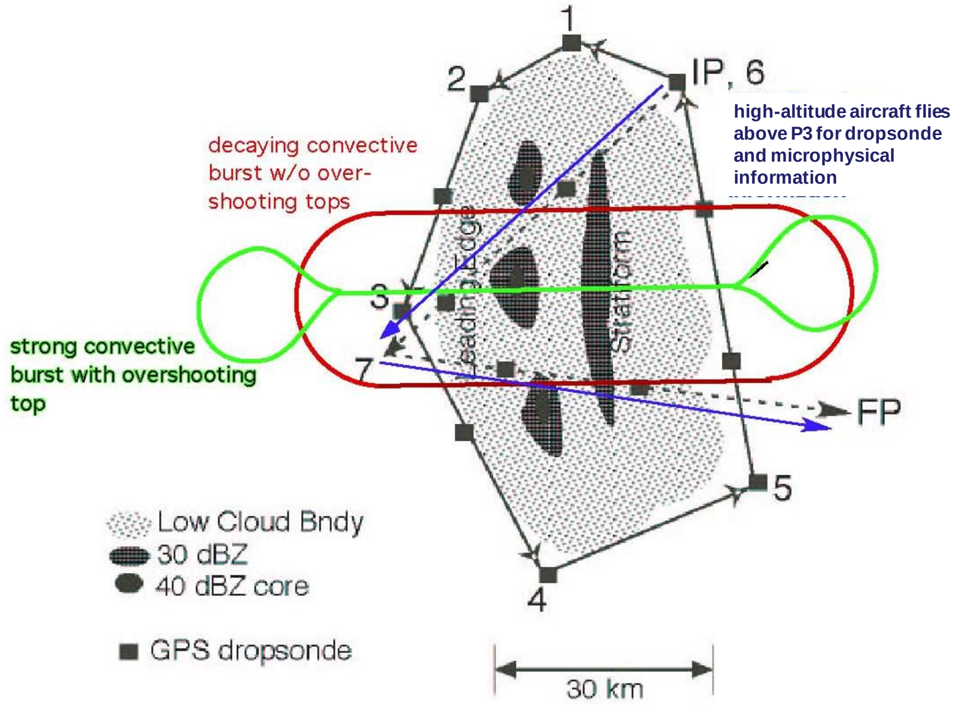


Figure 10-4: P-3 Convective burst module.

- Altitude: 12,000 ft (4 km) altitude preferable.
- Expendables: Release dropsondes at turn points and at intermediate points as indicated in Figure. Additionally, release 1-2 drops during penetration of convective system. No more than 15 dropsondes needed for this module.
- Pattern: Circumnavigation (IP to point 6) by single P-3. Then fly convective crossing (6-7-FP). Repeat circumnavigation (time permitting) at low altitude (1500-2500 ft depending on safety constraints). If available, high-altitude aircraft (e.g., ER-2 or Global Hawk) flies either racetrack or bowtie pattern during P-3 circumnavigation, flies vertically aligned with P-3 during convective crossing
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: The environment of a tropical wave or organized area that has shown a history of persistent deep convection, or a tropical depression.

When to Target: Any time prior to or just after designation of system as a tropical depression.

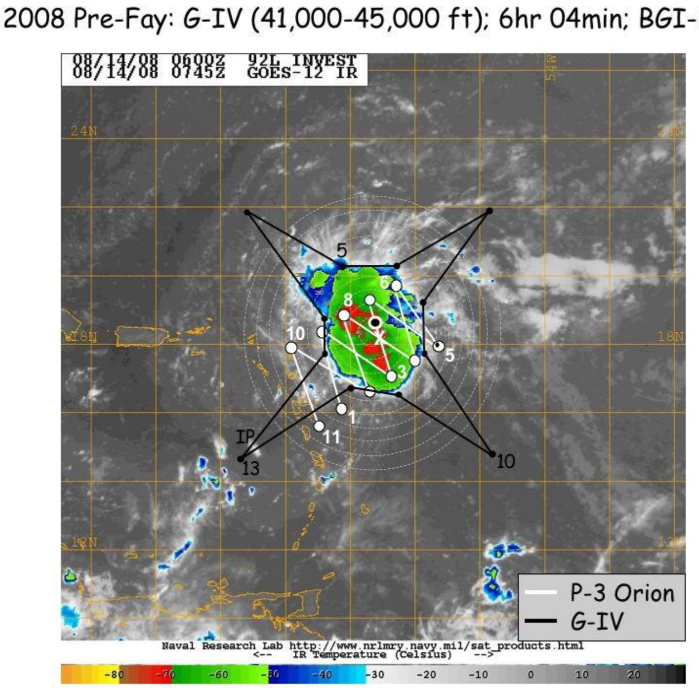


Figure 10-5: G-IV Pouch module.

- Altitude: 41-45,000 ft.
- Pattern: G-IV flies as close to cold cloud shield on inner radii as is deemed safe.
- Expendables: Release G-IV drops at all turn points and midpoints of radial legs.

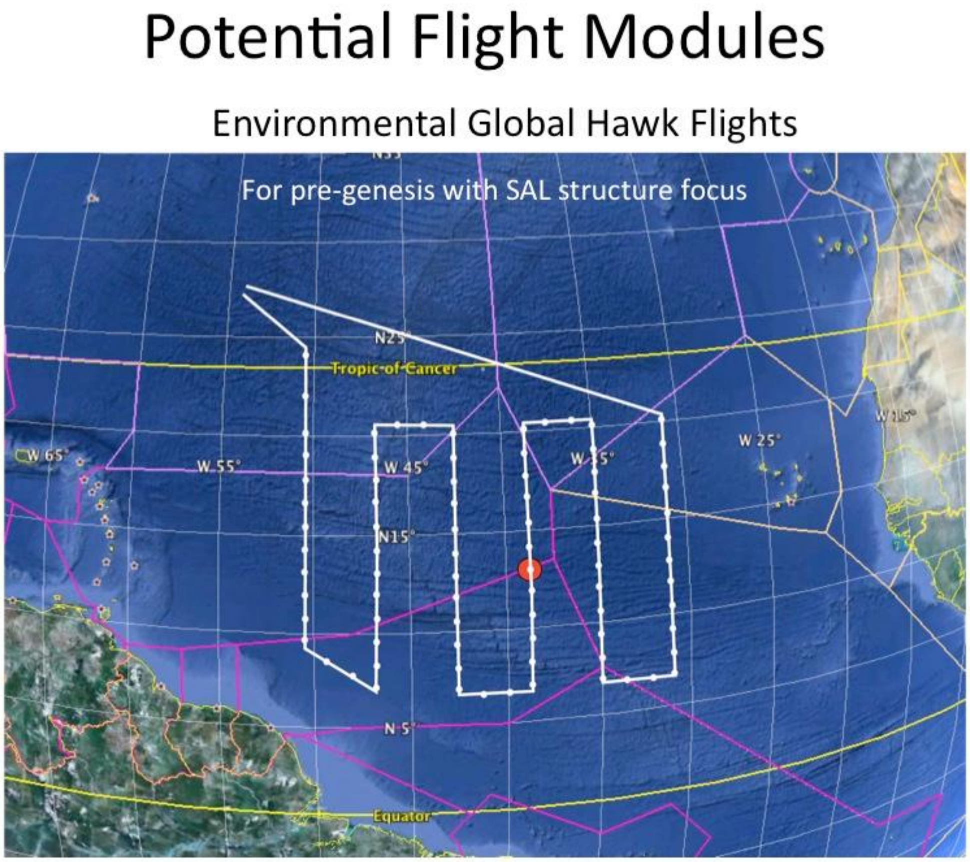
Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical depression or tropical storm (convection likely to be active at time of takeoff).

When to Target: During tropical depression stage, or if the tropical storm is in the early stage of its development.



Potential Flight Modules

Environmental Global Hawk Flights

For pre-genesis with SAL structure focus

Figure 10-6: Sample lawnmower flight pattern for GH over a developing TC in the central Atlantic.

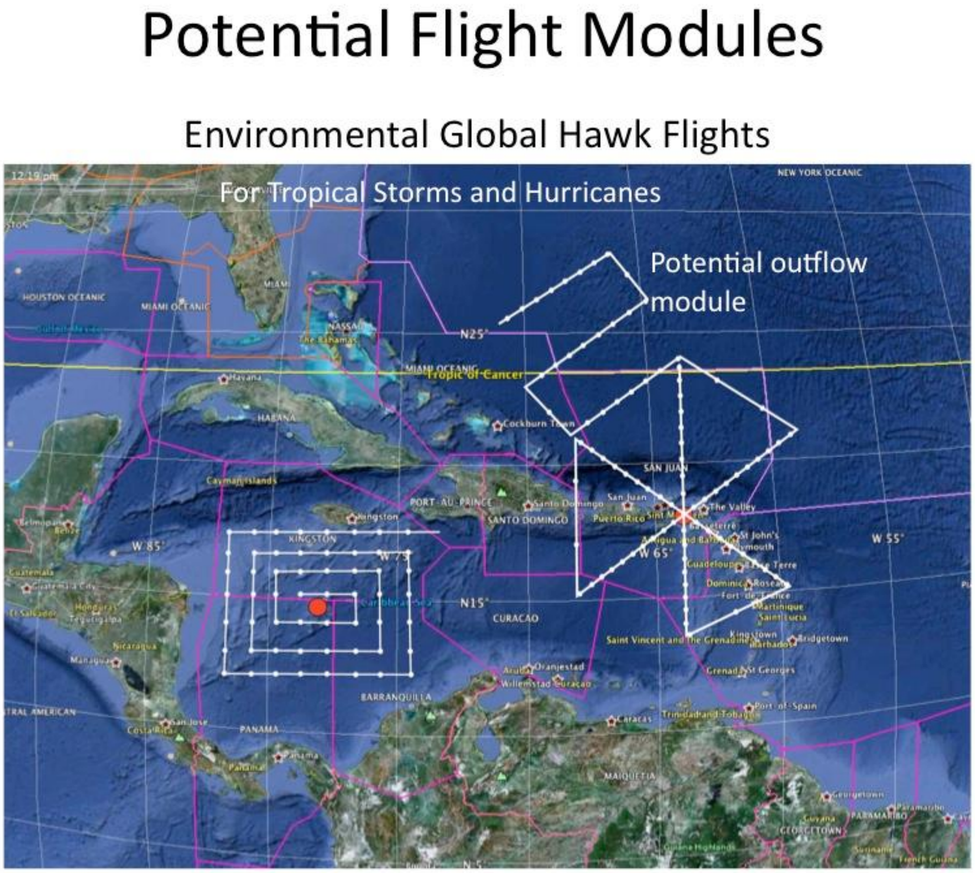
Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical depression or tropical storm (convection likely to be active at time of takeoff).

When to Target: During tropical depression stage, or if the tropical storm is in the early stage of its development.



Potential Flight Modules

Environmental Global Hawk Flights

Figure 10-7: Sample square-spiral (in West Caribbean) and outflow module (in West Atlantic) flight patterns for GH's over two developing TC's in the Gulf of Mexico.

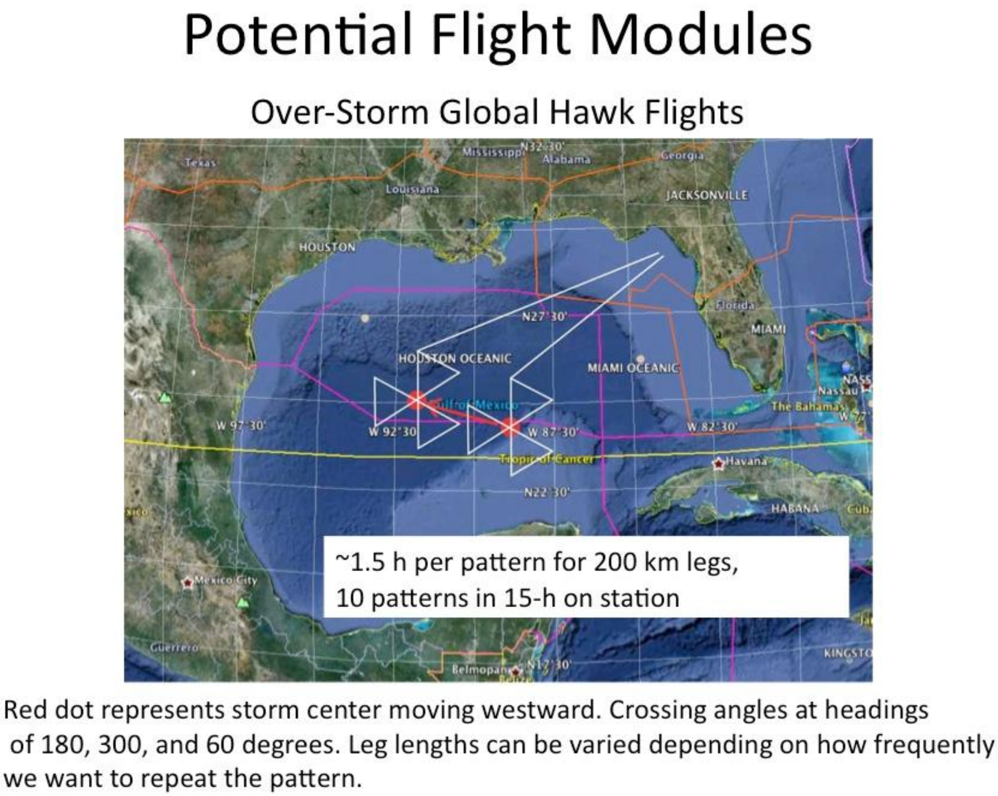
Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor

Objective: To sample the wind, temperature, and moisture fields within and around a tropical disturbance that has the potential to develop into a tropical depression.

What to Target: A tropical depression or tropical storm (convection likely to be active at time of takeoff).

When to Target: During tropical depression stage, or if the tropical storm is in the early stage of its development.



Potential Flight Modules

Over-Storm Global Hawk Flights

~1.5 h per pattern for 200 km legs,
10 patterns in 15-h on station

Red dot represents storm center moving westward. Crossing angles at headings of 180, 300, and 60 degrees. Leg lengths can be varied depending on how frequently we want to repeat the pattern.

Figure 10-8: Sample figure-4 flight pattern for GH over a developing TC in the Gulf of Mexico.

11. Experiment: Rapid Intensification Experiment (RAPX)

Principal Investigator(s): John Kaplan, Robert F. Rogers, and Jason P. Dunion

Motivation:

While some improvements have been made in operational tropical cyclone intensity forecasting in recent years (DeMaria et al. 2007), predicting changes in tropical cyclone intensity (as defined by the 1-min. maximum sustained wind) remains problematic. Moreover, the operational prediction of rapid intensification (RI) has proven to be especially difficult (Kaplan et al. 2010) and given the significant impact of such episodes, has prompted the Tropical Prediction Center/National Hurricane Center (TPC/NHC) (NOAA 2012) to declare it as its top forecast priority. The difficulty of forecasting RI stems from a general lack of understanding of the physical mechanisms that are responsible for these rare events. Generally speaking researchers have attributed RI to a combination of inner-core, oceanic, and large-scale processes. The SHIPS Rapid Intensification Index (RII) presented in Kaplan et al. (2010), the best predictive scheme for RI to date, relies mainly on large-scale fields and broad characteristics of the vortex, such as environmental vertical wind shear and departure of the vortex from its empirical maximum potential intensity (which is itself largely derived from sea-surface temperature (SST)), as well as some characteristics of deep convection within the inner core, including the symmetry of inner-core convection around the storm center. This scheme is able to explain roughly 25% of the skill in RI forecasts in the Atlantic basin (Rogers et al. 2013), with the remainder being attributable either to other processes not being accounted for in this methodology or constrained by predictability limits. The goal of this experiment is to collect datasets that can be utilized both to initialize 3-D numerical models and to improve our understanding of RI processes across multiple scales, with the overarching goal of improving our ability to predict the timing and magnitude of RI events.

Objective:

To employ both NOAA P-3 and G-IV aircraft to collect oceanic, kinematic, and thermodynamic observations both within the inner-core (i.e., radius < 220 km) and in the surrounding large-scale environment (i.e., 220 km < radius < 440 km) for systems that have been identified as having the potential to undergo RI within 24-72 h. The SHIPS RII will be the primary guidance that is used for selecting candidate systems for the short-term time periods (lead time ≤ 48 h) while both statistical/dynamical and 3-D numerical models will be used for the longer time ranges (i.e. beyond 48 h).

Hypotheses:

- By gathering observations that span spatial scales from 10s to 100s of kilometers it is possible to improve our understanding of the atmospheric and oceanic conditions that precede RI, particularly within the less observed inner-core region.
- Characteristics of the tropical cyclone inner core, both on the vortex- and convective-scale, contribute a non-negligible amount to explaining the variance in the prediction of RI.
- The aforementioned multi-scale RAPX data sets can be used both to initialize and evaluate numerical model forecasts made for episodes of RI and successful completion of these tasks will lead to improved numerical/statistical model predictions of RI.

Links to IFEX goals:

- **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

Mission Description:

The P-3 aircraft will dispense AXBTs and GPS dropsondes and collect Doppler radar data while flying a rotating figure-4 pattern (see sample pattern shown in Fig. 11-1) in the inner-core with leg lengths of ~90-180 km at the maximum safe altitude (~8k-12k feet) for avoiding graupel. The AXBTs and GPS dropsondes should be dispensed on each leg with a spacing of ~30-40 km to provide adequate coverage for deducing the radial variations in kinematic and thermodynamic storm properties. The desired AXBT/GPS dropsonde deployment strategy is for both an AXBT and GPS dropsonde to be dispensed in tandem at both the endpoints and midpoint of each leg of the figure-4 pattern so that ~11 AXBT/GPS pairs are dropped during the course of each completed figure-4 leg (pattern) as shown in Fig. 11-1. The P-3 may also fly a Convective Burst Module (similar to that flown for the tropical cyclone genesis experiment) or an Arc Cloud Module if the opportunity to conduct such flight patterns presents itself.

The G-IV should fly the environmental pattern shown in Fig. 11-2 at an altitude of ~42-45 K ft dispensing dropsondes at radii of 220, 330, and 440 km to measure the thermodynamics and kinematic fields in the near storm environment. These particular radii were chosen since collecting data in this region is crucial for computing the vertical shear and upper-level divergence both of which have been shown to be strongly correlated with RI. The radii of the innermost ring of G-IV drops shown in Fig. 11-2 can be adjusted outward if necessitated by safety considerations. However, the radii of the other rings of drops should then also be adjusted to maintain the specified spacing. Depending on the time of day, aircraft duration limitations, and safety considerations, the lengths of the G-IV inner (outer) points could be shortened (extended) to ~200 km (~500 km) if an opportunity to sample a diurnal pulse “cool ring” presents itself (see TC Diurnal Cycle Experiment).

As noted above, this experiment requires that both the P-3 and G-IV be utilized. In addition, it is highly desirable that the P-3 aircraft fly a rotating figure-4 pattern (see Fig. 11-1) in the inner-core while the G-IV simultaneously flies the environmental surveillance pattern shown in Fig. 11-2a every 12 h. Although this mission can still be conducted if the G-IV aircraft flies a synoptic surveillance pattern instead of the one shown in Fig. 11-2a, such a flight pattern should only be flown in the event that the G-IV has been tasked by the NHC to conduct an operational synoptic surveillance mission and thus would otherwise be unavailable for use in conducting research type missions. Furthermore, if either the P-3 or G-IV aircraft cannot fly every 12 h the experiment can still be conducted provided that the gap between missions for any one of the two aircraft does not exceed 24 h. As an additional option, the G-IV aircraft may also be requested to fly an octagonal survey pattern like that shown in Fig. 11-2b. The use of such a pattern should provide an enhanced capability to collect high-resolution Doppler radar measurements within and just outside the storm’s inner-core region. Finally, when possible this experiment may also make use of the NASA Global Hawk aircraft.

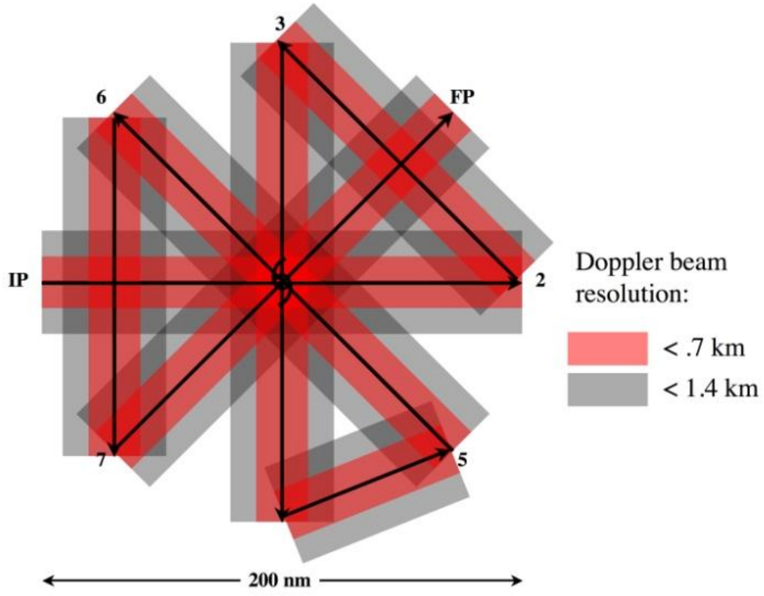


Figure 11-1: Sample rotated figure-4 flight pattern for RAPX mission. The red shading denotes locations where vertical spacing of Doppler beam < 0.7 km, grey shading where vertical spacing < 1.4 km. GPS dropsondes should be released at all turn points (past the turn after the aircraft has leveled), at midpoints of inbound/outbound legs, and at center point between IP/2 and 5/6. If available, release AXBT's coincident with dropsondes at turn points, midpoints, and center points. Note that the above in-storm P-3 flight pattern requires about 3-4 hours to complete.

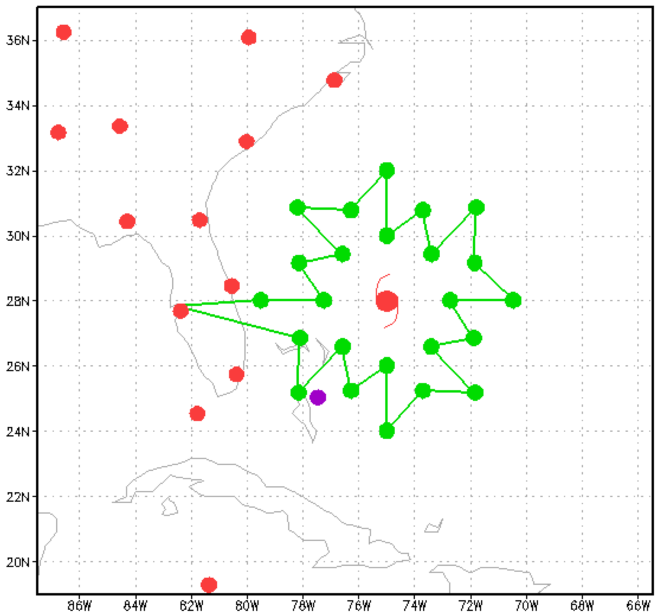


Figure 11-2a: A sample G-IV flight pattern for the RAPX mission. The green dots denote the desired dropsonde locations at 220, 330, and 440 km radius from the storm center. Note that the end points of each leg can be rounded slightly as required for aircraft flight considerations. The flight pattern shown in Fig. 2 (excluding ferry time to and from the storm) requires about 6 hours to complete.

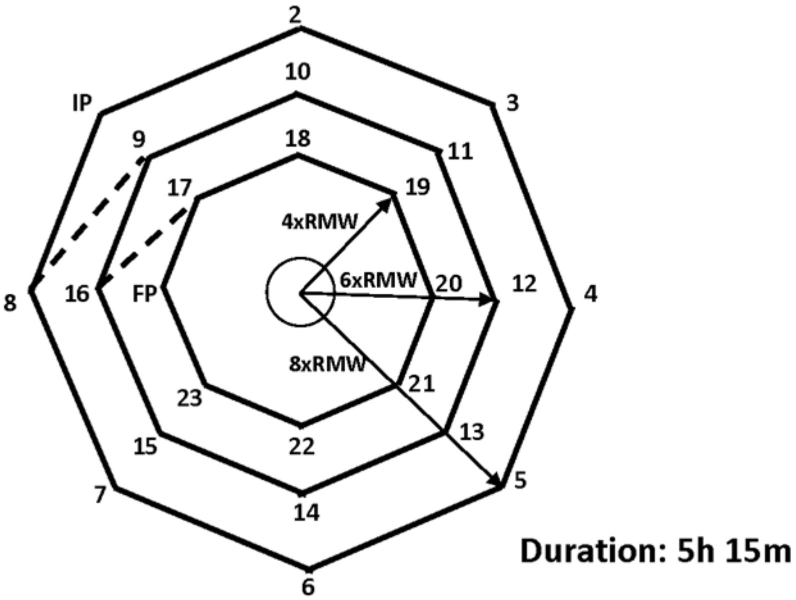


Figure 2b: G-IV outer-core survey pattern

- Altitude: 40-45 kft
- Expendables: Deploy dropsondes at all turn points. No more than 24 GPS drops needed.
- Pattern: The pattern is flown with respect to the surface storm center. Three concentric octagons are flown clockwise at decreasing radii of 8xRMW, 6xRMW, and 4xRMW, where RMW is the estimated radius of maximum azimuthal-mean tangential wind. For example, if RMW = 18 nm, the maximum radial extent of the pattern is 144 nm. Dashed lines show transitions between rings.
- Instrumentation: Set airborne Doppler radar to scan F/AST on all legs.

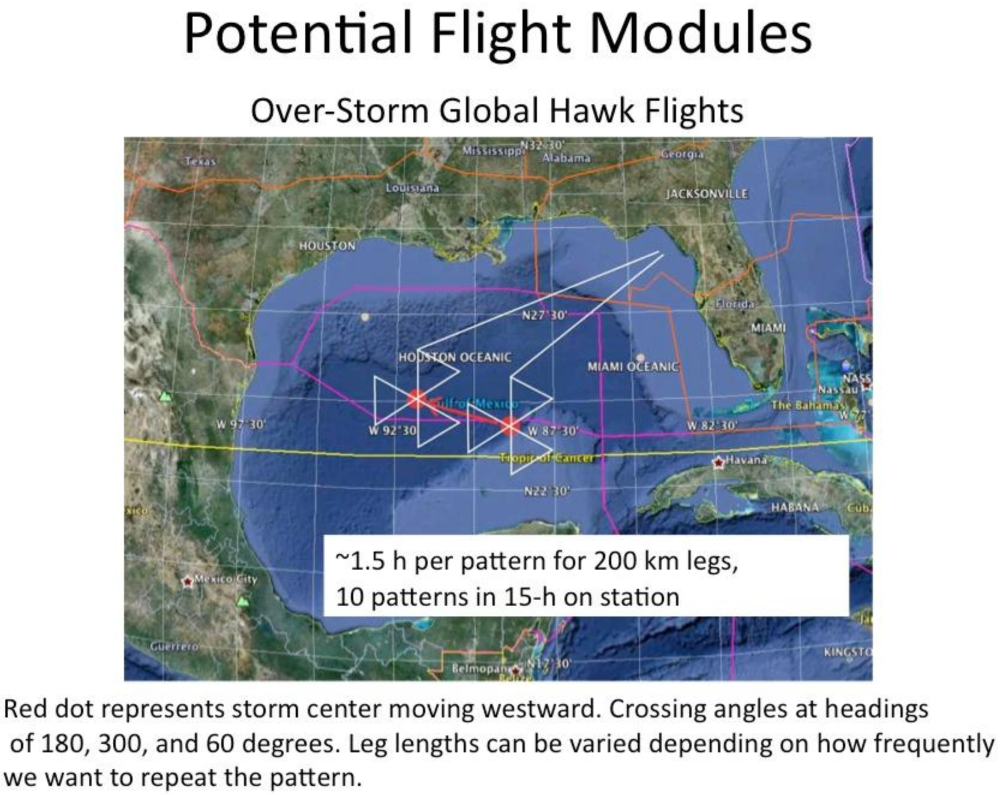
Analysis Strategy

This experiment seeks to perform a multi-scale analysis of the conditions both before and during RI. Specifically, we will use GFS, GPS dropsonde, and ocean buoy observations to analyze the changes in energy transfer at the ocean-atmosphere interface during the time period of the experiment. Also, changes in the inner-core kinematic and thermodynamic structure will be examined using NOAA P-3 Doppler radar, flight-level, and GPS dropsonde data within the inner-core region (i.e., radius <220 km). Inner-core analyses will include an analysis of the symmetric and asymmetric vortex structure, vortex tilt, and inner-core vertical shear derived from airborne Doppler and dropsonde data and statistics of vertical velocity, vorticity, and reflectivity from airborne Doppler. Finally, an analysis of the near-storm large-scale environment (i.e., 220 km < radius < 440 km) will be conducted using the high-resolution GFS analyses that contain the assimilated GPS dropsonde data deployed from NOAA G-IV aircraft. This near storm sampling effort will include observations of low to mid-level (~600-925 hPa) moisture and shear magnitude in the region upshear from the storm center (R<500 km). These observations will be used to assess a new RII moisture predictor that uses microwave-derived total precipitable water imagery to detect dry air in the upshear TC environment. The overarching hypothesis of this analysis strategy is that by performing similar analyses for multiple RAPX data sets collected during both RI and non-RI events it will be possible to determine the conditions that are triggers for RI and to evaluate numerical model performance during such events.

Coordination with Supplemental Aircraft

NASA will be conducting their Hurricane Severe Storm Sentinel (HS3) mission from Aug. 20 –Sept. 24. This mission will consist of two unmanned Global Hawk (GH) aircraft, flying at approximately 60,000 ft altitude with mission durations of up to 30 h. One GH will focus on flying patterns over the inner-core of tropical cyclones, while the other GH will focus on patterns in the environment of TC's. The primary science goals of HS3 are to better understand inner-core and environmental processes important in TC genesis, intensification, and extratropical transition.

When possible, it will be desirable to fly patterns with the NOAA aircraft that are coordinated with the GH aircraft. For the NOAA P-3, "coordinated" means flying radial penetrations where the P-3 and GH are vertically-stacked for at least a portion of the flight leg, preferably when the aircraft are approaching the center of the TC. The across-track displacement during such coordination should be kept as small as practicable, e.g., no greater than 5-10 km. In practice, the NOAA P-3 will likely fly its planned figure-4/butterfly/rotating figure-4 patterns as indicated in Fig. 11-1. The inner-core GH can fly patterns that are similar in geometry to the NOAA P-3 patterns (Fig. 11-3). To achieve coordination the inner-core GH would align its legs such that the GH will be stacked with the P-3. Given the relatively long turn around of the NASA Global Hawks (~24-hr), the NOAA P-3 could also coordinate with the NOAA G-IV and environmental Global Hawk on alternating days to attain nearly continuous 2-plane coverage of both the TC inner core and peripheral environment. The details of these coordinated missions would be handled on a case-by-case basis.



Potential Flight Modules

Over-Storm Global Hawk Flights

~1.5 h per pattern for 200 km legs,
10 patterns in 15-h on station

Red dot represents storm center moving westward. Crossing angles at headings of 180, 300, and 60 degrees. Leg lengths can be varied depending on how frequently we want to repeat the pattern.

Figure 11-3: Sample flight pattern for inner-core GH over a TC in the Gulf of Mexico.

12. Tropical Cyclone Landfall Experiment

Principal Investigators: John Kaplan and Peter Dodge

Links to IFEX: These modules supports the following NOAA IFEX goals:

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

Program Significance: The lifecycle of a TC often ends when it makes landfall and decays as it moves inland. During a hurricane threat, an average of 300 nm (550 km) of coastline is placed under a hurricane warning, which costs about $50 million in preparation per event. The size of the warned area depends on the extent of hurricane and tropical storm-force wind speeds at the surface, evacuation lead-times, and the forecast of the storm track. Research has helped reduce uncertainties in the track and landfall forecasts, and now one of the goals of IFEX is to improve the accuracy of the surface wind fields in TCs, especially near and after landfall. Improvements in diagnosing surface wind fields could decrease the uncertainty of the size of the hurricane warning area thereby reducing the cost of preparing for a landfalling hurricane.

There are still uncertainties in deriving surface wind estimates from flight-level and SFMR wind speeds collected near the coast. Changing bathymetry could change the breaking wave field, which could change both the roughness length at higher wind speeds as well as changing the microwave emissions. Evaluation of these effects may lead to adjustments to the operational surface wind speed algorithms. Data collected at the coast will also help to refine the Kaplan/DeMaria inland decay model that has been developed as part of a recently completed Joint Hurricane Testbed (JHT) project. Airborne Doppler radar data will also be transmitted to NCEP as part of another completed JHT project to assimilate radar data into the HWRF model.

Analysis of Doppler radar, GPS dropwindsonde, SFMR, flight-level and SRA or AWRAP data collected during hurricane flights can help achieve the IFEX goals for the 2013 Hurricane Field Program. A major goal is to capture the lifecycle of a TC and while landfall is usually at the end of the lifecycle the same data collection strategies developed for mature hurricanes over the open ocean can also be applied at landfall. Subsets of the data collected can be transmitted to NHC and to EMC, for assimilation into HWRF. The Doppler and GPS dropwindsonde data can be analyzed to derive three-dimensional wind fields to compare with output from the HWRF and data from the SRA can be compared to HWRF wave fields. In addition to shear and heat flux from the ocean, hurricanes at landfall experience other conditions that may affect intensity change. These include change in ocean wave action in shallow waters, change in surface roughness, drier and cooler inflow from the land, and topography. Radar, dropwindsonde, and SFMR data can help define those conditions. Decay over land is also important and data collected during and shortly after landfall should help refine both operational statistical decay models (such as the Kaplan/DeMaria model) and 3- dimensional numerical models like HWRF.

HRD developed a real-time surface wind analysis system to aid NHC in the preparation of warnings and advisories in TCs. The surface wind analyses are now used for post-storm damage assessment by emergency management officials and to validate and calibrate the Kaplan/DeMaria decay model. These wind analyses could also be used to initialize the operational storm surge model in real time.

As a TC approaches the coast, surface marine wind observations are normally only available in real time from National Data Buoy Center moored buoys, Coastal-Marine Automated Network (C-MAN) platforms, and a few ships. Surface wind estimates must therefore be based primarily on aircraft measurements. Low-level (<5,000 ft [1.5 km] altitude) NOAA and AFRES aircraft flight-level wind speeds are adjusted to estimate surface wind speeds. These adjusted wind speeds, along with C-SCAT and SFMR wind estimates, are combined with actual surface observations to produce surface wind analyses. These surface wind analyses were initially completed after the landfall of Hurricane Hugo in South Carolina and of Andrew in South Florida in support of post-landfall damage surveys conducted by FEMA. In recent years, these analyses have been produced in real time for operational use by the NHC for many of the TCs that have affected the Western Atlantic basin, including such notable landfalling storms as Opal (1995), Fran (1996), Georges (1998), Bret and Floyd (1999), Isidore (2003) and Frances, Ivan and Jeanne (2004), and Dennis, Katrina, Rita and Wilma (2005).

Dual-Doppler analysis provides a complete description of the wind field in the core. Recently the analysis techniques have been streamlined so real-time wind analyses can be computed aboard the aircraft and wind fields at selected levels transmitted from the aircraft to NHC and EMC. These wind fields are also quite useful for post-storm analysis. An observational study of Hurricane Norbert (1984), using a PDD analysis of airborne radar data to estimate the kinematic wind field, found radial inflow at the front of the storm at low levels that switched to outflow at higher levels, indicative of the strong shear in the storm environment. Another study used PDD data collected in Hurricane Hugo near landfall to compare the vertical variation of wind speeds over water and land. The profiles showed that the strongest wind speeds are often not measured directly by reconnaissance aircraft.

Recent GPS dropwindsonde data from near and inside the flight-level radius of maximum wind speeds (RMW) in strong hurricanes have shown remarkable variations of the wind with height. A common feature is a wind speed maximum at 300-500 m altitude. Theoretical and numerical modeling of the hurricane boundary layer suggests that the low-level jets are common features. The height of the jet varies by storm quadrant, and modeling indicates that this variation can be enhanced as a hurricane crosses land.

While collection of dual-Doppler radar data by aircraft alone requires two P-3 aircraft flying in well- coordinated patterns, time series of dual-Doppler data sets have been collected by flying a single P-3 toward or away from a ground-based Doppler radar. In that pattern, the aircraft Doppler radar rays are approximately orthogonal to the ground-based Doppler radar rays, yielding true Dual-Doppler coverage. Starting in 1997 the Atlantic and Gulf coasts were covered by a network of Doppler radars (Weather Surveillance Radar 88 Doppler [WSR-88D]) deployed by the National Weather Service (NWS), Department of Defense, and Federal Aviation Administration. Each radar transmits the base data (Level II) in near real time to a central site. These data are subsequently archived at the National Climatic Data Center. In precipitation or severe weather mode the radars collect volume scans every 5-6 min.

If a significant TC (major hurricane) moves within 215 nm (440 km) of the coast of the Eastern or Southern United States, then (resources permitting) a P-3 will obtain Doppler radar data to be combined with data from the closest WSR-88D radars in dual-Doppler analyses. The tail radar is tilted to point 20 degrees forward and aft from the track during successive sweeps (the fore-aft scanning technique [F/AST]). These analyses could resolve phenomena with time scales <10 min, the time spanned by two WSR-88D volume scans. This time series of dual-Doppler analyses will be used to describe the storm core wind field and its evolution. The flight pattern is designed to obtain dual-Doppler analyses at intervals of 10-20 min in the core. The Doppler data will be augmented by deploying dropwindsondes near the coast, where knowledge of the boundary-layer structure is crucial for determining what happens to the wind field as a strong storm moves inland. Dropwindsondes will also be deployed in the eyewall in different quadrants of the hurricane. To augment the core analyses, dual-Doppler data can also be collected in the outer portions of the storm, beyond the range of the WSR-88D, because the alternating forward and aft scans in F/AST mode intersect at 40 degrees, sufficient for dual-Doppler synthesis of wind observations.

Objectives:

Collect NOAA P-3 Doppler, flight-level, and SFMR surface wind data both within the inner-core (radius<120 nm) and near storm (120< radius < 240) environment to help improve and validate real- time and post-storm surface wind estimates in tropical cyclones.

Document the thermodynamic and kinematic changes in storm structure during and after landfall and improve our understanding of the factors that modulate changes in tropical cyclone intensity near the time of landfall.

Hypotheses:
It is possible to improve real-time surface wind estimates for landfalling tropical cyclones by obtaining in-situ inner-core and near storm wind data collected utilizing NOAA P-3 aircraft.

The above landfall datasets can be used to validate statistical and 3-D numerical model landfall surface wind forecasts.

Our understanding and ability to forecast changes in the structure and intensity of landfalling tropical cyclones can be enhanced utilizing the high-resolution kinematic and thermodynamic data sets collected during the aforementioned landfall research missions.

Mission Description: This is a *multi-option, single-aircraft* experiment designed to study the changes in TC surface wind structure near and after landfall. It has several modules that could also be incorporated into operational surveillance or reconnaissance missions. It is designed for one or two single-aircraft missions with a P-3 when a hurricane moves within 215 nm (400 km) of the U.S. coastline. The first of these 2 flights will typically consist of the real-time module followed by SFMR and/or Coastal Wind Profile modules. A second flight could complete the post-landfall module. If the storm either moves parallel to the coastline or moves slowly inland and resources permit, it may be repeated with a second flight. While the storm location relative to the coastline will dictate which combination of these modules will be flown, the real-time module will generally precede all of the others.

This experiment should only be flown in a major hurricane. In addition, specific landfall flights will only be requested if the mobile observing systems are also deployed. These additional observations are especially important to document the inland decay of a major hurricane.

The aircraft must have working lower fuselage and tail radars. The HRD workstation should be on board, so radar and GPS dropwindsonde data can be analyzed and transmitted to NHC. The SFMR should be operated, to provide estimates of wind speed at the surface. If the AWRAP or C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface wind speeds. If the SRA is working it also should collect wave and sweep heights to characterize the storm surge and breaking wave field near the coast. If the scanning LIDAR is available, then it should be operated to obtain wind profiles in the clear air regions, especially in the offshore flow.

If some of the portable Doppler radars (Shared Mobile Atmospheric Research and Teaching Radar [SMART-R] and/or Doppler on Wheels [DOW]), portable profilers and portable wind towers are deployed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. 12-1, this will provide valuable data for the inland decay model. If possible, one of the DOWs should be positioned relative to the nearest WSR-88D such that the dual-Doppler lobes cover the largest area of onshore flow possible. In the schematic shown in Fig. 12-1, one of the DOWs is positioned north-west of the Melbourne WSR-88D so that one dual-Doppler lobe is over the coastal waters and the other covers the inland region. The profiler is positioned in the inland dual-Doppler lobe to provide independent observations of the boundary layer to anchor the dual- Doppler analysis.

All modules support real-time and post-storm surface wind analyses. The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars. The two modules can be easily incorporated into a tasked operational mission.

Real-time module: The real-time module combines passes over marine surface platforms with one or more figure-4 patterns in the core of the hurricane (Fig. 12-1.) The aircraft flies at or below 5,000 ft (1.5 km), so that flight-level wind speeds can be adjusted to 30 ft (10 m) to combine with measurements from marine surface platforms. Flight-level and dropwindsonde data obtained near the platforms will be used to validate the adjustment method. Note that if the storm is outside of WSR-88D Doppler range then the figure-4 pattern could be repeated before returning home.

The landfall flight pattern should take advantage of buoys or C-MAN sites nearby, if those platforms are expected to experience wind speeds > 25 ms^{-1}. The aircraft descends at the initial point and begins a low- level figure-4 pattern, possibly modifying the legs to fly over the buoys (Fig. 12-1). The radar will be in F/AST mode. If time permits the aircraft would make one more pass through the eye and then fly the dual- Doppler option. In this example, the pattern would be completed in about 2.5 h. Dropwindsondes would be deployed near the buoys or C-MAN sites, and additional dropwindsondes will be deployed at or just inside the flight-level RMW.

Note that the optimal volume scans for this pattern will be obtained when the storm is 32-80 nm (60-150 km) from the radar, because beyond 80 nm (150 km) the lowest WSR-88D scan will be above 5,000 ft (1.5 km) which is too high to resolve the low-level wind field. Within 32 nm (60 km) the volume scan will be incomplete, because the WSR-88D does not scan above 19.5 degrees. It is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage.

Analysis Strategy: Flight level, Doppler radar, dropsonde and SFMR data transmitted in real time will be ingested into the H*Wind archive, where the observations are standardized to average 1 minute data at a standard height of 10 m in an open exposure. These data, in addition to other surface observations will be combined into analyses of surface wind speed that will be provided to forecasters. The quality controlled data will also be available for assimilation into models such as HWRF. The analyses can also be used to validate surface winds in model output fields, as explained in more detail in module 3.

Coastal Survey module: When the hurricane is making landfall, this module will provide information about the boundary layer in the onshore and offshore flow regimes. Figure 12-2 shows an example for a hurricane making landfall near Melbourne, Florida. On the first coastal pass the P-3 would fly parallel 10-15 km offshore to obtain SFMR surface wind speeds (1-2 in Fig. 12-2). The track should be adjusted so that the SFMR footprint is out of the surf zone. The second pass should as close to the coast as safety permits, to sample the boundary layer transitions at the coast in onshore and offshore flow (3-4 in Fig. 12-2). The first pass should be at 5,000 ft (1.5 km) or less, and the aircraft could climb to higher altitudes for the second pass. On both of these passes the aircraft should fly to 150 km or the radius of gale-force wind speeds and release dropwindsondes at the RMW and at intervals of 12.5, 25, 50, 75 and 100 or 125 km on either side of the storm track, to sample both onshore and offshore flow regimes. Finally, to better sample the adjustment of the off shore flow from land to ocean a short leg would be flown from the coast spiraling towards the storm center. Three to four dropwindsondes would be deployed quite near the coast, followed by 3-4 dropwindsondes spaced every 20-30 km along the trajectory. The Doppler radar will be in F/AST mode, to provide wind estimates on either side of the aircraft track. This module could be flown when the hurricane is making landfall or after the storm moves inland. The pattern could be flown in ~2 h.

Analysis Strategy: In addition to the data processing described in modules 1 and 3, the Doppler radar swath data will be edited and synthesized into wind fields. The winds will be compared with dropsondes and SFMR, AWRAP, and/or LIDAR data to characterize the differences between the onshore and offshore flow.

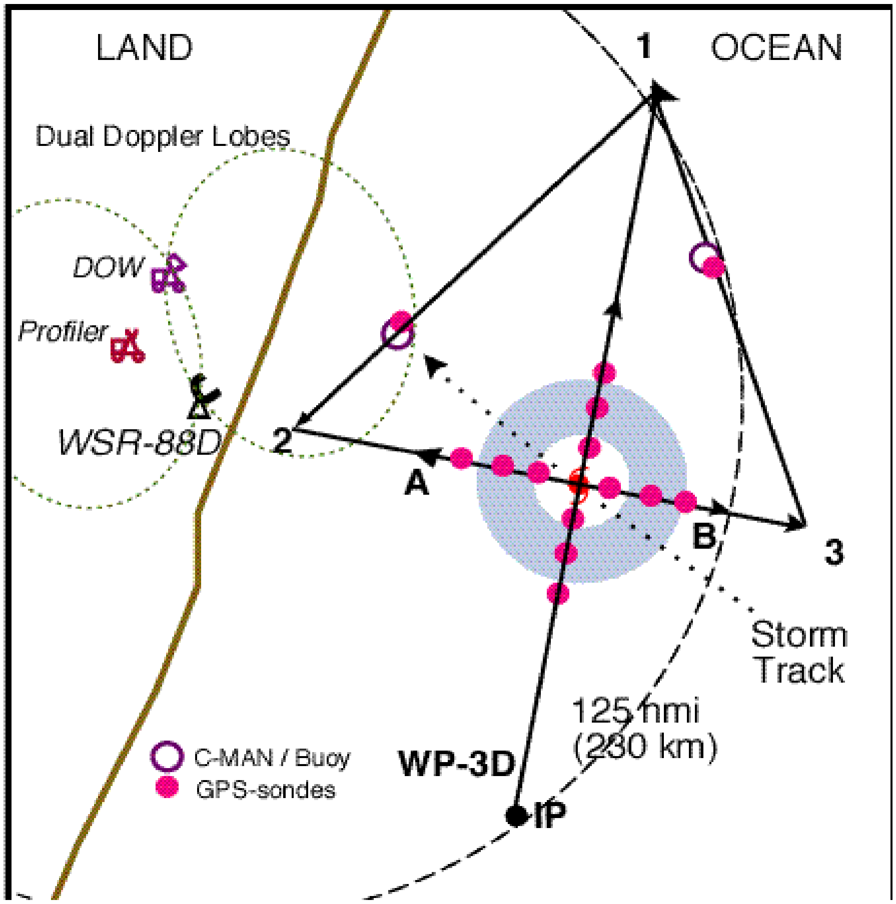


Figure 12-1: Real-time module.

- TAS calibration required. The legs through the eye may be flown along any compass heading along a radial from the ground-based radar. The **IP** is approximately 100 nm (185 km) from the storm center. Downwind legs may be adjusted to pass over buoys.
- P-3 should fly legs along the WSR-88D radials.
- Set airborne Doppler radar to F/AST on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

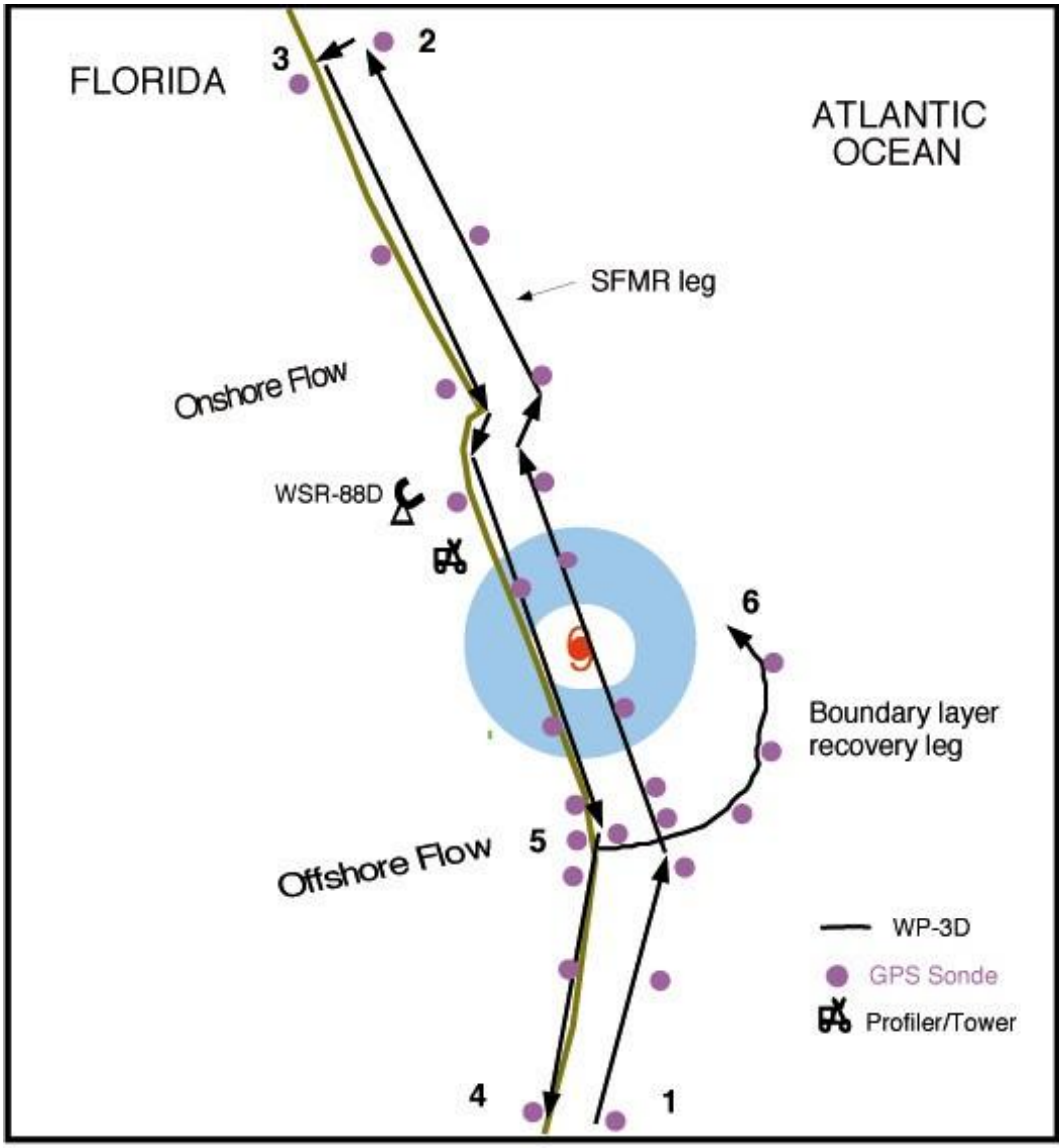


Figure 12-2: Coastal Survey pattern.

- First pass starts 150 km from center or at radius of gale-force wind speeds, whichever is closer. Pass from **1-2** should be 10-15 km offshore for optimum SFMR measurements. Release dropwindsondes at RMW, and 12.5, 25, 50, 75 and 100 or 125 km from RMW on either side of storm in legs **1-2** and **3-4**. Dropwindsondes should be deployed quickly at start of leg **5-6**, and then every 10-15 km hereafter.
- Set airborne Doppler to scan in F/AST on all legs, with single PRF > 2400 and 20% tilt. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

13: Saharan Air Layer Experiment (SALEX): Arc Cloud Module

Principal Investigator: Jason Dunion

Motivation:

Arc clouds are common features in mid-latitude thunderstorms and mesoscale convective systems. They often denote the presence of a density current that forms when dry mid-level (~600-850 hPa) air has interacted with precipitation. The convectively-driven downdrafts that result reach the surface/near-surface and spread out from the convective core of the thunderstorm. Substantial arc clouds (i.e., >100 km in length and lasting for several hours) are also common features in the tropics (Figure 13-1), particularly on the periphery of African easterly waves (AEWs) and tropical cyclones (TCs). However, the physical processes responsible for such tropical arc clouds as well as their impacts on the short-term evolution of their parent disturbances are not well understood.

The mid-level moisture found in the *moist tropical* North Atlantic sounding described by Dunion (2011) is hypothesized to be insufficiently dry to generate extensive near-surface density currents around an African easterly wave (AEW) or tropical cyclone (TC). However, Dunion (2011) also described two additional air masses that are frequently found in the tropical North Atlantic and Caribbean during the summer months and could effectively initiate the formation of large arc clouds: (1) the Saharan Air Layer (*SAL*) and (2) *mid-latitude dry air intrusions*. Both of these air masses were found to contain substantially dry air (~50% less moisture than the *moist tropical* sounding) in the mid-levels that could support convectively-driven downdrafts and large density currents. Furthermore, outward-propagating arc clouds on the periphery of AEWs or TCs could be enhanced by near-surface super-gradient winds induced by the downward transport of high momentum air. Since most developing tropical disturbances in the North Atlantic are associated with a mid-level jet and/or mesoscale convective vortex near a state of gradient balance, any convectively-driven downdrafts would inject high momentum air into a near-surface environment that often contains a weaker horizontal pressure gradient. In such cases, density currents may be temporarily enhanced during local adjustments to gradient balance. Finally, tropical arc clouds may be further enhanced by outward-propagating diurnal pulses that originate from the convective core of the tropical disturbance (see HRD's "TC Diurnal Cycle Experiment"). New GOES IR TC diurnal pulsing imagery indicates that arc clouds tend to form along the leading edge of outwardly propagating "cool rings" that are associated with these regularly occurring TC diurnal pulses. The diurnal pulses reach peripheral radii where low to mid-level dry air is often located (e.g. 300-500 km) at remarkably predictable times of day (e.g. 400 km at ~1200-1500 LST). Therefore, UW-CIMSS real-time TC diurnal pulsing imagery will be used to monitor the diurnal pulse propagation throughout the local morning hours and signs of arc cloud formation.

It is hypothesized that the processes leading to the formation of arc cloud events can significantly impact an AEW or TC (particularly smaller, less developed systems). Specifically, the cool, dry air associated with the convectively-driven downdrafts that form arc clouds can help stabilize the middle to lower troposphere and may even act to stabilize the boundary layer, thereby limiting subsequent convection. The arc clouds themselves may also act to disrupt the storm. As they race away from the convective core region, they create low-level outflow in the quadrant/semicircle of the AEW or TC in which they form. This outflow pattern counters the typical low-level inflow that is vital for TC formation and maintenance. As arc clouds propagate away from the tropical disturbance, they visibly emerge from underneath the central dense overcast that can obscure them from visible an infrared satellite view. Therefore, when arc clouds are identified using satellites, they are often in the middle to later stages of their lifecycles. Hence, the mechanism of enhanced low-level outflow is likely occurring at the time of satellite identification, while the mechanism of cooling/drying of the boundary layer has already occurred (though the effects may still be observable in the aircraft, GPS dropsonde and satellite data). This necessitates that the arc clouds be identified and sampled as early in their lifecycle as possible using available aircraft observations (e.g. flight-level, GPS dropsonde and Doppler radar data) and satellites (e.g. visible, infrared and microwave imagery).

Objectives: The main objectives of the TC/AEW Arc Cloud Module are to:

- Collect observations across arc cloud features in the periphery of AEWs or TCs using aircraft flight-level data and GPS dropsondes to improve our understanding of the physical processes responsible for their formation and evolution, as well as how these features may limit short-term intensification;

Links to IFEX: This experiment supports the following NOAA IFEX goals:

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

Mission Description:

This multi-option research module is designed to utilize the WP-3D [flight-level (flying at multiple levels above 1500 feet) and GPS dropsonde data] or G-IV (GPS dropsonde data) aircraft. Although this module is not a standalone experiment, it could be included as a module within any of the following HRD research missions: TC Diurnal Cycle Experiment, TC Genesis Experiment, TC Rapid Intensity Experiment, or TC Shear Experiment, or as part of operational G-IV Synoptic Surveillance and NHC-EMC-HRD Tail Doppler Radar (TDR) missions. Total precipitable water (TPW) satellite imagery will be used to identify mid-level dry air (≤45 mm TPW) in the periphery of the AEW or TC. These areas of mid-level dry air will be favorable locations for arc cloud formation, especially when TC diurnal pulses are passing radii where this low to mid-level dry air is located. UW-CIMSS real-time TC diurnal pulsing imagery will be used to track these favored regions where arc clouds might form (i.e. along the leading edge of the cool ring). Also, the 200-850 hPa shear vector may be an additional indicator of arc clouds formation. When TPW imagery indicates the presence of mid-level dry air and the shear vector is indicating a shear direction toward the storm center (in that same quadrant or semicircle), arc cloud formation may be especially favorable. These targeted areas will be regions of preferred arc cloud formation and should be monitored closely using satellite imagery (preferably 1 km visible and 37 GHz microwave) during the mission. Depending on connection rates on the aircraft, supplemental communications via X-Chat with scientists on the ground would be desirable, especially given the unpredictability and rapid evolution of arc cloud features.

<u>Option #1: G-IV aircraft</u>. Once an arc cloud feature has been identified, a GPS dropsonde sequence (preferably running perpendicular to the arc cloud) should be made between the convective area where the arc cloud originated to at least 50 km beyond the leading edge of the arc cloud. Special attention should be paid to the transition zone across the leading edge of the arc cloud and to the environment adjacent to the convective core area where the arc cloud originated (behind the arc cloud). GPS dropsonde spacing should be ~35 km and the transect can be made inbound (sampling in front of, across, and then behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC. In addition to the more common arc cloud that propagates away from the AEW/TC, a second arc cloud has occasionally been observed propagating in toward the AEW/TC. This second arc cloud appears to spawn from the same convective region as the outbound arc cloud and simply moves toward the AEW/TC instead of away from it. If a second inward propagating arc cloud is identified, the GPS dropsonde sequence should be extended to span the environments ahead of (relative to arc cloud motion) both arc clouds. Figures 13-2 and 13-3 provide example G-IV flight patterns across arc cloud candidates. This option can be easily incorporated into pre-existing flight patterns with minimal additional time requirements.

<u>Option #2: WP-3D aircraft</u>: After an arc cloud feature has been identified, a multi-level flight pattern running

perpendicular to the arc cloud should be initiated. The Doppler radar should operate in F/AST mode to permit sampling of the three-dimensional winds throughout any precipitating arc clouds. The *initial* pass should extend between the convection where the arc cloud originated to at least 20 km beyond the leading edge of the arc cloud. Flight altitude should be >3000 m to permit the deployment of multiple GPS dropsondes. Special attention should be paid to the transition zone across the leading edge of the arc cloud and to the environment adjacent to the convection where the arc cloud originated (behind the arc cloud). GPS dropsonde spacing should be ~20 km [reduced to ~10 km spacing closer (≤20 km) to the arc cloud] and the transect can be made inbound (sampling in front of, across, and then behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC. For the *second* pass, the aircraft should turn and descend to ~1000 m before proceeding back along the same transect extending from the originating convection to at least 20 km beyond the leading edge of the arc cloud. For the *final* pass, the aircraft should again turn and descend to ~500 m before again proceeding along a similar transect across the arc cloud. Flight altitudes for the second and final passes can be adjusted as needed for aircraft safety, but should sample as low as possible in order to capture any near-surface density current with the flight-level sensors. No dropsondes should be deployed on the second and final low-level passes. After the final low-level pass, the primary flight pattern can be resumed. The total time to complete this option should not exceed 60 min, and in most cases can be completed in less time. Figures 13-2, 13-3, and 13-4 show sample fight patterns for this multi-level option.

Note: If other experiment goals, time constraints, and/or aircraft safety would prevent the low-level passes, this option could be altered to include only the initial pass with the dropsonde deployment sequence at altitudes >3000 m.

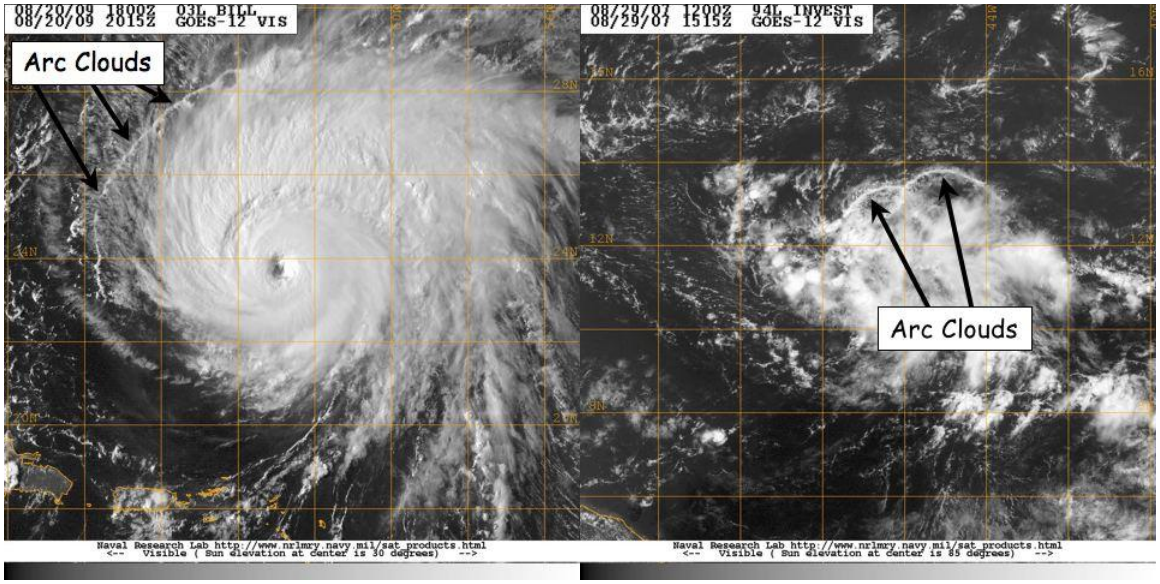


Figure 13-1: GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2009 Hurricane Bill and (right) 2007 Pre-Tropical Depression Felix.

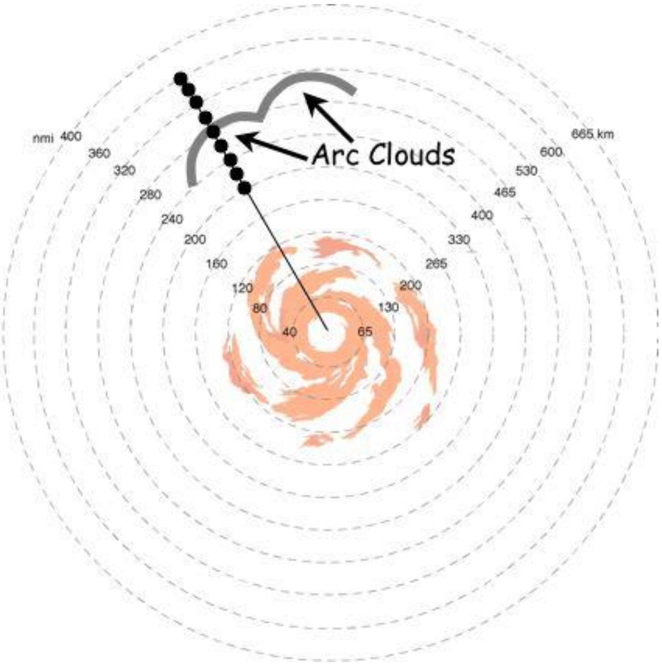


Figure 13-2: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the arc cloud are candidates for this module. When multiple arc clouds are present, the feature closest to the pre-determined flight track is desirable.

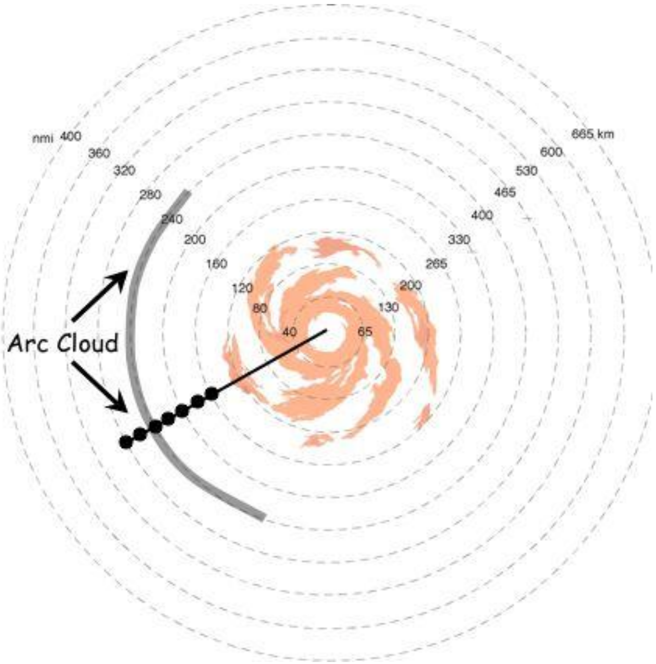


Figure 13-3: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the arc cloud are candidates for this module.

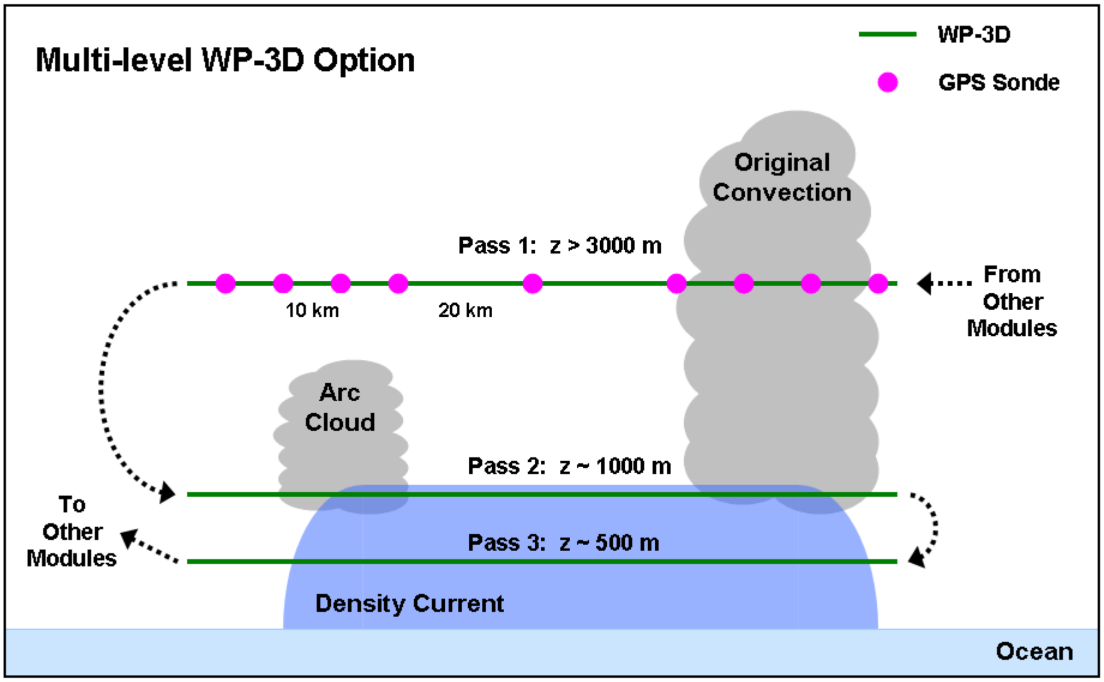


Figure 13-4: The WP-3D flight track for the multi-level option. Azimuth and length of initial midlevel pass with GPS dropsonde sequence will be dictated by the pre-determined flight plan. Lengths of the low-level passes should span much of the distance between the arc cloud and its initiating convection, while flight altitudes should be near the top and middle of any near-surface density currents (adjusting for safe aircraft operation as needed).

Analysis Strategy

This experiment seeks to collect observations across arc cloud features in the periphery of AEWs or TCs using aircraft flight-level data, Doppler data and GPS dropsondes to improve our understanding of the physical processes responsible for their formation and evolution, as well as how these features may limit short-term intensification. The GPS dropsonde data will be used to calculate changes in static stability and possible impacts on surface fluxes both ahead of and behind the arc cloud (e.g. enhanced stability/reduced surface fluxes behind the arc cloud leading edge). Also, kinematics and thermodynamic associated with arc cloud events will also be compared to corresponding locations in model analysis fields (e.g, GFS and HWRF).

14. Hurricane Boundary Layer Entrainment Flux Module

Principal Investigator(s): Jun Zhang and Gary Barnes (U. Hawaii)

Primary IFEX Goal: 3 - Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

Motivation and Background: Tropical cyclones interact with the ocean through the boundary layer, obtaining heat and moisture as the enriched fuel, and transferring momentum to the ocean in the form of currents and waves. An improved knowledge of mechanisms underlying air-sea exchange across the boundary layer is essential for interpreting physical, dynamical and thermodynamical processes, and hence for the development of models with realistic prognostic capabilities forecasting or simulating tropical cyclones. Unless model parameterizations of surface fluxes, vertical mixing and entrainment processes are complete and well founded, the models will have limited predictive capability under hurricane intensity change.

The equivalent potential temperature (θ_e) of the eyewall column has been directly related to the minimum sea-level pressure or intensity that a tropical cyclone achieves (Riehl and Malkus 1960, Emanuel 1986, Betts and Simpson 1987). The source of the air for the eyewall updraft is primarily the inflow layer that has its lower boundary at the sea surface. It is well established that the increase of θ_e is chiefly due to the flux of sensible and especially latent heat at the air-sea interface. However, the flux at the sea surface is but one part of the energy budget that determines the θ_e of the inflow, and ultimately the eyewall column. The fluxes through the top of the inflow layer, a result of convective scale motions or entrainment, can remove as much energy as was gained through the sea surface. In the right environmental conditions convective-scale downdrafts, merging at the surface to form a cooler, drier outflow in the subcloud layer, can reduce θ_e of the inflow layer and have a negative impact on TC intensity (Powell 1990b).

In contradistinction to this scenario there is evidence for situations, especially in the annulus adjacent to the eyewall, where the θ_e in the layer above the inflow can be warmer than that found in the inflow (Barnes 2008). This annulus is where surface wind speeds are increasing rapidly and where the stratiform rain and weakly subsiding air found in this region (Houze and Marks 1984) may serve to inhibit energy loss through the deeper troposphere by suppression of convective clouds. Radial-height cross-sections of θ_e from observations (e.g., Hawkins and Imbembo 1976, Jorgensen 1984, Wroe and Barnes 2003) and from numerical simulations (e.g., Rotunno and Emanuel 1987) reveal that θ_e increases substantially in this annulus adjacent to the eyewall. Entrainment of this warmer θ_e can result in an additional energy source to the inflow (Barnes and Powell 1995, Wroe and Barnes 2003). The overarching point is that the vertical profile of the total enthalpy flux divergence is what is required for the determination of the θ_e budget for the inflow, and the θ_e of the eyewall column.

Losses or gains through the top of the inflow have been argued to be an important but poorly measured component of the energy budget (Barnes and Powell 1995, Wroe and Barnes 2003). Recent flux measurements demonstrate that there is a downward sensible heat flux contributing to the energy content of the inflow (Zhang et al. 2008, 2009). Accurate determination of the fluxes at the top of the inflow layer, coupled with the change in the energy content within the inflow layer estimated with the GPS sondes, would allow us to determine the surface fluxes as a residual of the energy budget. The experiment is designed to estimate these fluxes directly by utilizing the GPS sonde observations at 10 m, and the AXBT data. To date the challenging conditions found within a TC has prevented the community from accurately determining the surface fluxes so vital to hurricane thermodynamics. Accurate determination of the changes in the energy content of the inflow and of the losses or gains at the top of the inflow allows us to circumvent the problem of measuring the surface fluxes directly.

Objectives

- Estimate the energy content of the inflow to the eyewall;
- Determine the sensible and latent fluxes through the top of the hurricane boundary layer;
- Determine the air-sea fluxes both as a residual to an energy budget and via the bulk aerodynamic formulae;
- Investigate the effect of turbulent transport processes near the top of the inflow layer on the hurricane intensity change.

Module overview: This is a multi-option, single-aircraft module that is designed to directly measure momentum and enthalpy fluxes near the top of the inflow layer, as well as the energy of the inflow layer. This module can be included or linked with any of the following missions: Genesis experiment, or NHC- EMC-HRD Three-dimensional Doppler Winds Experiment missions, or Arc cloud experiment, or TC Landfall and Inland Decay Experiment, or UAS Experiment. A combination of data sources from GPS sondes, AXBTs, high frequency turbulence sensors and Doppler radar on NOAA-42RF are applied to determine the quantities listed in the above objectives. Turbulence sensors need to be calibrated at the start of the field season as described in the turbulence calibration module. The stepped-descent module and the box module are also described below.

Turbulence Calibration Module (2-3 hours)

The calibration module only needs be executed on separate flights at beginning of the field season. The following maneuvers are requested for turbulence sensors calibration:

1). Dynamic Yaw--2 sets:

First set, vary sideslip angle (beta) by +/- 4 degrees. This maneuver requires 5 full sinusoids, with one consisting of left 4 degrees, back through center, right 4 degrees, back to center--one sinusoid. Second set, set angle variation, and perform faster roughly +/- 2.5 degree variation with 25 sec period.

2). Acceleration/Deceleration (AC/DC) run--1 set: Start at normal flight speed, slow to minimum sustainable flight speed, increase to maximum flight speed, slow minimum flight speed, return to normal speed. Try to maintain constant altitude (vary angle of attack).

3). Wind Circles: Two 360° standard rate turns: first clockwise, then counter-clockwise. We need 360° of data to be in a coordinated turn, so after the pilot enters the turn and it is coordinated, only then 'start the clock'.

4). Wind box: Straight and level box, 2 min on each side, standard rate 90° turn on the corners. The box consists of 4 two-minute legs, with 90 degree standard rate turns after the completion of each leg. The box should be set up to fly one leg into, the next cross, the third out of, and the fourth cross wind direction. Indicated airspeed should be 210-220 kt.

5). Pitch (angle of attack) maneuvers--2 sets of 5: Five sinusoids with angle attack variations of +/-5 to 7 degrees. One complete sinusoid should have a period of 15 to 20 seconds. Upon completion of one set, fly straight and level roughly 2 minutes and begin second set.

All of these maneuvers should be aligned with the wind. The boxes should have legs parallel and perpendicular to the wind. The calibrations should be completed at the mean radar altitude where the measurements were conducted or roughly 1,000 ft (300 m). The maneuvers should be conducted in smooth air (as smooth as possible).

Stepped-descent module (40 minutes):

The module is flown between the eyewall and an outer rainband by NOAA-43, which is equipped with the turbulence sensors. It does not require any penetration of convective cells, the eyewall or convective rainbands. Preference is for a region that is either rain-free or stratiform rain only. For the simplest experiment 5 legs would be flown, each about 40 km or 5 minutes in duration (Fig. 14-1 and 14-2). The pattern would begin with a pass at 3 to 4 km altitude rapidly jettisoning 4 GPS sondes spaced approximately 10-km apart. During this pass 2-3 AXBT's would also be deployed to determine the SST. Airborne radiometers (SFMR) would also provide an estimate of surface wind speeds, and if there are enough scatterers in the volume the Doppler radar can be used to determine mesoscale wind and divergence. The first leg (at ~ 3 km altitude) can be done in conjunction with the standard figure-4 patterns.

The GPS sondes and Doppler wind lidar (DWL) are used to estimate the boundary layer height to the eyewall and the mean conditions of the boundary layer and the lower portion of the layer above. Because it is difficult to determine the height of the inflow layer at real time, the height of the maximum wind speed is defined to be top of the boundary layer, which is around 500 – 1000 m. The inflow layer top is expected to be 1-2 km in height.

We can use the dropsonde and DWL data at the end of outbound radar leg to diagnose the boundary layer height. Then we turn back into the storm to do the stair-step. The aircraft would descend to 600 m above the inflow top (about 2400 m) and fly toward the eyewall along an approximate radial. This leg will cover 40 km or require about 5 minutes. The aircraft will then turn and descend ~500 m and fly out-bound for 5 minutes. Two more legs will be completed, each another 500 m below the previous pass. The last pass will be 700 to 800 m above the sea. If the aircrew deems it safe a final pass could be flown 400 to 500 m above the sea. All legs will finish with a turn upwind to keep the legs nearly vertically aligned and in the same portion of the TC. Time to complete the module is about 40 min including descents and turns.

These five passes and the GPS sondes will allow for a determination of the sensible and latent heat fluxes (total enthalpy flux) as a function of height and radial distance adjacent to the eyewall or a convective rainband from the top of the inflow layer to 500 m altitude. The combination of the vertical profiles of equivalent potential temperature (θ_e) and the determination of the fluxes at the top of the inflow layer will allow an estimate of the air-sea fluxes as a residual and directly through the application of the bulk aerodynamic formulae applying AXBT, SFMR, and 10 m observations obtained from the GPS sondes. The scheme will allow us to infer the magnitude of the transfer coefficients necessary to achieve energy balance, provide insight to the role of dissipative heating, and determine the role of entrainment of warmer θ_e through the top of the inflow layer.

Box Module (20-25 minutes):

If we wish to estimate divergence and there are too few scatterers to obtain this estimate from the Doppler radar we would like to execute a box pattern (Fig. 14-3) near the top of the inflow layer (1 – 2 km); this may add about 20-25 minutes to the module. This additional stage is beneficial, but not essential to estimate the fluxes or to complete the energy budget. It allows us to avoid constraining assumptions about the flow (we would have to assume no divergence due to the tangential wind component).

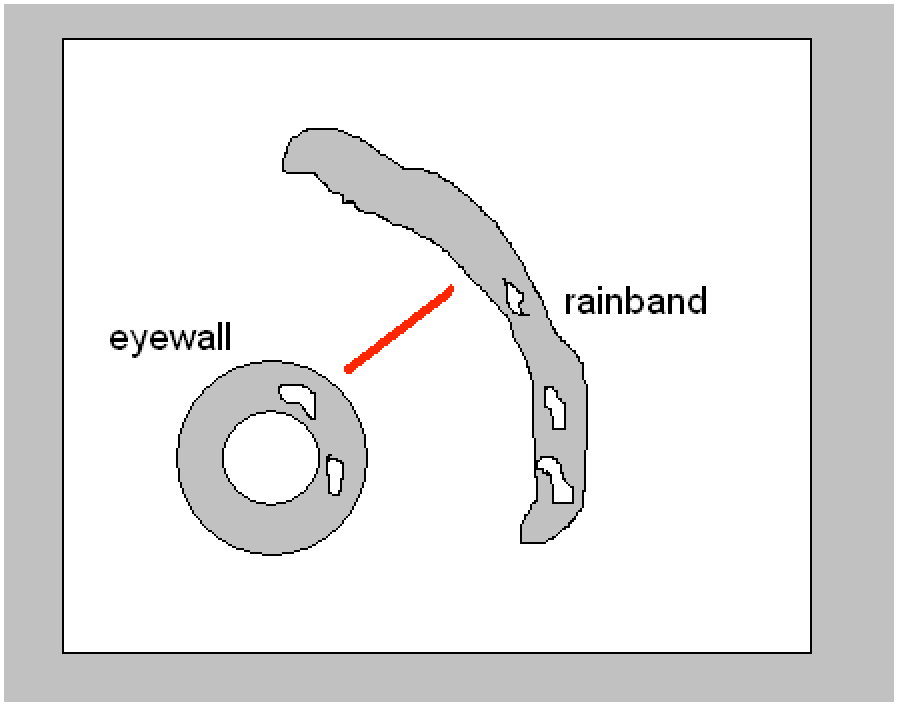


Figure 14-1: Plan view of the preferred location for the stepped-descent module. Red line shows aircraft track.

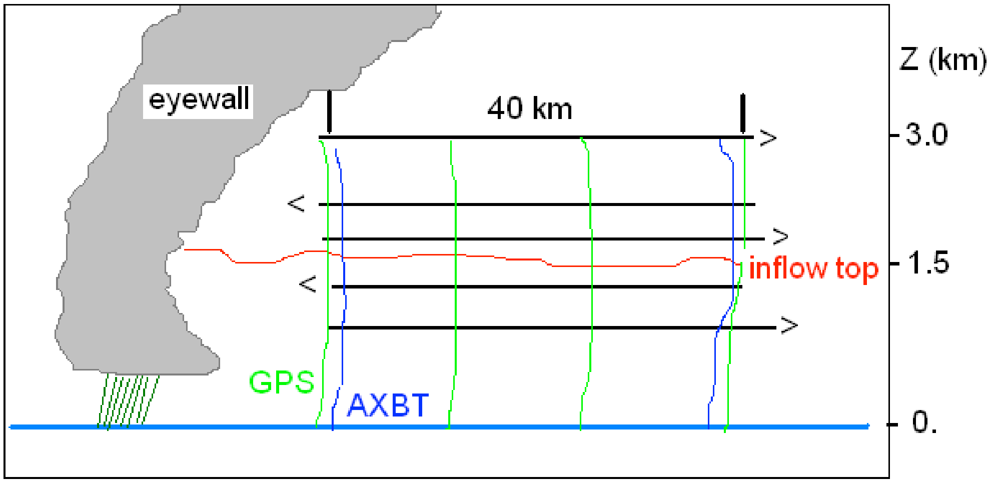


Figure 14-2: Vertical cross-section of the stepped-descent module.

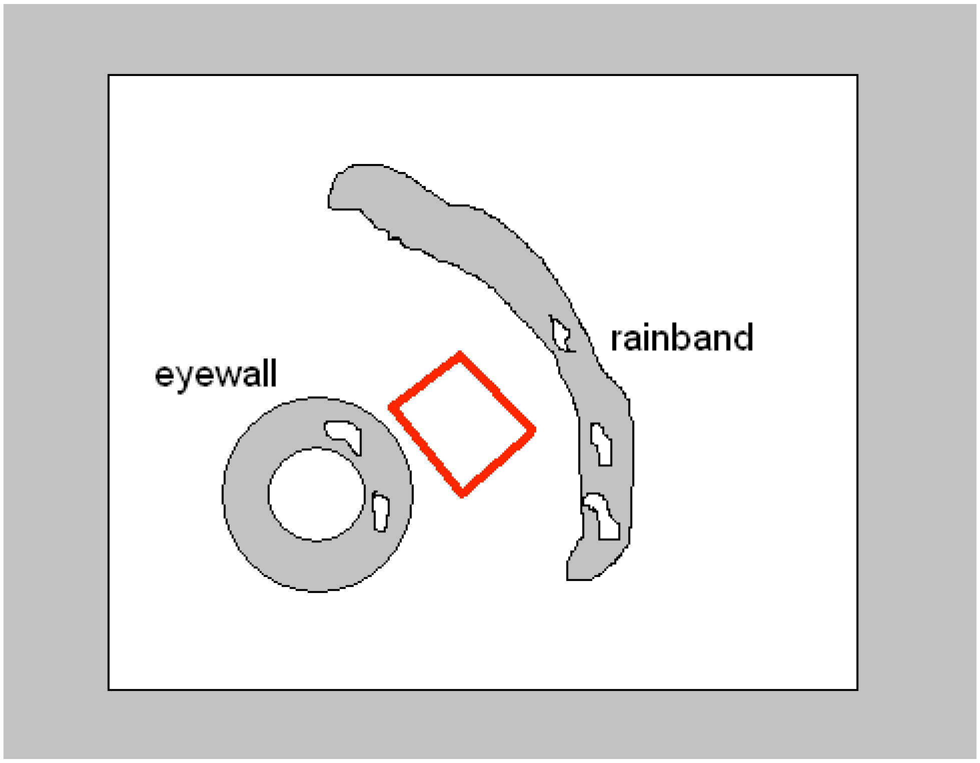


Figure 14-3: Box module used to calculate divergence if no scatterers exist in the volume.

15. Offshore Wind Module

Principal Investigator: Mark Powell

This module is designed as a multi-agency (NOAA, Department of Energy, Department of the Interior) supplemental data collection effort to gather hurricane environmental information in the vicinity of proposed offshore wind farms. Offshore wind energy is seen as an important component in President Obama’s goal of the U.S. supplying 80 % of energy needs from clean energy by the year 2030. The Bureau of Ocean Energy Management (BOEM) has identified several wind energy and lease areas in federal waters off the Atlantic coast and the Department of Energy has identified additional areas as demonstration projects for offshore wind power development. For offshore wind energy to develop into a new industry, the turbines must be designed to withstand extreme environmental conditions that occur during hurricanes.

Modern offshore turbines are huge structures with masts near 100 m above the surface and rotor zones extending to near 180 m. Conventional offshore turbines are erected upon foundations constructed in shallow (<40 m) water but new designs for deep water turbines are in operation off Norway and Portugal and expected off the coast of Maine as part of a DOE funded program to get demonstration projects in the water. Current standards for the design of tall offshore structures are governed by power law wind profiles specified with constant roughness or wind profiles based on Norwegian Sea that are unrepresentative when compared to GPS sonde based hurricane wind profiles. Turbulence intensity specifications used for the design of offshore wind turbines specified according to a marine roughness that increases with wind speed. To better document design wind profiles in hurricane conditions, additional GPS sonde and airborne Doppler wind profiles are needed in relatively shallow water areas in the vicinity of the proposed wind farm locations. In addition, sea surface temperature and ocean current profiles are needed to help specify atmospheric stability and subsurface water loading, and wave height and directional wave spectrum measurements from NOAA’s wide-swath radar altimeter are needed to determine wave loading.

Samples of the mean wind profile, ocean current profiles, wave heights and spectrum, sea surface temperature, and profiles of air density, temperature, humidity, and rainfall will assist design engineers in specifying materials and construction that will allow wind farms to survive hurricane conditions. Since this module is generally a “piggyback” mission, we request additional AXBT, AXCP, and GPS sonde launches in the vicinity of the wind farm location. The PI will provide data collection coordinates to the Lead Project Scientist of the primary mission. This module is requested whenever a NOAA aircraft is flying and the hurricane is projected to be within 150 nm of an identified offshore wind development site (Table 15-2).

As an example, we show a “fly-by” pattern in Fig. 15-2 in which the wind farm location is near the route to or from the storm or near an existing leg of the primary experiment flown that day. In this case two AXBT and AXCP drops would help establish the SST and ocean current profiles while 4 GPS sondes are dropped in succession. It would be preferable to repeat the pattern and collect these measurements on the inbound or outbound routes to the storm, or as part of the pattern in the storm.

Since the Hurricane Field Program will already be in operation and experiments flown, the offshore wind module is a cost effective solution for participating federal agencies and industry partners to collect critical data relevant to the design risk. Since flight hours have already been dedicated to existing HFP experiments, those experiments have priority. The opportunity to fly the offshore mission as a piggy-back module is at the discretion of the Field Program Director. In order to fly the module, support for expendables is required. In addition, collection of data from many of the specialized data and analysis systems (e.g. Doppler radar, Scanning radar altimeter, H*Wind) depends on availability and may require additional support.

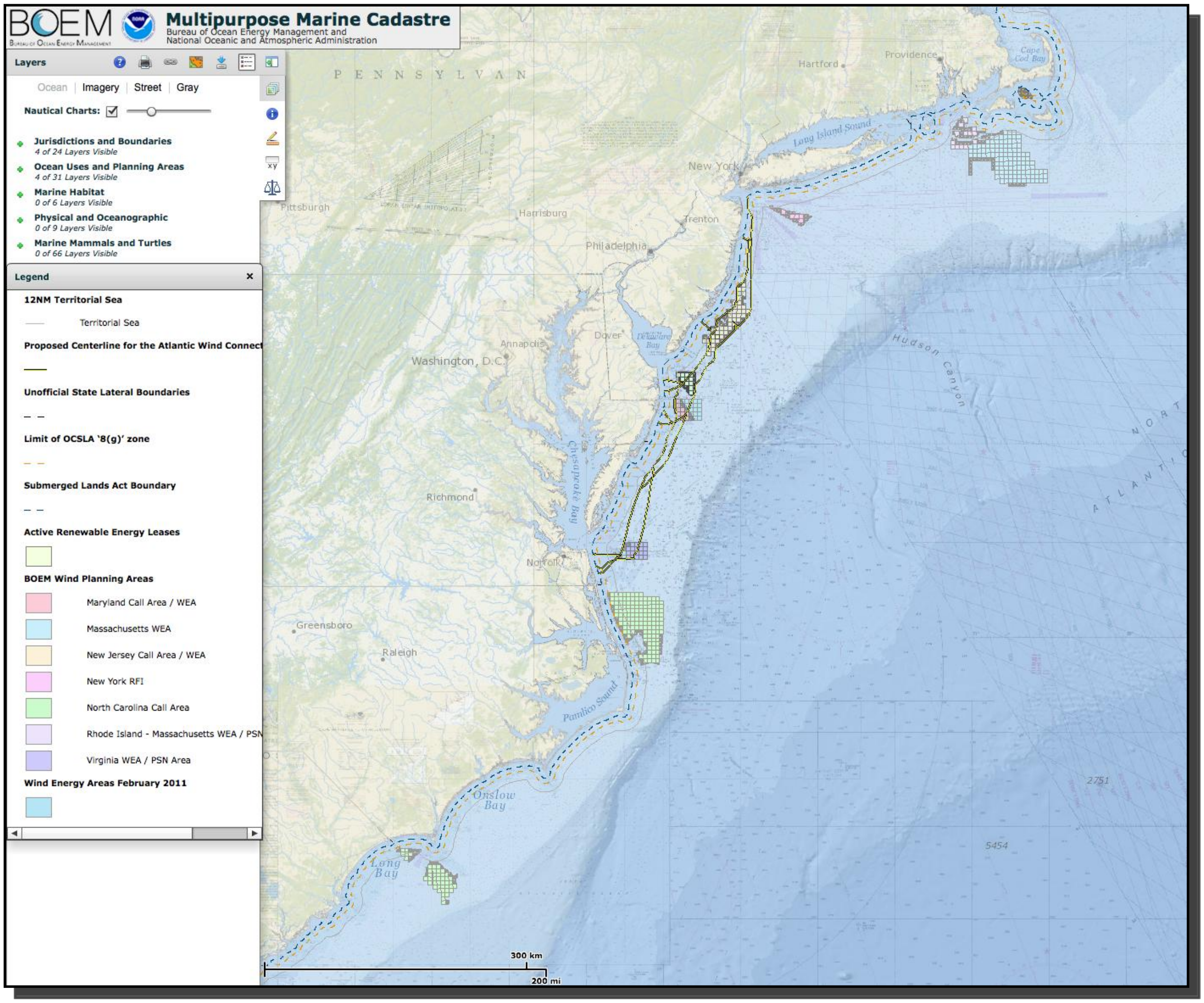


Figure 15-1: Potential offshore wind farm and Atlantic Wind Connection subsurface transmission line locations in federal waters off the U. S. Atlantic coast. Additional areas include state waters off Maine, Nantucket Sound MA, Block Island RI, Atlantic City NJ, Virginia Beach VA, and near Port Isabel TX (Table 15-1).

Offshore Wind Farm	Location	State or Federal
Baronyx	Offshore Cameron County near Port Isabel, TX (Rio Grande N and S)	State
Fisherman’s Energy	Atlantic City, NJ (3 miles offshore)	State
Dominion Virginia Power	Virginia Beach	Federal
Statoil North America (Hywind Maine)	Boothbay Harbor	State
University of Maine (DeepCwind)	Monhegan Island	State
Deepwater Wind	Block Island (5 mi SE)	State
Cape Wind	Nantucket Sound (Horseshoe shoal)	State
Maryland Wind Energy Area	See Fig. 15-1	Federal
Rhode Island Wind Energy Area	See Fig. 15-1	Federal
New Jersey Wind Energy area	See Fig. 15-1	Federal
Maryland Wind Energy Area	See Fig. 15-1	Federal
Virginia Wind Energy Area	See Fig. 15-1	Federal
Delaware	See Fig. 15-1	Federal
North Carolina	See Fig. 15-1	Federal
South Carolina	See Fig. 15-1	Federal
Georgia	Lease request for a MET mast off Tybee Island	Federal

Table 15-1: Listing of DOE funded demonstration projects and other offshore wind developments planned or projected in state and federal waters.

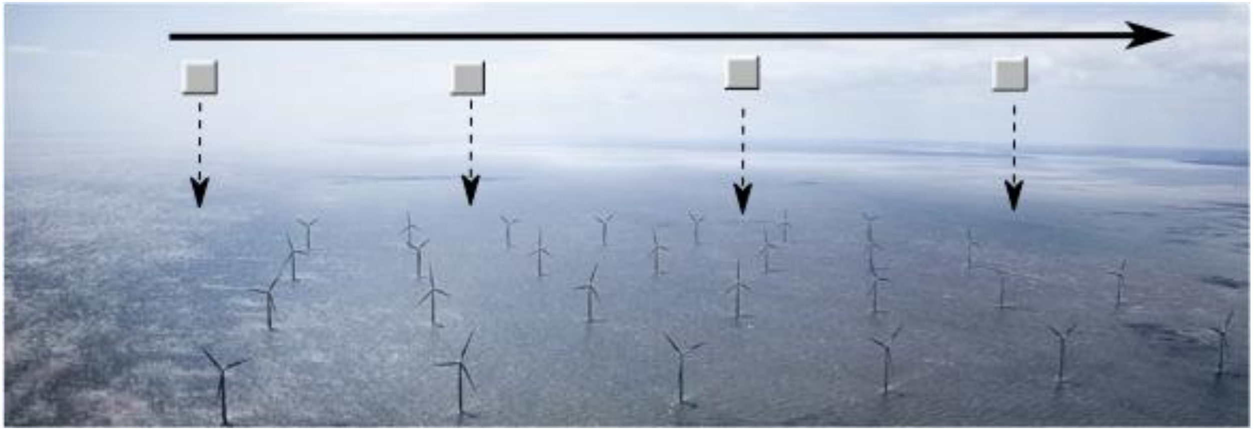
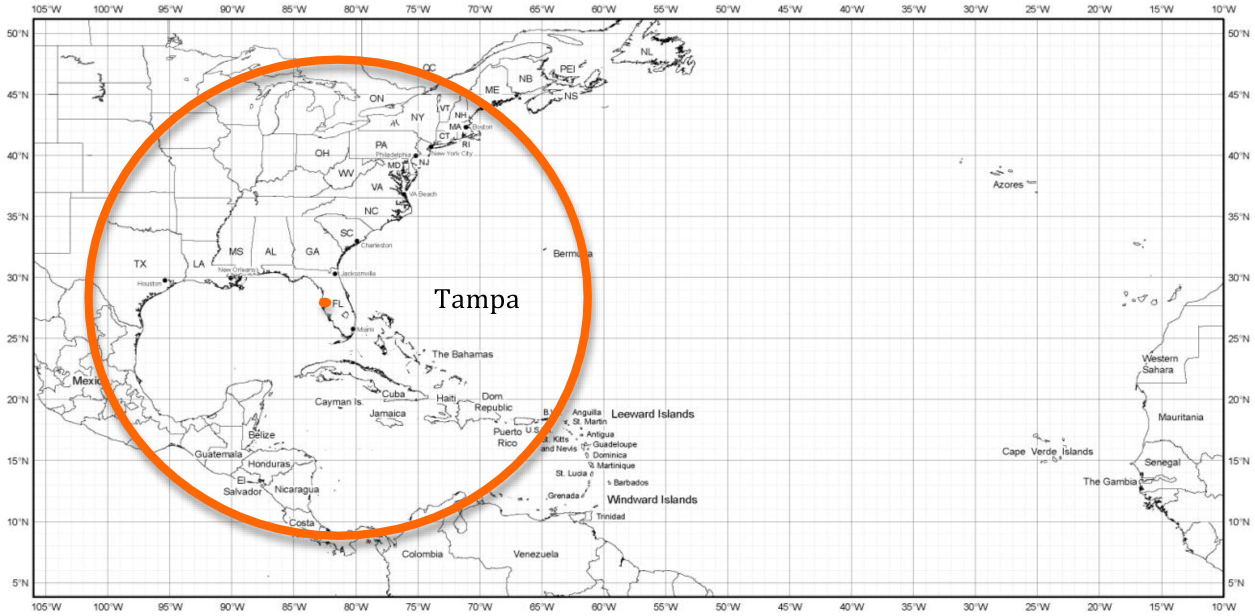


Figure 15-2: Schematic of piggyback pattern showing hypothetical wind farm fly-by with expendable launches at a 2-4 km interval. No U.S. wind farms are yet in operation. (Dong Energy Gunfleet Sands 1farm off SE England)

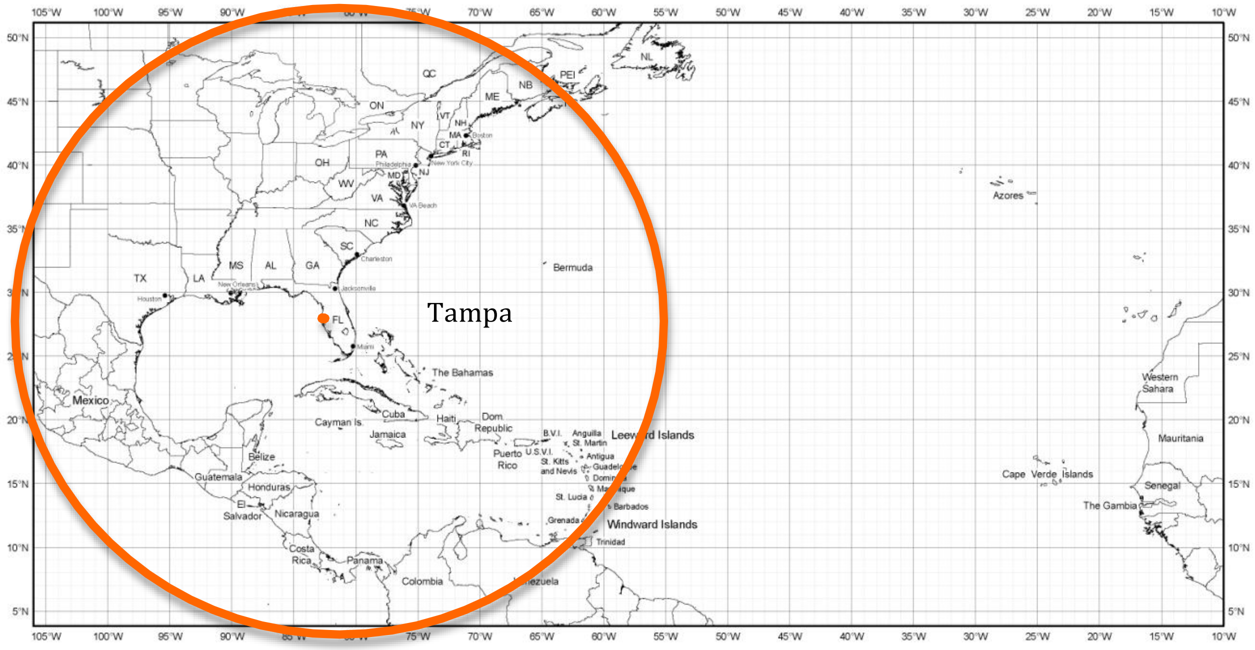
Table 15-2: Expendables (Ex) and aircraft (A/C) measurement systems required for conducting offshore wind experiment

Observing system	Measurement	Number	Type
GPS sonde	Pressure, Temperature, Humidity, Velocity	4-10	Ex
AXBT	Ocean temperature profile	2-4	Ex
AXCP	Ocean current profile	2-4	Ex
Stepped Frequency Microwave Radiometer (SFMR)	Surface wind speed rain rate		A/C
NOAA wide-swath radar altimeter	wave height and directional wave spectrum		A/C
Airborne Doppler radar	3D wind velocity, rain rate		A/C
Lower fuselage radar	reflectivity		A/C
H*Wind	Analysis of surface wind field		All available observations

Supplemental: Operational Base Maps



Map 1: Primary Atlantic operating bases and approximate operating ranges for the NOAA P-3



Map 2: Primary Atlantic operating bases and approximate operating ranges for the NOAA G-IV.