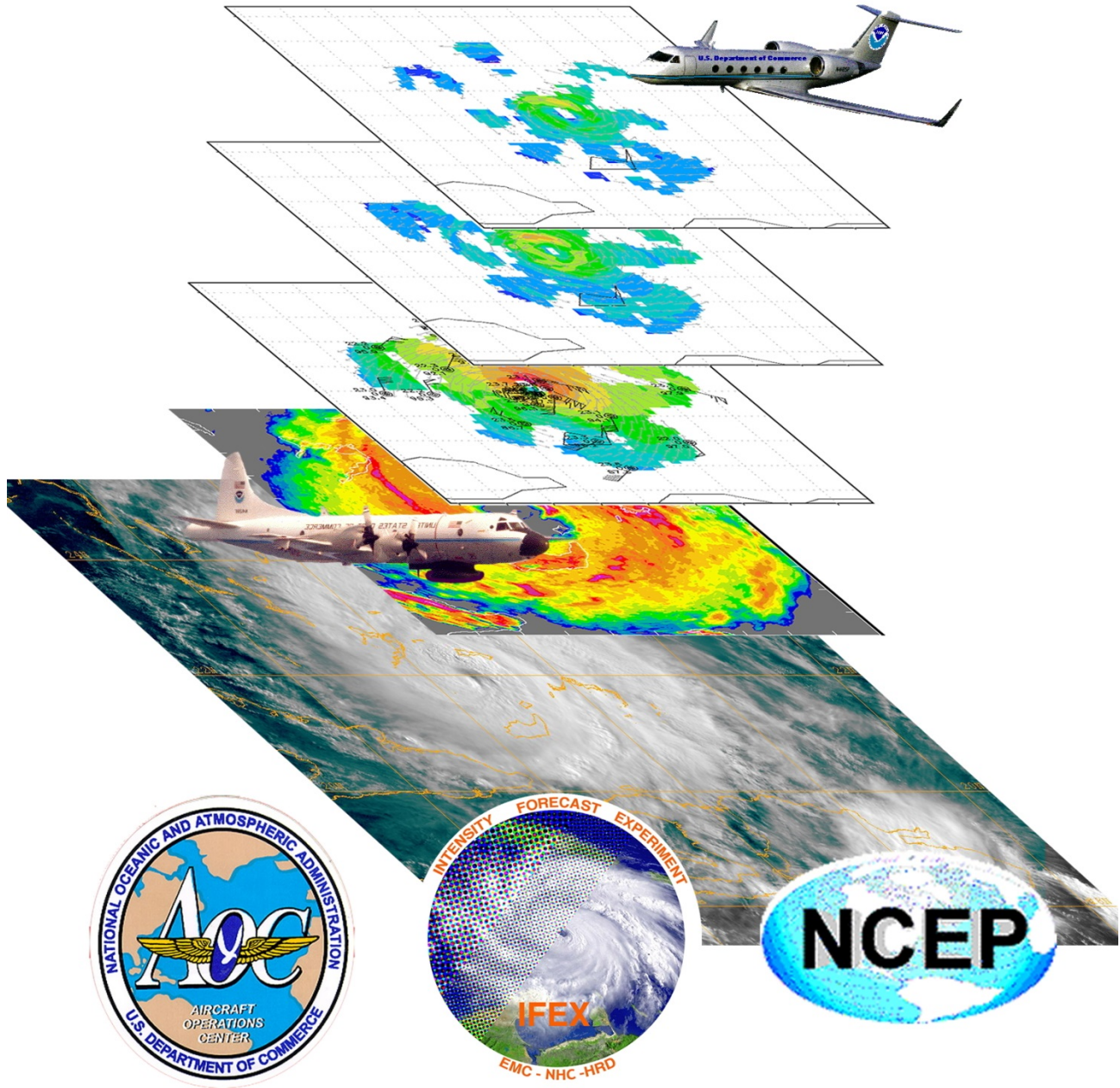


Hurricane Field Program 2014

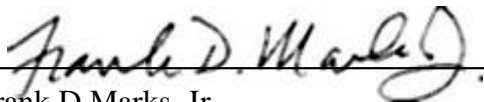


2014 Hurricane Field Program Plan

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, Robert Black, Joe Cione, Peter Dodge, Jason Dunion, John Gamache, Sundararaman Gopalakrishnan, John Kaplan, Shirley Murillo, Robert Rogers, Eric Uhlhorn, Jun Zhang, Jian-Wen Bao, Gary Barnes, Mark Bourassa, Luca Centurioni, Paul Chang, Dave Emmitt, Chris Fairall, Gustavo Goni, George Halliwell, Heather Holbach, Rick Lumpkin, Michael Riemer, Nick Shay, and Vijay Tallapragada



Frank D Marks, Jr
Director, Hurricane Research Division

1 June 2014

Date

TABLE OF CONTENTS

INTRODUCTION	1
1. Description of Intensity Forecasting Experiment (IFEX).....	1
2. Experiment and module summaries.....	2
OPERATIONS	5
1. Locations.....	5
2. Field Program Duration.....	5
3. Research Mission Operations.....	5
4. Task Force Configuration.....	5
5. Field Operations.....	5
5.1 Scientific Leadership Responsibilities.....	5
5.2 Aircraft Scientific Crews.....	5
5.3 Principal Duties of the Scientific Personnel.....	5
5.4 HRD Communications.....	5
6. Data Management.....	6
7. Operational Constraints.....	6
8. Calibration of Aircraft Systems.....	6
EXPERIMENT AND MODULE DESCRIPTIONS	7
IFEX GOAL 1	
1a. P-3 Three-Dimensional Doppler Winds Mission.....	7
1b. G-IV Tail Doppler Radar Experiment.....	17
2a. Optimizing Observations to Better Evaluate and Improve NOAA’s HWRF Operational Model.....	25
2b. TC Ocean Response.....	32
IFEX GOAL 2	
3a. Doppler Wind Lidar (DWL) SAL Module.....	39
3b. DWL Boundary Layer Module.....	42
4. NESDIS Ocean Winds and Rain Experiment.....	44
5. Small Unmanned Aerial Vehicle Experiment (SUAVE).....	46
6. SFMR High-Incidence Angle Measurements Module.....	55
IFEX GOAL 3	
7. TC in Shear Experiment.....	57
8. TC Diurnal Cycle Experiment.....	77
9. TC-Ocean Interaction Experiment.....	82
10. Convective Burst Module.....	89
11. Rapid Intensification Experiment (RAPX).....	91

12. Tropical Cyclone Landfall Experiment.....	96
13. Saharan Air Layer Experiment (SALEX): Arc Cloud Module.....	102
14. Hurricane Boundary Layer Entrainment Flux Module.....	108
15. Offshore Wind Module.....	112
SUPPLEMENTAL: OPERATIONAL MAPS.....	112
Map 1: Primary Atlantic operating bases and operating ranges (P-3).....	116
Map 2: Primary Atlantic operating bases and operating ranges (G-IV)	116

2014 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.

(2a) **Optimizing Observations to Better Evaluate and Improve NOAA’s HWRF Operational Model:** 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.

(2b) **TC Ocean Response:** The ocean-sampling component of experiment (2a).

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

(3a) **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).

(3b) **DWL Boundary Layer Module:** The DWL will be evaluated as an additional observing system that can increase the spatial coverage of wind estimates to improve the initial state of the HWRF model, and to reduce model biases through improved representation of the boundary layer physical processes.

(4) 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 of 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.

(5) 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.

(6) SFMR High-Incidence Angle Measurements Module: The objective of this module is to determine the relationship between the SFMR measured surface brightness temperature and the ocean surface wave field characteristics.

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) Convective Burst Module: The objective of this module is to sample the wind, temperature, and moisture fields within and around an area of deep convection at high time frequency and to utilize them in high-resolution data assimilation experiments.

(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) Hurricane Boundary Layer Entrainment Flux Module: 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) Offshore Wind Module: 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 N42RF and N43RF aircraft will be available with two flight crews available for back to back missions. The Gulfstream IV-SP (N49RF) aircraft will be available 01 June with two flight crews available for back to back missions. 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 2014.

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 2014. Also, the G-IV aircraft should be available, on a non-interference basis with tasked operational missions from 01 June to 31 October 2014.

5. Field Operations

5.1 *Scientific Leadership Responsibilities*

The implementation of the 2014 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 2014 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 2014 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 scatterometry in high-wind conditions over the ocean by collecting surface scatterometry 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

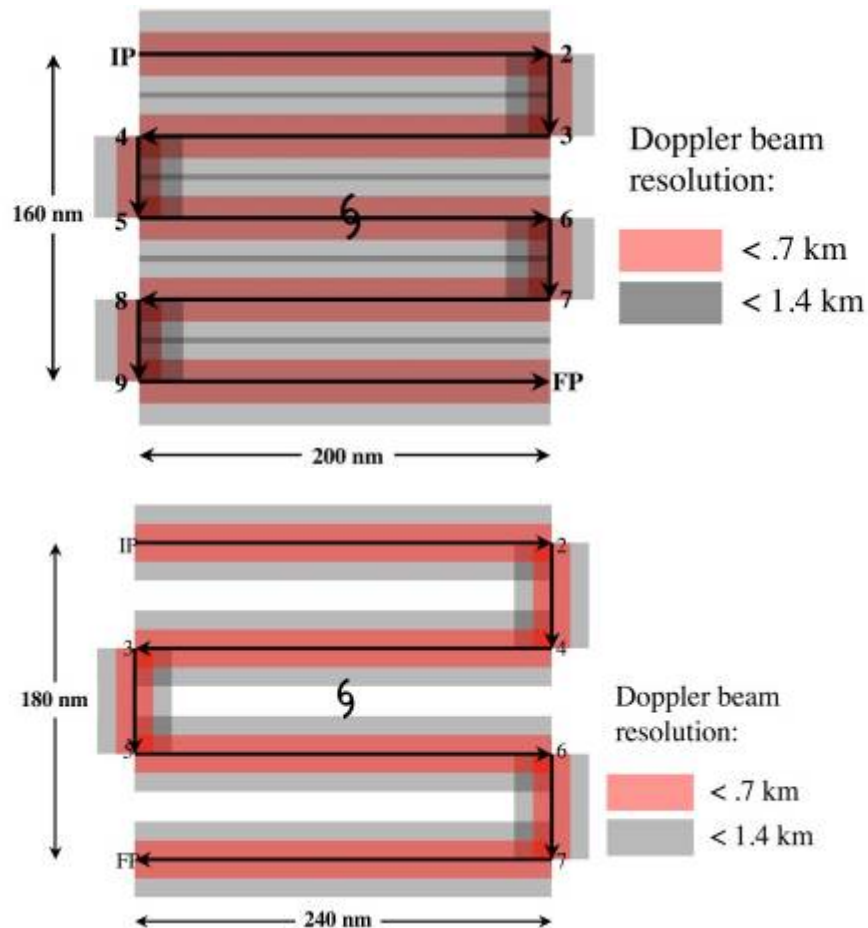


Figure 1a-1: Display of Doppler coverage for A (upper panel) and B (lower panel) lawnmower patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 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

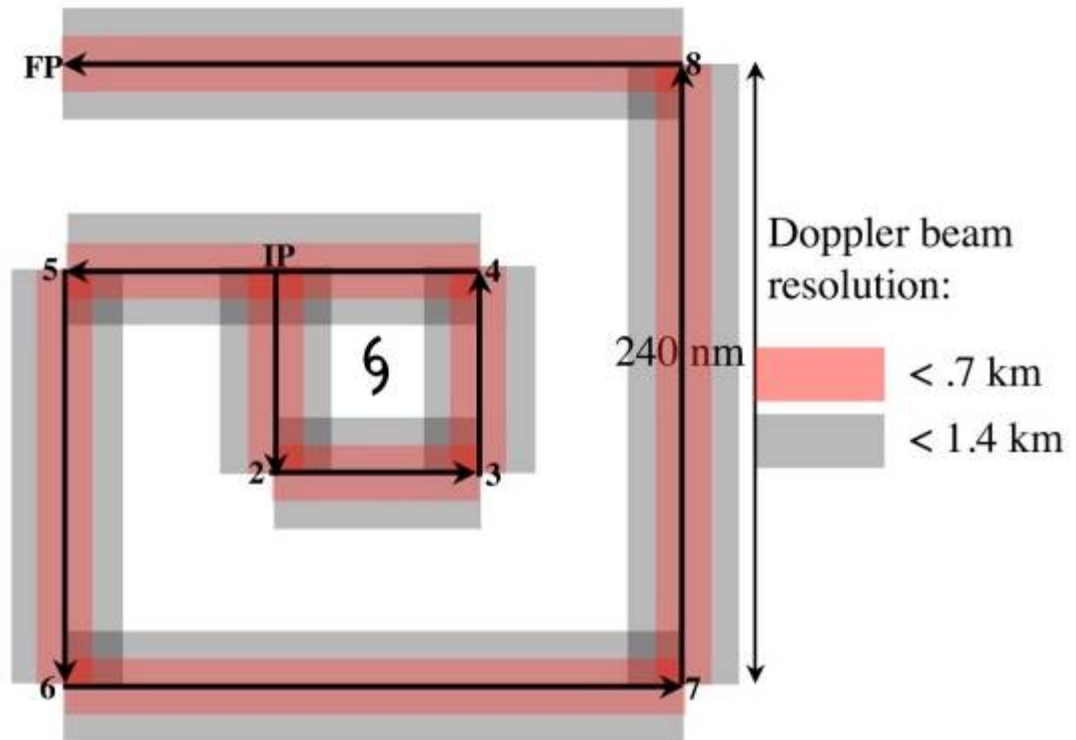


Figure 1a-2: Doppler radar coverage for box-spiral pattern A. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately 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

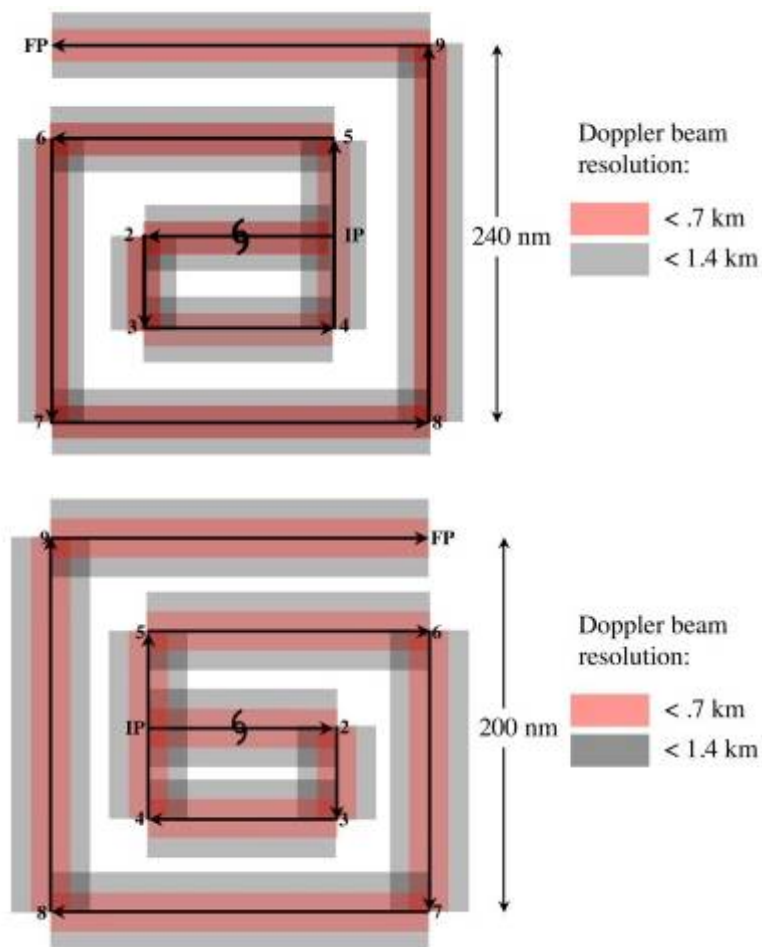


Figure 1a-3: Doppler radar coverage for box-spiral pattern with 200- (top) and 240- (bottom) nm legs. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 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

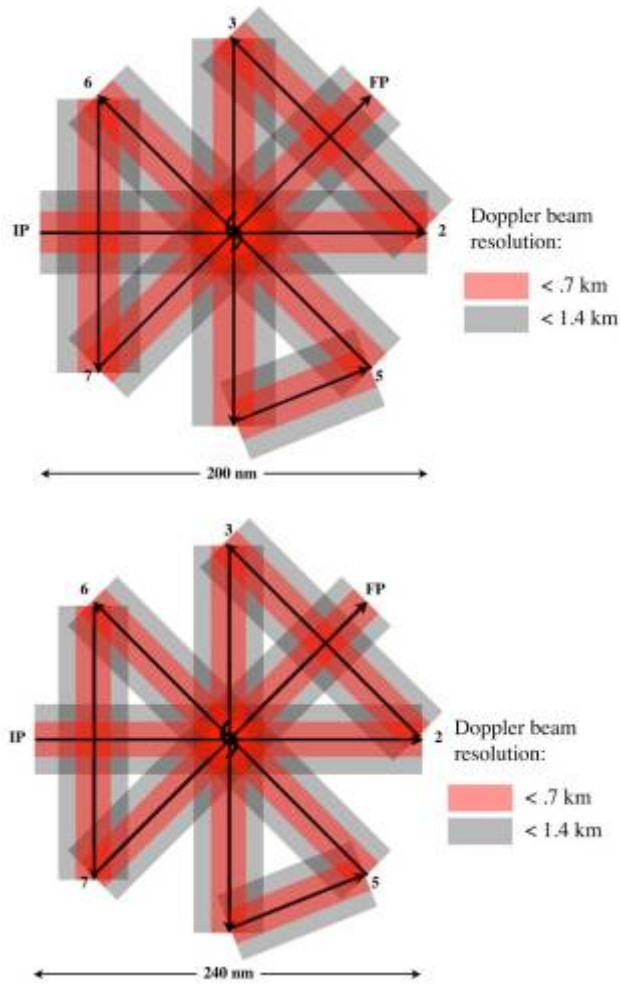


Figure 1a-4: Doppler radar coverage for radial extents of 100 (top) and 120 (bottom) nm of the rotating figure-4 patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent 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

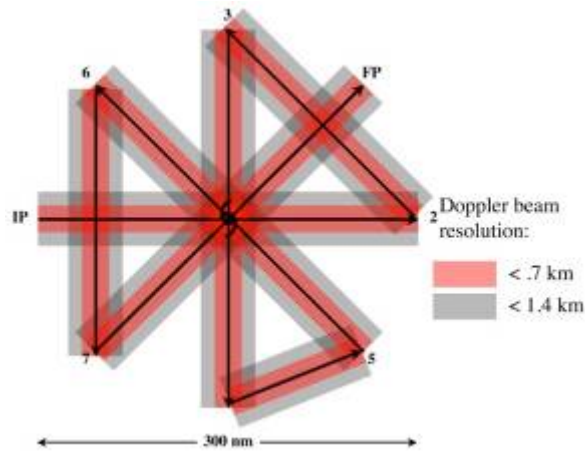


Figure 1a-4 (continued): Doppler radar coverage for 150-nm legs for a rotating figure-4. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

- 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

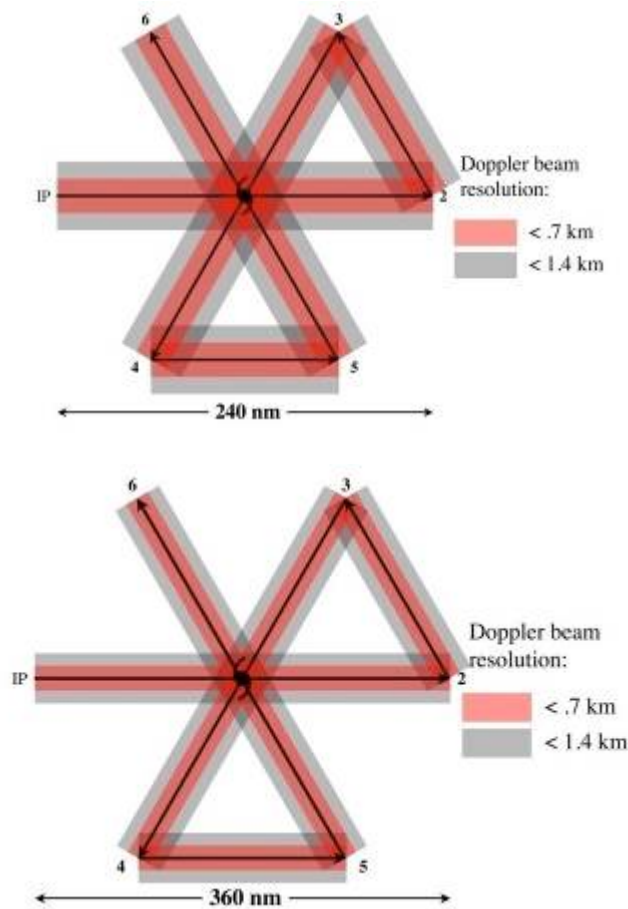


Figure 1a-5: Doppler radar coverage for 120- (top) and 180- (bottom) nm legs for the Butterfly pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 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

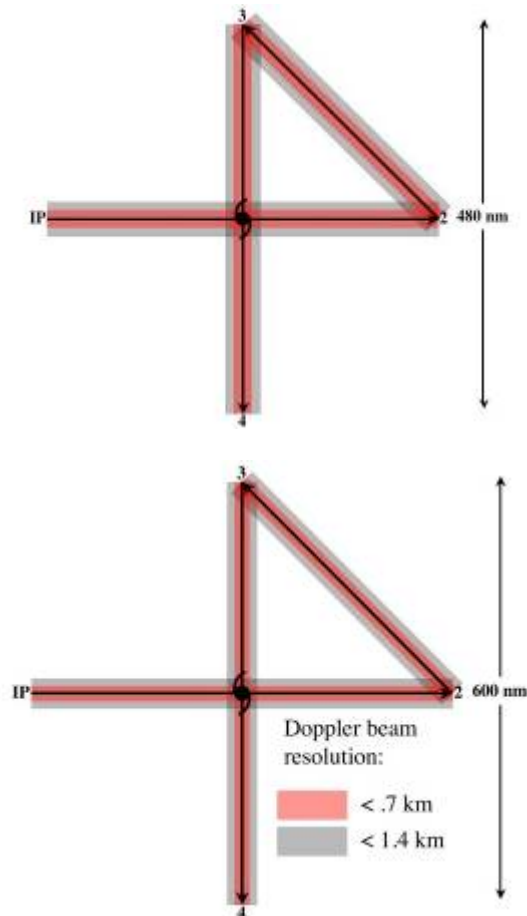


Figure 1a-6: Doppler radar coverage for 300-nm legs for a single figure-4 pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from 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 dropwindsone 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. Dropwindsones 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 2014, 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 2014 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 data 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-tasks surveillance requirements (i.e., sampling the TC environment with GPS dropsondes) and the EMC-tasks 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 2014.

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.

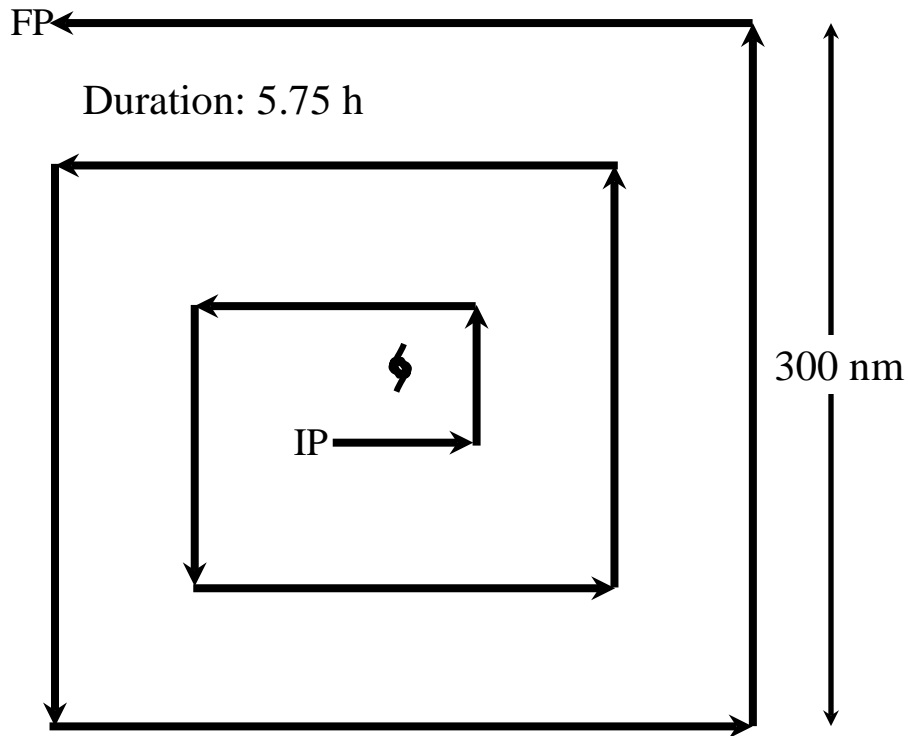


Figure 1b-1: G-IV tail Doppler radar pattern – Square Spiral (outward)

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.

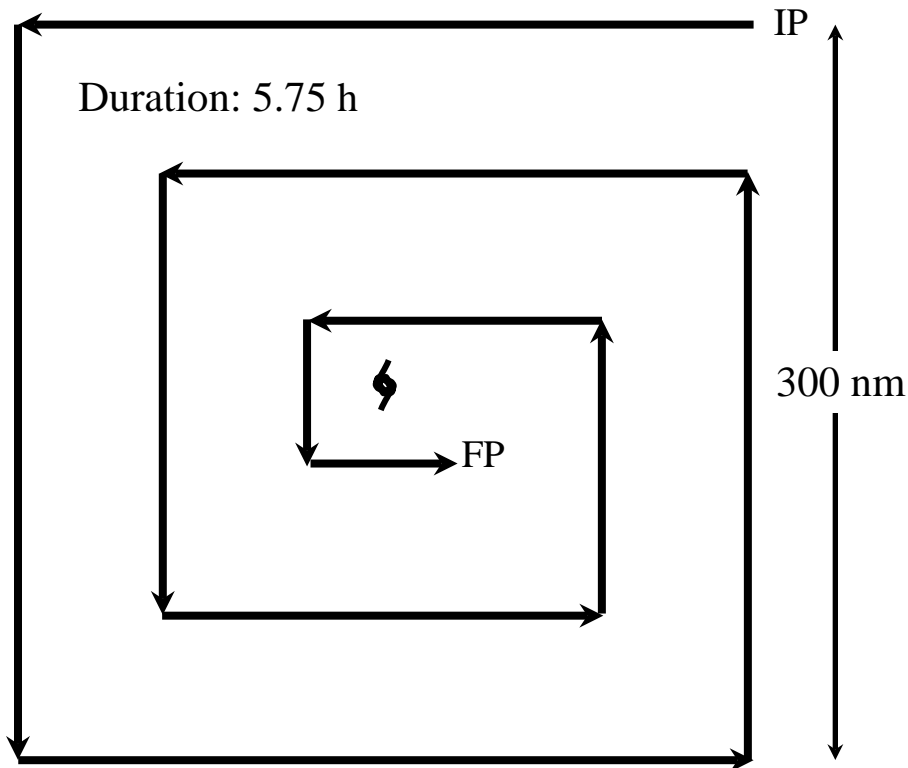


Figure 1b-2: G-IV tail Doppler radar pattern – Square Spiral (inward)

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 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.

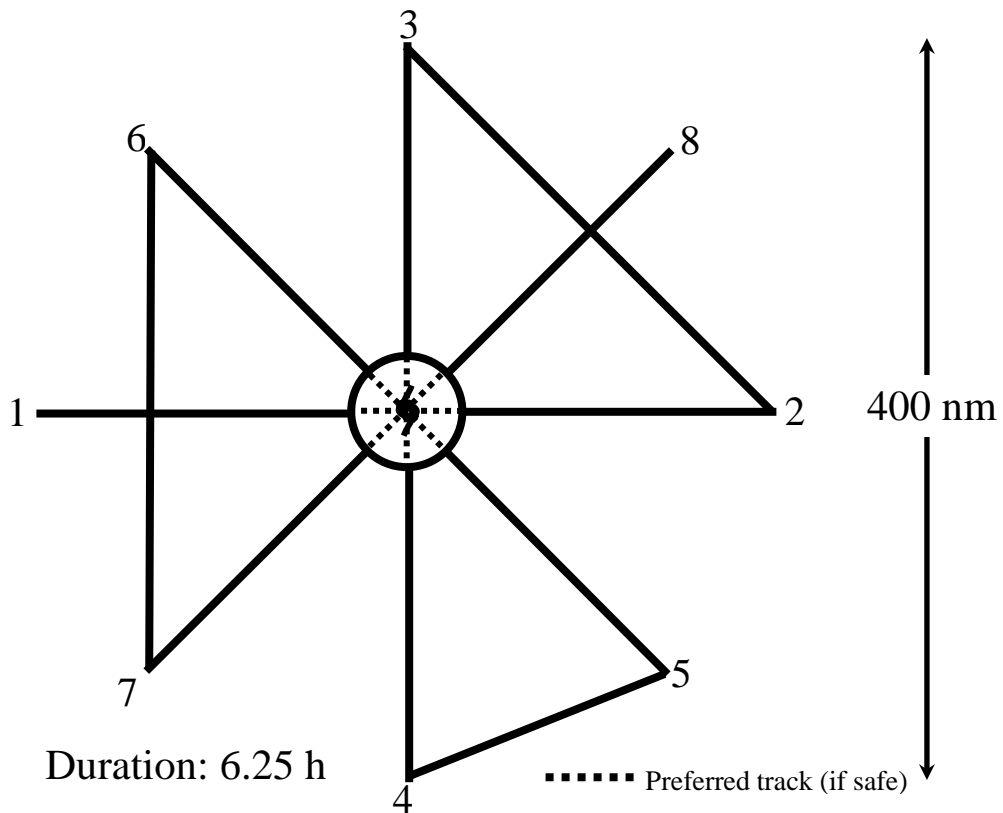


Figure 1b-3: G-IV tail Doppler radar pattern – Rotating Figure-4

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.

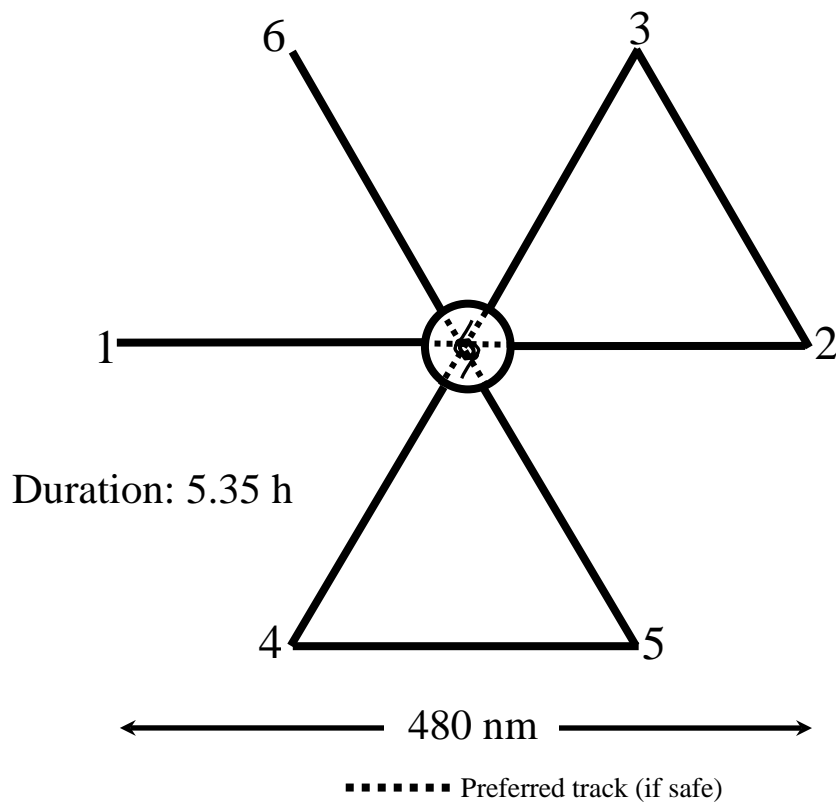


Figure 1b-4: G-IV tail Doppler radar pattern – Butterfly

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.

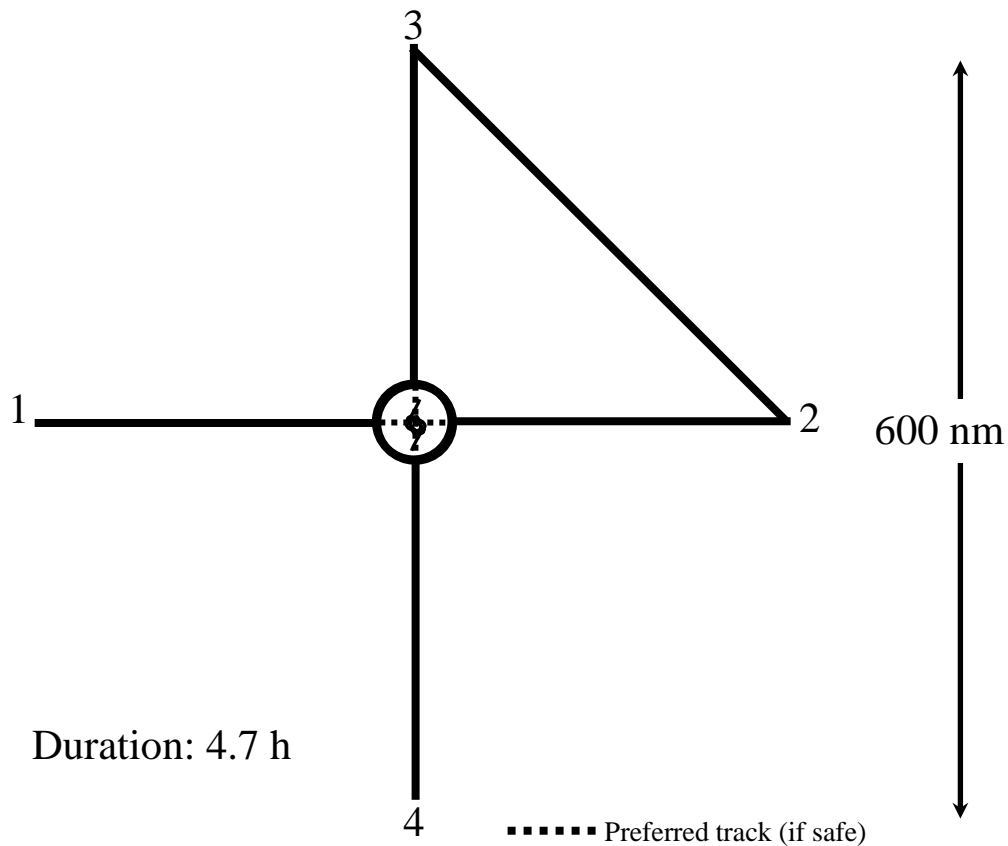


Figure 1b-5: G-IV tail Doppler radar pattern – Single Figure-4

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.

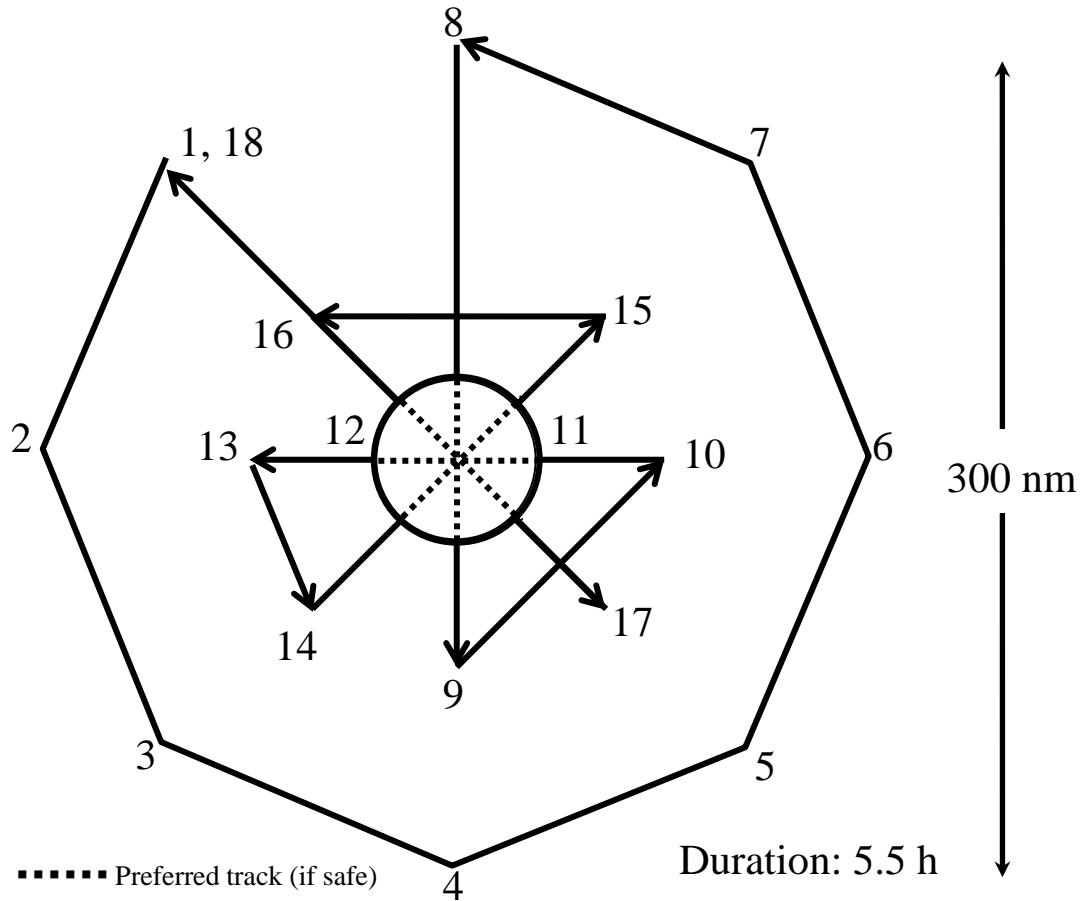


Figure 1b-6: G-IV tail Doppler radar pattern – Surveillance/TDR Combination

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.

2a. Optimizing Observations to Better Evaluate and Improve NOAA’s Hurricane Weather Research and Forecasting Operational Model

Principal Investigator(s): J. Cione, E. Uhlhorn, J. Dunion, S. Gopalakrishnan, V. Tallapragada, R. Lumpkin, R. Rogers, J. Zhang, R. Black, 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, as well as 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 convective activity, hurricane structure and storm intensity change, including:

- Air-sea energy exchange and boundary layer processes
- Convection (storm scale and surrounding environment)
- Dynamic/thermodynamic processes (storm scale and surrounding environment)
- Cloud microphysics

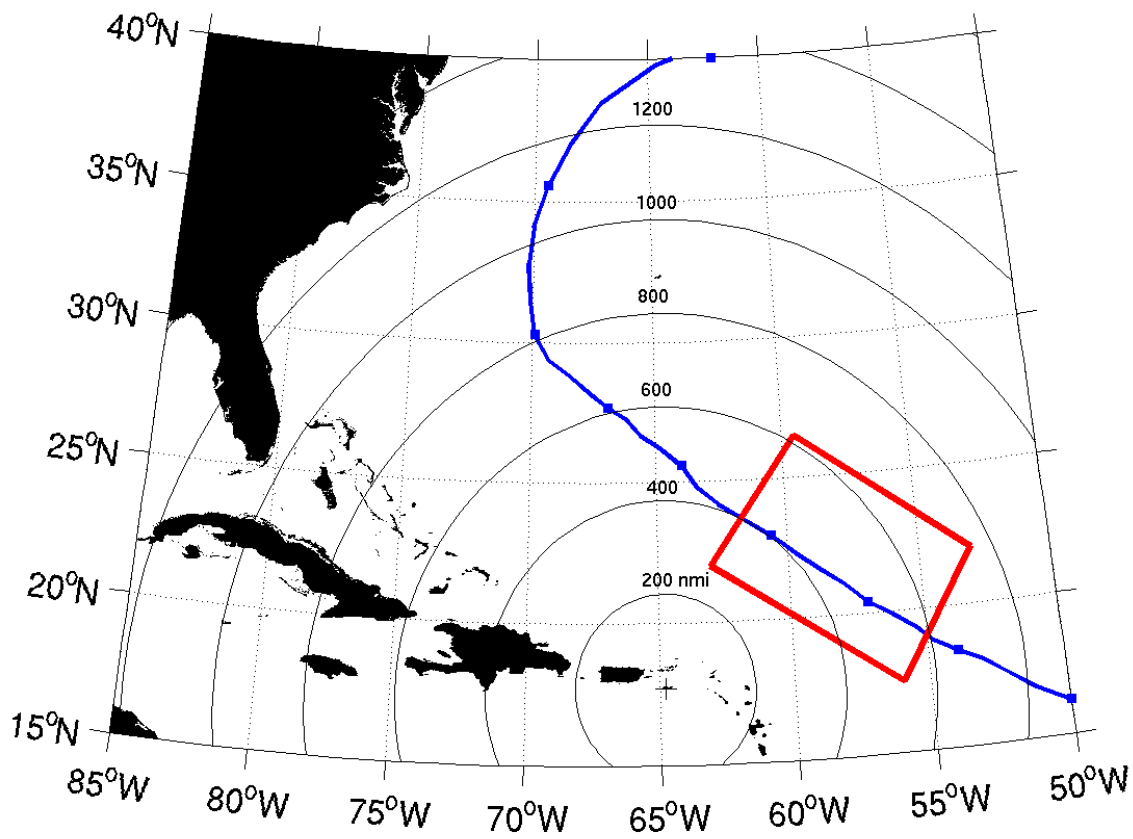


Figure 2a-1: Storm track (blue), and observation region (red box), optimally suited for multi-aircraft experiment. Range rings are 200 nmi relative to forward operating base at STX (TISX). Track marks are spaced every 24 hrs.

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 threatening the U.S. coastline. An optimal geographical situation is shown in Fig. 2a-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.

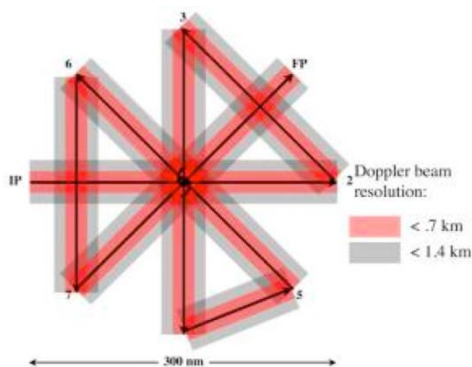
Capturing structure associated with outer TC environment will be primarily the responsibility of the NOAA GIV aircraft (N49RF). One of the preferred patterns that will be employed is the “starfish” configuration already outlined in several existing HFP experiments (most notably in the RI experiment). Another possible pattern that could be utilized is the circumnavigation flight plan currently described in the shear experiment. 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.

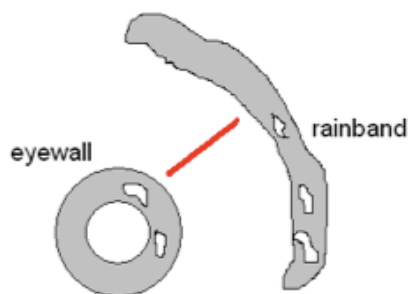
The second P-3 (likely N43RF) would be tasked to sample pre-determined, high-value areas of interest within specified region(s) of the storm.

A visual depiction of the verbal description above follows:

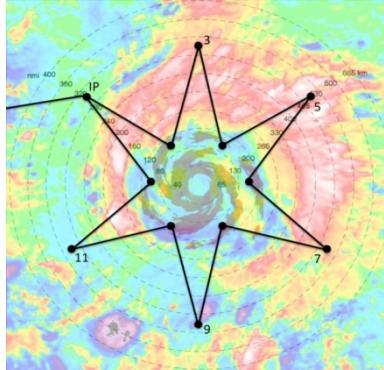
One NOAA P3 → Captures the core, storm scale circulation (e.g. Current TDR mission profiles)



2nd NOAA P3 → Responsible for sampling predetermined areas of interest outside the immediate TC high wind inner core (e.g. Entrainment flux module)



NOAA GIV → Primarily responsible for capturing the tropical cyclone's surrounding larger scale environment



As previously mentioned, the processes that will be targeted include air sea exchange, vertical/horizontal transport resulting from convective activity (including boundary layer entrainment and cloud microphysical processes), interactions with the surrounding environment, and ocean response. These are 3 high-priority research foci for this experiment:

- a) **Air-sea exchange:** At the initiation of the observing period, the pre-storm, in-storm, and post-storm oceanic environment is sampled to estimate horizontal and vertical ocean structure which is forecasted to respond to TC forcing (sampling ideally begins 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 of surface drifting probes in coordination with the 53rd WRS. The pre-storm "field" is designed to extend over a significant area to capture a multi-day event. The Ocean Response Experiment (1), the Hurricane Boundary Layer Entrainment Flux Module (2), the Small Unmanned Aircraft Vehicle Experiment (SUAVE) (4), and the Hurricane Boundary Layer Inflow Module (3) support the pre-storm element of the air-sea exchange focus.

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 estimate surface fluxes. The operational P-3 three-dimensional Doppler winds mission supports the in-storm element of the air-sea exchange focus. Finally, a post-storm survey mission will be conducted to look at 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. The Ocean Response Experiment (1) supports the post-storm element of the air-sea exchange focus.

- b) **TC Inner Core Processes ($R < \sim 150$ km):** The convection-scale P-3 executes one or more experiments/modules to sample convective bursts, outer rain-band structure, boundary layer thermodynamic and kinematic fields, mid-level moisture, boundary layer top entrainment, and surface energy exchanges using a combination of flight-level data, LF radar, tail Doppler radar, W-band radar, Doppler Wind Lidar, GPS dropsondes, and low flying UAS. The Hurricane Boundary Layer Entrainment Flux Module (2), the Hurricane Boundary Layer Inflow Module (3), SUAVE (4), the Doppler Wind Lidar (DWL) Boundary-layer Module (8), Rapid Intensification Experiment (5), Microphysics-Aerosol/Cloud droplet measurement option (6), the Saharan Air Layer Experiment: arc cloud module (7), TC Diurnal Cycle Experiment (10), TC in Shear

Experiment (11) and Convective Burst Module (12) support the TC Inner Core Processes focus of this experiment.

- c) **TC Environment Processes ($R > \sim 150$ km):** The 2nd P-3 and G-IV execute one or more experiments/modules to sample low-level advective transport of moisture from the environment, TC boundary-layer moisture, mid-level moisture, easterly jets and aerosols in the Saharan Air Layer, environmental conditions that promote rapid intensification, diurnal variations in cirrus canopy thermodynamics and outflow, and the impact of convectively driven downdrafts and outflow boundaries on TC structure and the TC boundary layer. In order to promote measurements of the impact of the environmental moisture and vertical wind shear on the storm, the G-IV aircraft is tasked with deploying GPS dropwindsondes between 200 and 400 km distance from the storm center. The general flight pattern consists of quasi-radial legs to and from the annulus limits around the storm. SUAVE (4), the Hurricane Boundary Layer Entrainment Flux Module (2), the Hurricane Boundary Layer Inflow Module (3), the Doppler Wind Lidar (DWL) Boundary-layer Module (8), Rapid Intensification Experiment (5), Microphysics-Aerosol/Cloud droplet measurement option (6), the Saharan Air Layer Experiment: arc cloud module (7), the Doppler Wind Lidar (DWL) SAL Module (9), the TC Diurnal Cycle Experiment (10), TC in Shear Experiment (11) and the Convective Burst Module (12) support the TC Environmental Processes focus of this experiment.

There are several research experiments/modules that support the air-sea interaction, TC Inner Core Processes, and TC Environment Processes foci of this overarching experiment. These experiments/modules include:

1) **TC-Ocean Response Experiment** (Uhlhorn, Lumpkin, Centurioni, Shay)

Goal: To observe and improve our understanding of the upper-ocean's response to near-surface wind forcing during TC passages. Specific objectives are to: 1) Quantify the influence of the underlying ocean on atmospheric boundary layer thermodynamics and ultimately TC intensity; and 2) Document the capabilities of the operational coupled model forecast system to accurately capture and represent these processes. Refer to the HFP TC-Ocean Response experiment for additional details.

Model evaluation component: Capturing accurate estimates of ocean response to TC forcing is critically important in a coupled atmosphere-ocean modeling system. This module will help better quantify model performance as it relates to ocean model initialization, storm-scale upper ocean cooling and post storm, cool wake realization (which, in turn, could impact future tropical systems that traverse similar ocean environments).

2) **Hurricane Boundary Layer Entrainment Flux Module** (J. Zhang, G. Barnes)

Goal: Directly measure turbulent fluxes near the top of the inflow layer. Determine the air-sea fluxes both as a residual to an energy budget and via the bulk aerodynamic formulae. Refer to HFP Hurricane Boundary Layer Entrainment Module and SUAVE (module 2) for additional details.

Model evaluation component: Turbulent fluxes are the key boundary layer conditions for numerical models. How energy is transported in the hurricane boundary layer is crucial to the hurricane maintenance and intensification. Observations that are collected during this experiment module will be used to evaluate the robustness of the operational coupled model forecast system (e.g. HWRF) to represent turbulent fluxes and energy budget in the inflow layer.

3) **Hurricane Boundary Layer Inflow Experiment** (J. Zhang, E. Uhlhorn, J. Cione)

Goal: Directly measure the thermodynamic and kinematic structure of the hurricane inflow layer radially and vertically to the best extent possible. Refer to the HFP Boundary Layer Inflow experiment and SUAVE (module 3) for additional details.

Model evaluation component: 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. Improved documentation of the storm inflow layer will enable detailed comparisons with numerical simulations. These comparisons should lead to subsequent improvements in physical representativeness of the inflow layer in operational models.

4) **SUAVE** (Cione)

Goal: utilize observations from unmanned aerial vehicles to enable enhanced high resolution comparisons between tropical cyclone boundary observations of temperature, moisture and wind with similar

thermodynamic and kinematic output from NOAA's regional and global operational models. Refer to the HFP SUAVE for additional details.

Model evaluation component: Given the inherent difficulty of flying manned aircraft at very low altitudes in a tropical cyclone, utilization of low altitude UAS has drawn significant interest in recent years. Given the preponderance of 'instantaneous' data collection within this region of the storm (GPS, SFMR), UAS offer a unique opportunity to expand beyond today's limited data collection techniques by continuously sampling pressure, temperature winds and moisture within the low-level hurricane boundary layer environment. Such efforts, should improve future model initialization and validation efforts.

5) **RAPX** (Kaplan, Rogers, Dunion)

Goal: 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. Note: Will require modification to a 24h aircraft refresh cycle. Refer to the HFP RAPX for additional details.

Model evaluation component: Recent analyses of airborne Doppler and dropsonde data have shown statistically significant differences in both the environmental and the inner-core structures of TC's that undergo RI from those that remain steady state. Such structures include the inner- and outer-core vorticity field, inflow depth and strength, and number and radial distribution of convective bursts. The data collected as a part of this experiment will span scales ranging from the environmental down to the convective and PBL scale. It will enable an evaluation of various features of the operational modeling system, including the sufficiency (or lack thereof) of the horizontal resolution, and the microphysical and planetary boundary layer parameterization schemes.

6) **Microphysics - Aerosol/Cloud droplet measurement option** (B. Black)

Goal: determine the natural range and number concentrations of the sub-cloud aerosol that is CCN in hurricanes that are far from land, unaffected by pollutants using new droplet spectra probes, a cloud liquid water meter, the Droplet Measurement Technologies (DMT) dual-chamber CCN counter, a DMT wide-band Integrated Bio-Aerosol sensor (WIBS-IV) and a CN counter. Refer to the HFP Microphysics experiment for additional details.

Model evaluation component: The observations collected herein will be utilized in due course for the evaluation of the HWRF model microphysics parameterizations. As presently configured, these parameterizations assume a fairly small number concentration of cloud droplets in the storm. These numbers derive from observations in fair-weather marine cumuli conducted more than 30 years ago. Such an assumption might not be valid in a hurricane, where copious sea-salt aerosols are generated, as this affects the colloidal stability of the clouds.

7) **SALEX-Arc Cloud Module** (Dunion)

Goal: Collect observations in mid-level dry layers (e.g. the SAL) that are hypothesized to be a necessary ingredient for the formation of strong downdrafts and subsequent outflow boundaries & arc clouds. Target observations ahead of and behind arc cloud features to sample the horizontal gradients of temperature, moisture, and winds (e.g. outflow) from ~600 hPa to the surface. Refer to the HFP SALEX experiment for additional details.

Model evaluation component: Arc clouds in the periphery of TCs represent the leading edge of large outflow boundaries that bring cool, dry air and enhanced outflow into the lower levels of the atmosphere. These rarely observed environments are formed in the presence of precipitation falling through mid-level dry air and are hypothesized to limit short-term TC intensification. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the SAL and arc cloud environments.

8) **Doppler Wind Lidar (DWL) Boundary-layer Module** (J. Zhang)

Goal: Characterize the distribution and variations of kinematic boundary layer heights in hurricanes. Identify and document the characteristics of organized eddies such as boundary-layer rolls. Refer to the HFP DWL Boundary Layer module for additional details.

Model evaluation component: Boundary layer rolls are quasi-two dimensional features that can affect the surface flux transport and modulate the mean boundary layer structure. Observations that are collected during

this experiment module will be used to evaluate the robustness of the operational coupled model forecast system (e.g. HWRF) to represent boundary layer rolls.

9) Doppler Wind Lidar (DWL) SAL Module (Dunion)

Goal: Characterize the suspended Saharan dust and mid-level (~600-800 hPa) easterly jet that are associated with the 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 region ($R \approx 150$ km). Refer to the DWL SAL module for additional details.

Model evaluation component: The SAL's mid-level easterly jet and low- to mid-level dry air will be sampled using a combination of observations collected from GPS dropsondes and the P3DWL. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the SAL's low humidity and embedded mid-level easterly jet.

10) TC Diurnal Cycle Experiment (Dunion)

Goal: Sample the thermodynamic and kinematic environment of 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. 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., $200 \text{ km} < \text{radius} \leq 400 \text{ km}$) for systems that have exhibited signs of diurnal pulsing in the previous 24 hours. Employ the NOAA G-IV jet to sample the temperature, moisture, and winds at the TC cirrus canopy level before, during, and after the time of local sunset. Note: Will require modification to a 24h aircraft refresh cycle. Refer to the HFP TC Diurnal Cycle experiment for additional details.

Model evaluation component: The predictable propagation of TC diurnal pulses in both space and time each day makes them fairly easy to sample at various radii around the storm. Thermodynamic and kinematic observations will be made of the diurnal pulses from the surface to the cirrus canopy and will include outflow layer sampling, as well as areas of enhanced convergence, moisture, or vertical motions at various levels of the troposphere. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the TC diurnal cycle.

11) TC in Shear Experiment (Reasor)

Goal: Examine changes in the structural evolution, convective asymmetry, intensity change, and moisture envelope (TC isolation) of TCs experiencing a significant increase in environmental wind shear. Note: Will require modification to a 24h refresh cycle. Refer to the HFP TC in Shear experiment for additional details.

Model evaluation component: It is widely accepted that vertical shear can have a significant impact on tropical cyclone structure and intensity change. A goal of this experiment is to better diagnose, quantitatively how, and to what extent, vertical shear effects hurricane structure, intensity and intensity change.

12) Convective Burst Module (Rogers)

Goal: 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. Refer to the HFP Convective burst module for additional details.

Model evaluation component: The data collected will be useful for evaluating the model-generated fields of vertical velocity, hydrometeor concentration, and reflectivity. Vertical profiles of the structure and high-frequency evolution of the mean and distribution (e.g., via contoured frequency by altitude diagrams) of these fields, along with derived properties such as vertical mass flux, will be calculated from the airborne radar. These fields will be compared with model output to evaluate the performance of the microphysical parameterization scheme and provide a benchmark for comparing potential changes to the formulation of the microphysical and planetary boundary layer parameterizations.

2b. TC Ocean Response

Principal Investigator(s): Eric Uhlhorn (HRD), Joe Cione (HRD), Rick Lumpkin (PhOD), Nick Shay (U. Miami/RSMAS), Gustavo Goni (PhOD)

Collaborators: Luca Centurioni (SIO), George Halliwell (PhOD), Elizabeth Sanabia (USNA)

HRD Point of Contact: Eric Uhlhorn

Primary IFEX Goals:

- 1 – Collecting observations that span the TC lifecycle in a variety of environments for model initialization and evaluation
- 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 improving understanding of the ocean's role in air-sea interaction and controlling TC intensity by making detailed measurements of these processes in storms. 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 to:

1. Quantify the influence of the underlying ocean on atmospheric boundary layer thermodynamics and ultimately storm intensity.
2. Quantify the capabilities of the operational coupled model forecast system to accurately capture and represent these processes

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

Rationale:

Ocean effects on storm intensity. Upper ocean properties and dynamics 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.

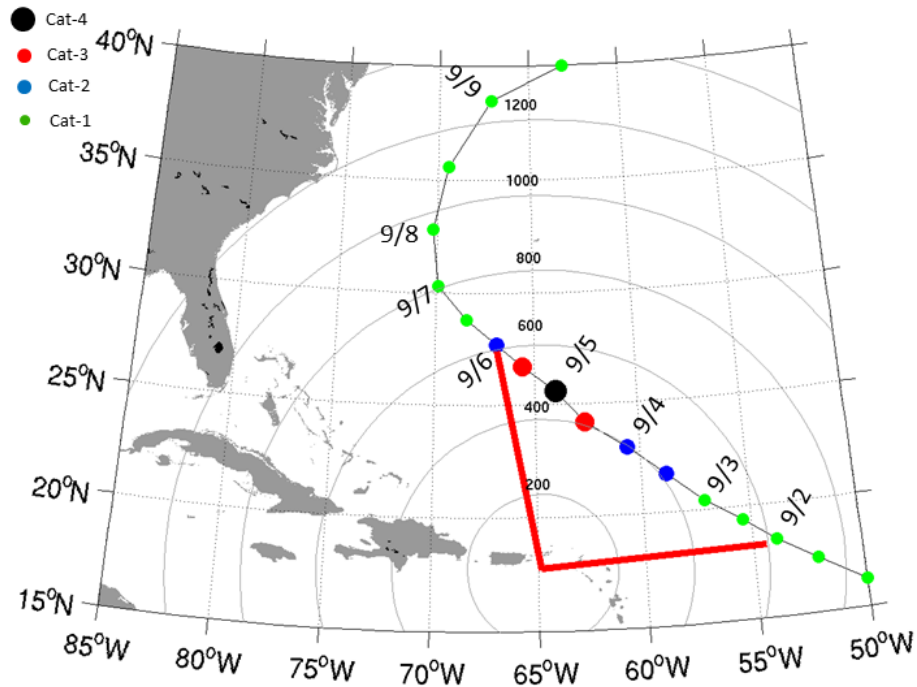


Figure 2b-1: Storm track with locations plotted every 12 hours. of Range rings are 200 nmi relative to forward operating base at St. Croix, USVI (STX/TISX), and red line delineates storm locations within 600 nmi of STX. In this example, the storm center remains within 600 nmi for 4 days.

This multi-aircraft experiment is ideally conducted in geographical locales that avoid conflict with other operational requirements, for example, at a forward/eastward-deployed base targeting a storm not imminently threatening the U.S. coastline. As an example, an optimal situation is shown in Fig. 2b-1, with missions operating from St. Croix, USVI. A TC of at least minimal hurricane intensity is desired. In this example, the hypothetical storm remains within 600 nmi (a reasonable maximum distance) for four days, and at no time is forecasted to be a threat to land, including the U.S. coast.

2b-1. Expendable profiler surveys from P-3 aircraft

Flight sequence:

Pre-storm: To establish the pre-storm upper ocean thermal and mass structure prior to a storm's arrival, a pre-storm expendable survey will be conducted. This mission will consist of deploying a large grid of AXCTDs/AXBTs to measure the three-dimensional temperature and salinity fields (Fig. 2b-2). This flight would occur **48 hours prior to storm arrival**, based primarily on the forecasted track, and optimally covers the forecast cone-of-error. A total of **50-60 probes** would be deployed, depending on mission duration, and spaced approximate 0.5 deg. apart. The experiment is optimally conducted where horizontal gradients are relatively small, but AXCP probes may be included if significant gradients (and thus currents) are expected to be observed. Either P-3 aircraft may be used as long as it is equipped with ocean expendable data acquisition hardware.

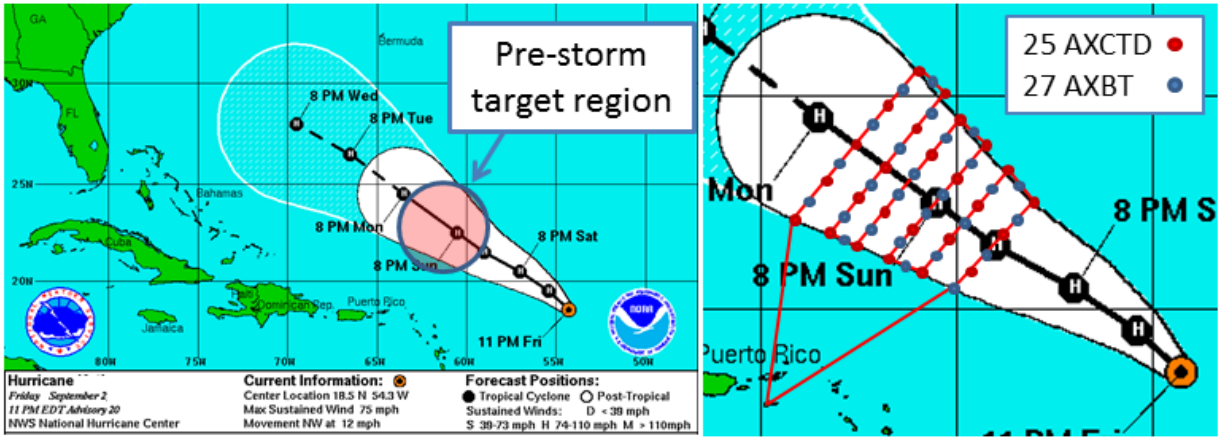


Figure 2b-2: Left: NHC official forecast track, which pre-storm ocean sampling region highlighted. Target region is centered ~48 hours prior to forecast arrival of storm. Right: P-3 flight track (red line) and ocean sampling pattern consisting of a grid of AXCTD/AXBT probes. Probes are deployed at ~0.5 deg. intervals. Total time for this pattern is estimated to be ~9 hours.

In-storm: Next, a mission is executed within the storm over the ocean location previously sampled (Fig. 2b-3). This flight shall be conducted by the **P-3 carrying the Wide-swath Radar Altimeter (WSRA)** for purposes of mapping the two-dimensional wave field. The flight pattern should be a **rotated Figure-4**, and up to **20 AXBTs** should be deployed in combination with GPS dropwindsondes. Note that other experimental goals can and should be addressed during this mission, and a multi-plane mission coordinated with the other P-3, as well as G-IV, is desirable.

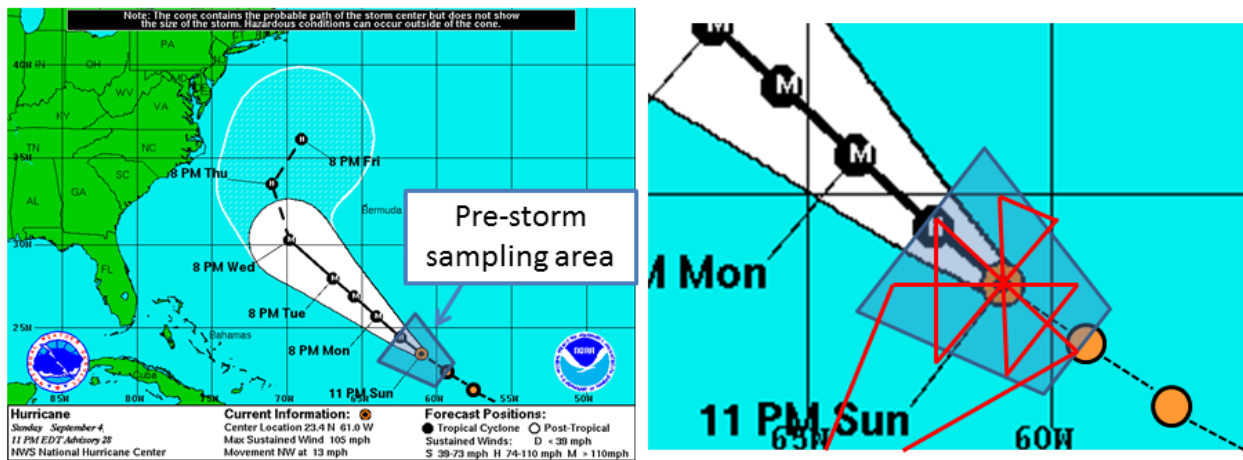


Figure 2b-3: Left: NHC official forecast track at time of in-storm mission, with pre-storm sampled region highlighted. Right: P-3 in-storm flight pattern centered on storm and over previously-sampled ocean area. Typical pattern is expected to be a rotated Fig-4. Total flight time ~8 hrs.

Post-storm: Finally, a post-storm expendable survey shall be conducted over the same geographical location to assess ocean response, with slight pattern adjustments made based on the known storm track (Fig. 2b-4). Approximately **60-70 probes** would be deployed (depending on duration limits), consisting mainly of **AXBTs/AXCPs** to map the three-dimensional temperature and currents, ideally 1-2 days after storm passage. In

the Fig. 2b-4 example, the pattern extends 470 km along the storm track, which in this example is $\sim 0.75\Lambda$, where $\Lambda = 2\pi V/f$ is the inertial wavelength. Ideally, up the pattern should extend up to 1Λ to resolve a full ocean response cycle. The storm speed V and flight duration limits will dictate whether this is possible. As for the pre-storm survey, either P-3 may be used.

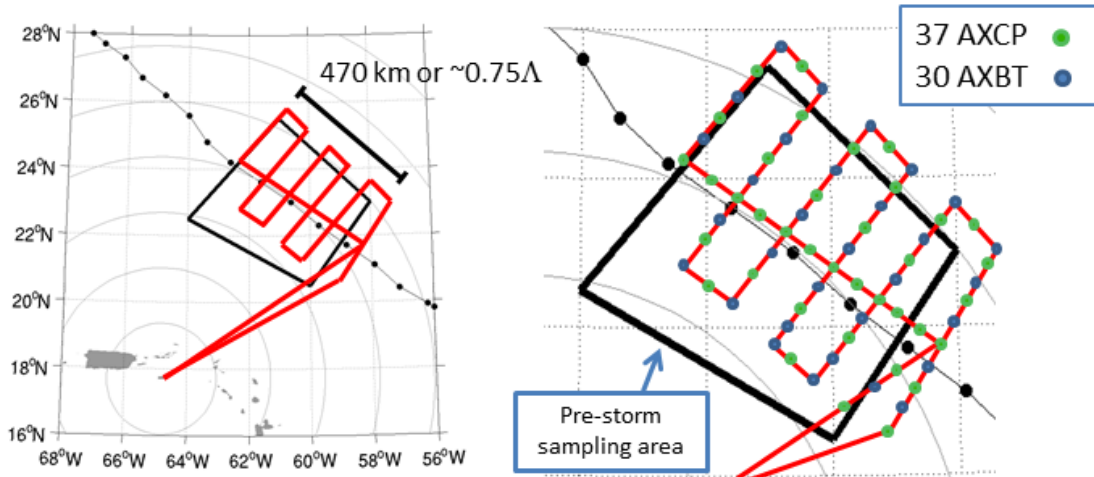


Figure 2b-4: Left: Post-storm ocean sampling flight pattern (red line), over previously-sampled area (black box). In this example, the pattern extends around 470 km in the along-track dimension, or around 0.75 of a near-inertial wavelength. Right: Flight pattern with expendable drop locations, consisting of a combination of AXCP and AXBT probes.

2b-2. Coordinated float/driftedeployment by AF C-130

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. 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.

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. A number of 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.

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 2b-5 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, and the lines are approximately in the same location as the pre-storm P-3 expendable probe survey. Instrumentation should be deployed 24-48 hours prior to storm arrival. 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- The in-storm mission will be conducted by the P-3 as previously described. Efforts will be made to deploy AXBTs during the mission near the locations of drifters/floats as reported in real time. 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.

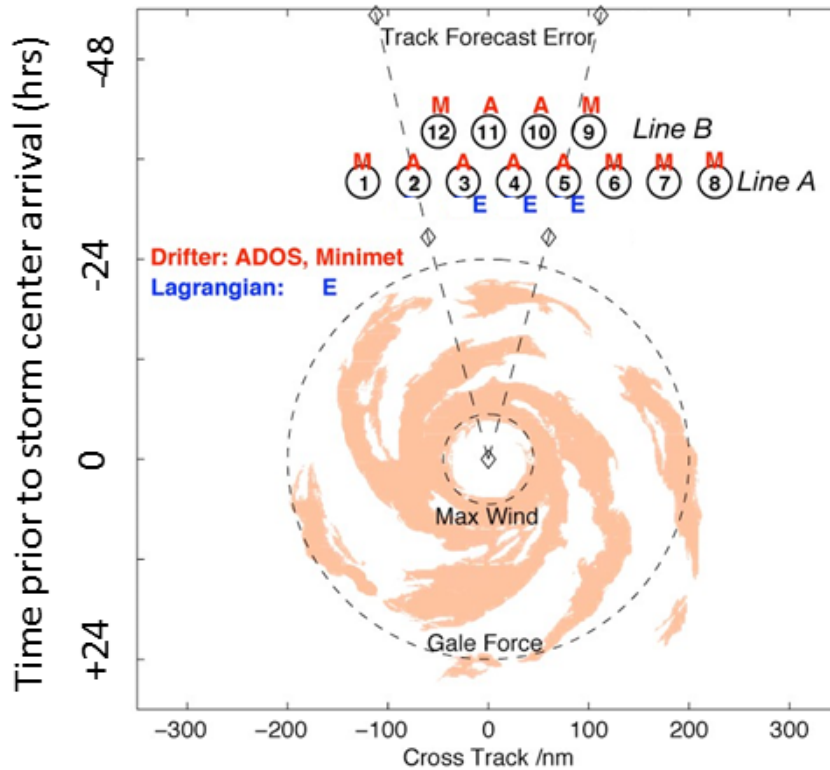


Figure 2b-5: Drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of ADOS thermistor chain (A) and minimet (M) drifters, and EM-APEX Lagrangian floats (E). Two items are deployed at locations 3, 4 and 5, and one item elsewhere.

2b-3 Ocean glider deployments

To complement the aircraft-based experiments, it is also a goal to test the new observation capabilities of ocean gliders in hurricanes. For the first time, current velocity profiles will be obtained from Seagliders to assist

hurricane forecast models to reproduce the key ocean dynamic processes associated with tropical storm-induced surface ocean cooling. The main objectives of the proposed work are to implement upper ocean observations from Seagliders, to evaluate their impact on and to improve: (1) hurricane intensity forecasts and (2) hurricane seasonal forecasts; using a combination of these new sustained observations, targeted observations, data analysis, and current NOAA operational forecast models. Of critical importance will be the joint analysis of the data collected through this project with those obtained through targeted observations, WP-3D and WC-130J flights that deploy a suite of atmospheric sensors.

3.1. Ocean Observations

A pilot array of two Seagliders will be deployed to carry out sustained and targeted upper-ocean profiling of temperature (T), salinity (S), and current velocities (u,v) in the AWP region (Figure 2b-6). Seagliders are cost-effective observational underwater vehicles used for targeted and sustained upper-ocean T, S, and (u,v) observations, they operate easily in open waters, even under hurricane strength winds, and can be navigated across moderately strong currents. The Seagliders are durable, autonomous, and have a low-drag and hydrodynamic shape and use battery power to control their buoyancy to move vertically, and use their wings to guide themselves forward along a remotely programmed trajectory (Eriksen et al. 2001). When their batteries run out, the Seagliders can be recovered and then refurbished and redeployed immediately. Their small size (~2m long) and low weight (~50 kg) allow for an easy deployment and recovery by two people from a small vessel. Seagliders transit at approximately 20-25 km/day while executing 8-10 T-S profiles/day to 1,000 meters and of (u,v) to 200m. They can navigate approximately 4,000 km and collect and transmit about 1,600 profiles during a 6- month deployment. While surfaced, they can also download any new instructions for altering the navigation route. Data will be transmitted in real-time into the GTS. In this work, each Seaglider will provide data of approximately 2,700 profiles per year.

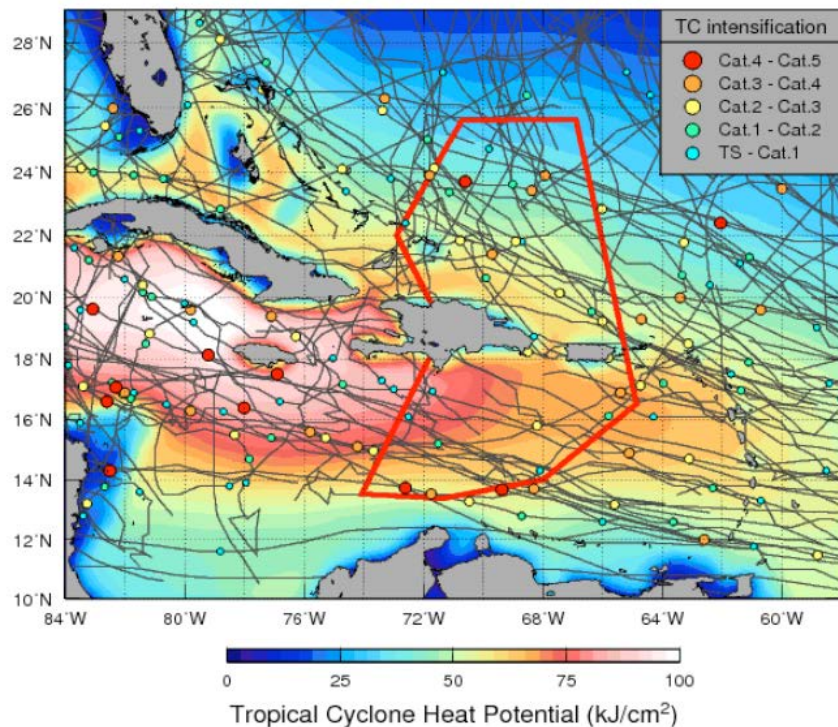


Figure 2b-6. The two regions (bounded with red lines) where Seagliders will be deployed. Tracks of Cat. 1-5 cyclones (in grey) in a region of the AWP during 1993-2011, with circles indicating the location of their intensifications. The background color is the Tropical Cyclone Heat Potential (proportional to the upper ocean heat content).

2b-4 AXBT deployments by TROPIC on AF C-130

In addition to the P-3 expendable ocean probe deployments described above, additional ocean temperature profiles will be obtained by AFRC WC-130J aircraft as part of the Training and Research in Oceanic and Atmospheric Processes in Tropical Cyclones (TROPIC) program under the direction of CDR Elizabeth Sanabia, Ph.D. (USNA). Several overlapping mission goals have been identified providing an additional opportunity for collaboration and enhancing observational data coverage. See www.onr.navy.mil/reports/FY11/mmsanabi.pdf for details.

3a. 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 2014 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 (SAL). 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.

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 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 region (R=~150 km);
- Quantify the capabilities of the operational coupled model forecast system to accurately capture and represent both the SAL's mid-level dry air (sampled by GPS dropsondes) and its ~600-800 mb mid-level easterly jet (sampled by GPS dropsondes and the P3DWL);

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;

Model Evaluation Component:

The SAL's mid-level easterly jet and low- to mid-level dry air will be sampled using a combination of observations collected from GPS dropsondes and the P3DWL. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the SAL's low humidity and embedded mid-level easterly jet. Data assimilation (DA) provides a natural platform to compare model output to observations by accounting for the underlying uncertainties of observations and model in a statistical framework. Normalization of model-observation differences by the total expected uncertainty allows for the identification of areas where lack of model performance is statistically the most

significant. Furthermore, the high-resolution, three-dimensional analyses that DA produces provide the best estimate of the SAL's thermodynamic and kinematic structure within the modeling framework. Such analyses can be directly compared to operational model output to understand how well the SAL structure is represented in operational models and the consequences for subsequent model forecasts.

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, SALEX-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 be determined on a case by case basis at the LPS's discretion.

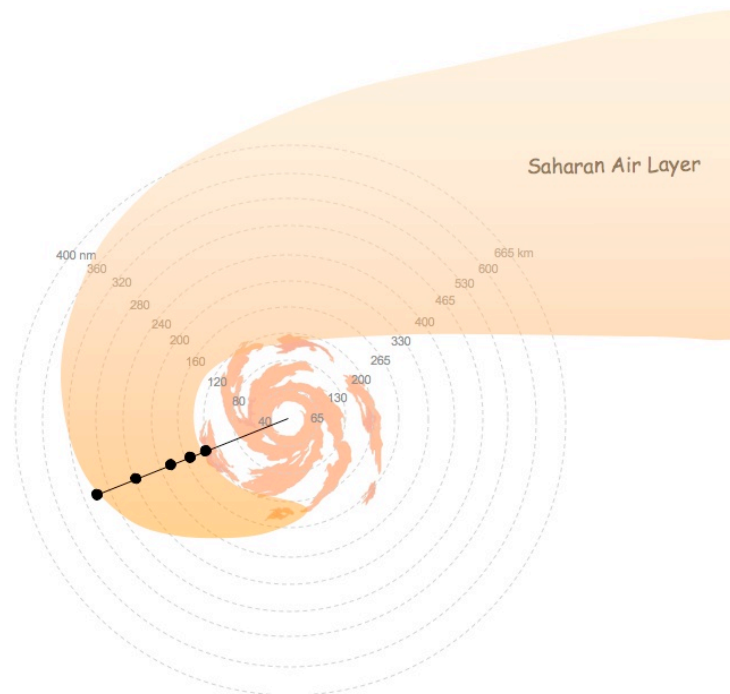


Figure 3a-1: Sample WP-3D flight track during the ferry to/from the storm and GPS dropsonde points for the P-3DWL SAL module.

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 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 26 Aug-29 Sep 2014. 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.

Potential Flight Modules



Figure 3a-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.

3b. DWL Boundary Layer Module

Principal Investigator(s): Jun Zhang and David Emmitt (SWA)

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;

Program Significance:

The boundary layer has been identified in prior studies to be of critical importance to hurricane intensification (e.g., Emanuel 1997; Smith et al. 2009). Despite the critical nature of this environment, routine collection of kinematic and thermodynamic observations in the boundary layer remains elusive (Black et al. 2007). Currently, boundary layer observations are very limited since the primary source of data is from point-source GPS dropsonde measurements (Zhang et al. 2013). The lack of data coverage at low levels is a primary reason why hurricane boundary layer structure and associated physical processes remain poorly represented in today's operational hurricane models (Zhang et al. 2012).

The DWL on NOAA P3 (N42) aircraft measures three-dimensional wind velocities with ~50 m vertical resolution and ~2 km horizontal resolution. This is a new tool for boundary layer observations in addition to the existing GPS dropsonde and Doppler radar. Airborne Doppler radars provide three-dimensional wind estimates only where there is precipitation, whereas a DWL can provide wind estimates wherever there are aerosols and very little cloudiness. The DWL will be evaluated as an additional observing system that can increase the spatial coverage of wind estimates to improve the initial state of the HWRF model, and to reduce model biases through improved representation of the boundary layer physical processes.

Objectives:

The main objectives of the DWL Boundary-layer Module are to:

- Characterize the distribution and variations of kinematic boundary layer heights in hurricanes;
- Identify and document the characteristics of organized eddy such as boundary-layer rolls;
- Quantify the capabilities of the operational hurricane models to accurately capture and represent boundary layer rolls.

Model Evaluation Component: Boundary layer rolls are quasi-two dimensional features that can affect the surface flux transport and modulate the mean boundary layer structure. Observations that are collected during this experiment module will be used to evaluate the robustness of the operational coupled model forecast system (e.g. HWRF) to represent boundary layer rolls.

Mission Description:

This module can be included in any of the following HRD research missions or experiments: TC Genesis Experiment, Shear Experiment, Saharan Air Layer Experiment, Arc Cloud Module or TC Landfall and Inland Decay Experiment or as part of operational NHC-EMC-HRD Tail Doppler Radar (TDR) missions.

This module will target sampling of the kinematic structure of the boundary layer with focus on investigating the characteristics of the boundary layer height and coherent structures. The module can be combined with other experiments or modules, as it does not necessarily require a specific flight track. If the DWL boundary-layer

module is given the priority, a box module with duration of 20-25 minutes (**Fig. 3b-1**) would be the preferred experimental setup. GPS dropsonde and flight-level data will be used to quantitatively evaluate the quality of the DWL measurements. The DWL will scan in the following modes with downward looking direction. The first is a full scan mode. The second mode follows a sector scanning strategy that allows an increase in the horizontal resolution of the wind retrieval. The optimal flight altitude is ~ 500 m when possible (or as low as safety permits). Cloud avoidance is crucial for the module which may require adjusting the flight altitude when cloud is encountered.

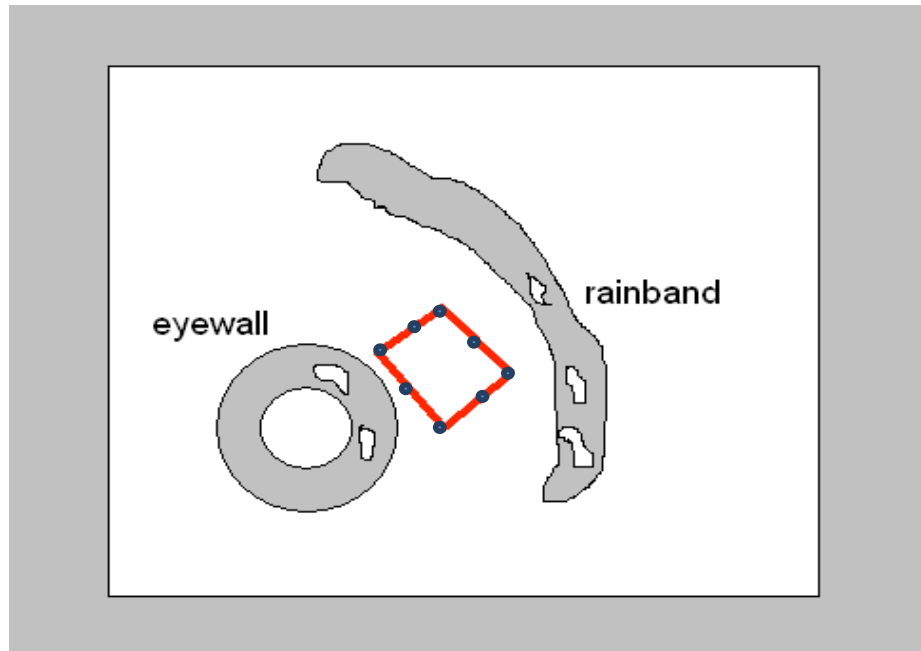


Figure 3b-1: Box module (20-25 minutes) for DWL observations at altitudes between 500 m and 1500 m as low as safety permits. The blue dots show the locations for releasing dropsondes.

References:

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4. 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, C_d : 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.

5. Small Unmanned Aerial Vehicle Experiment (SUAVE)

Principal Investigator: J. Cione (HRD)

Co-Investigator(s): Module 1a: S. Aberson (HRD); Module 2: J. Zhang (HRD); G Barnes (UH); Module 3: J. Zhang; E. Uhlhorn (HRD)

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

Direct link to the HFP model evaluation experiment: Conducting the UAS modules listed in this experiment (stand alone or as part of other HFP efforts) will enable enhanced high resolution comparisons between tropical cyclone boundary observations of temperature, moisture and wind with similar thermodynamic and kinematic output from NOAA's regional and global operational models.

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 Sensintel Corporation (formerly 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) similar to systems currently used by NOAA on the GIV and P-3 dropsonde systems. Unlike the GPS dropsonde 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 (e.g. Aerosonde). By leveraging existing NOAA manned aircraft assets, Coyote operations significantly reduce 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 Figure 5-1.

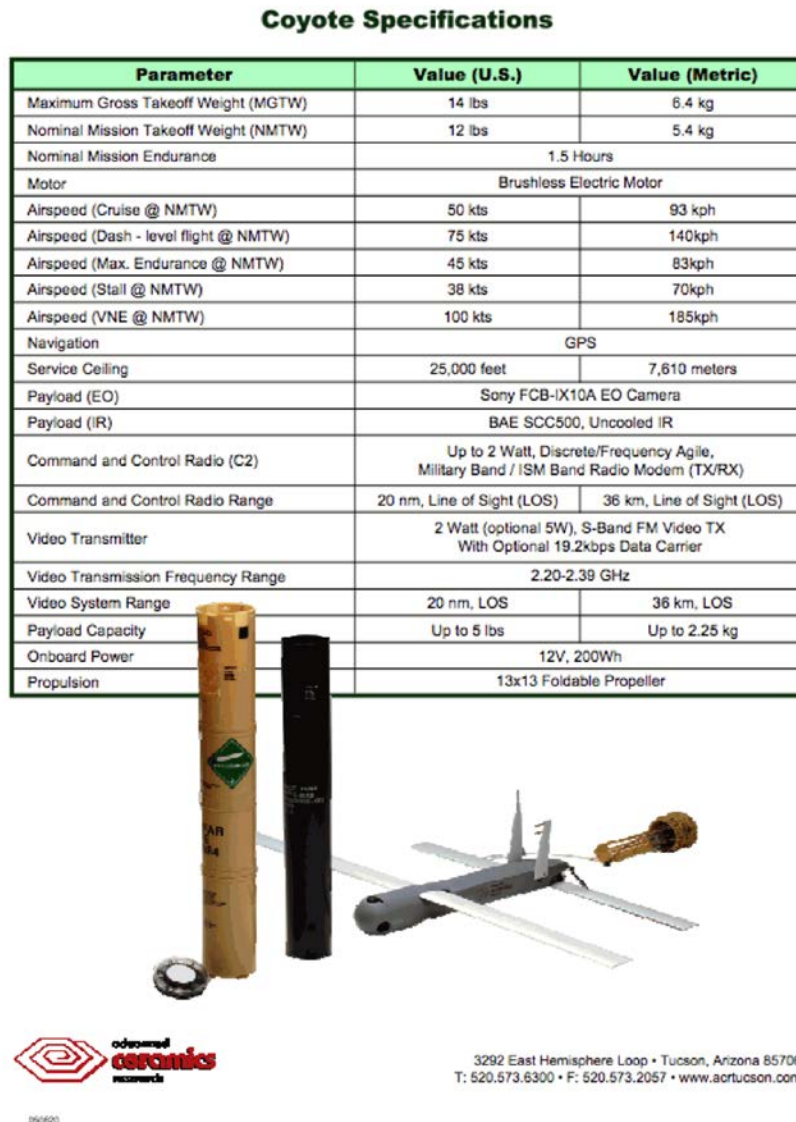


Figure 5-1: Coyote Unmanned Aerial System Specifications (Courtesy: Sensintel)

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 and Environmental Modeling 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 (*potentially give forecasters advanced warning as it relates to dangerous episodes of tropical cyclone rapid intensification*)
- Thermodynamic conditions (particular low level moisture) within the lower troposphere

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 from earlier NOAA UAS missions conducted in 2005 (Ophelia) and 2007 (Noel) while also fulfilling objectives from the recently funded Sandy Supplemental project entitled: *The Impact of Emerging Observing Technologies on Future Predictions of Hurricane Structure and Intensity Change*. As part of this NOAA supported effort, all UAS data collected will be made available to NOAA's National Hurricane and Environmental Modeling Centers.

General Coyote UAS Mission Description:

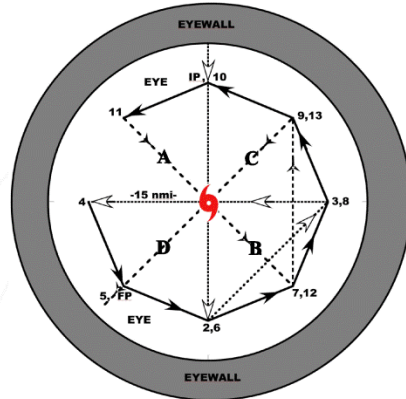
The primary objective of this experiment is further demonstrate and utilize the unique capabilities of a low latitude UAS platform in order to better document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. For this purpose, NOAA is proposing to use 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 that Coyote operators will have onboard the P-3. For testing and operations in 2014, the Coyote UAS will not be freely launched into the US National airspace. Instead, Coyote activities will be limited to include flights within the following areas: 1. Open ocean/International airspace within New York Center (COAs or State Designation of UAS aircraft may be required); 2. PIARCO controlled airspace (requiring international agreement with Barbados and/or Trinidad/Tobago officials); AVON Park controlled airspace (located east of Tampa, FL) for clear air testing.

Module/Option 1a: UAS Eye/Eyewall with P-3 loiter-

For this module the target candidate storm is a mature hurricane (likely strong category 2 or more) 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. In addition, other less restrictive Coyote-P3 modules are being developed and considered (see Module 1b). Iridium/satcomm communications between UAS and P-3 are planned. This capability will have the dual positive effect of minimizing risk to both science and safety. 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 ITRI METOC payload by comparing UAS measurements with coincident observations taken from dropsondes released from the P-3. 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 as opportunities arise AFRES C-130, Global Hawk UAS) as well as select satellite-based remote sensor platforms. In addition, a primary objective (but not an immediate requirement) for this effort will be to provide real-time, near-surface wind observations to the National Hurricane and Environmental Modeling Centers 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.

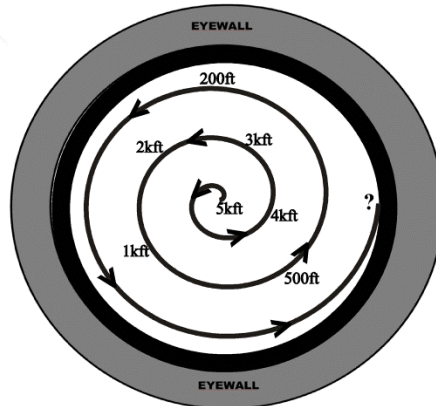
For this experiment, the NOAA P-3 will descend to just above the top of the cloud layer in the eye, and return to the previous altitude when the module is concluded. Assuming multiple UAS are available, both (~1.5h duration) modules could be conducted on the same mission. The eye-only module would be 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

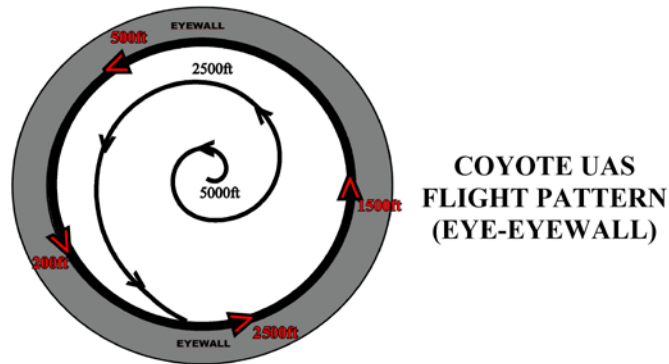
The P-3 approaches from the north at an altitude of 10,000ft, penetrates the eyewall into the eye, and performs a figure-4 (dotted line) in the eye. Midway during leg 3-4 the Coyote UAS is released. The P-3, remaining at 10,000ft, circumnavigates the eye in an octagon pattern and conducts another figure-4 rotated 45 degrees from the original (dashed line). Flight duration for this module 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 completing the pattern once again at point 'FP'. 14 Dropsonde releases should be conducted during the primary 1h module at the following locations: 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 4 through 11 and midway during leg 11-12. (Note: except for AXBT drop at point 4, it is acceptable to launch all remaining 8 AXBT probes during the optional 45 minute second module.)



**COYOTE UAS
FLIGHT PATTERN
(EYE ONLY)**

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

Coyote UAS - P3 Mature Hurricane Eye/Eyewall Module



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

Figures 5-2a-c. (P-3 eye, UAS eye, UAS eyewall)

Module/Option 1b: UAS Eye/Eyewall without P-3 loiter-

This module is identical to Module 1a with the notable exception that the P-3 does not loiter in the eye. For this module, the target storm can be weaker than in Module 1a (e.g. Category 1) since the P-3 will not loiter in the eye after releasing the UAS at altitude near the TC center of circulation. This module can be conducted in the day time or at night. The UAS patterns identified in Module 1a remain the same for Module 1b. However, the P-3 pattern for Module 1b would include repeated eyewall penetrations using a rotating figure 4 pattern (see Figure 5-3 below). So as to maximize the ability to compare P-3 based observations with UAS observations (primarily PTHU from GPS dropsondes and winds from Doppler radar) the radial legs for the P-3 aircraft should be kept to a minimum in order to maximize the number of eye/eyewall penetrations. For this reason legs ≤ 40 nm (measured from the IP to TC center) are preferred. Default P-3 penetration altitude is set to 10,000ft but can be adjusted as mission or storm specific conditions dictate.

For this module, GPS sondes will be released at all leg endpoints, directly in the eyewall and within the eye. This translates to 5 GPS when measured from leg end point to leg end point. In addition, AXBTs will be launched at all end points and for each eyewall penetration, which equates to 4 AXBTs per 'end point to end point' leg flown. The total number of GPS and AXBT deployed will depend upon how many penetrating legs are conducted. Based on the P-3 leg configuration described above, and assuming a 1hr UAS flight duration, 3 full penetrations should be possible.

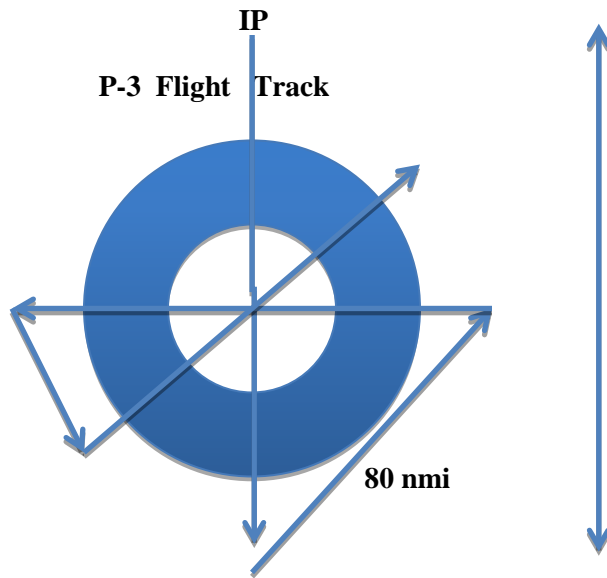


Figure 5-3. (P-3 ‘short leg’ figure 4 pattern)

Module/Option 2: Boundary Layer Entrainment/Convective Downdraft module-

This module builds upon and complements the existing ‘Hurricane Boundary-Layer Entrainment Flux Module’. No modifications to the existing P-3 patterns are required for this module. Instead, the low flying Coyote UAS will conduct very low (down to 100m) stepped descents in addition to patterns flown by the P-3 manned aircraft (see Figure 5-4). These very low altitude UAS patterns should allow for (a more direct) estimation of surface fluxes. In turn, the UAS-derived estimates can then be compared with surface fluxes computed by sampling the top of the boundary layer (residual method). In addition, it is also possible to conduct a UAS box pattern at 100-120m to complement the P-3 1-2km box pattern (not shown) that was designed to estimate divergence in precipitation-free areas.

It should also be noted that an additional goal of this module is to see how vertical mixing occurs above and within the boundary/surface layer just outside areas of active convection (e.g. near rainbands and radially outward of the TC’s primary convective envelop). A goal of this module is to compare observational details from these convectively driven processes with comparable output from high-resolution operational regional and global model simulations.

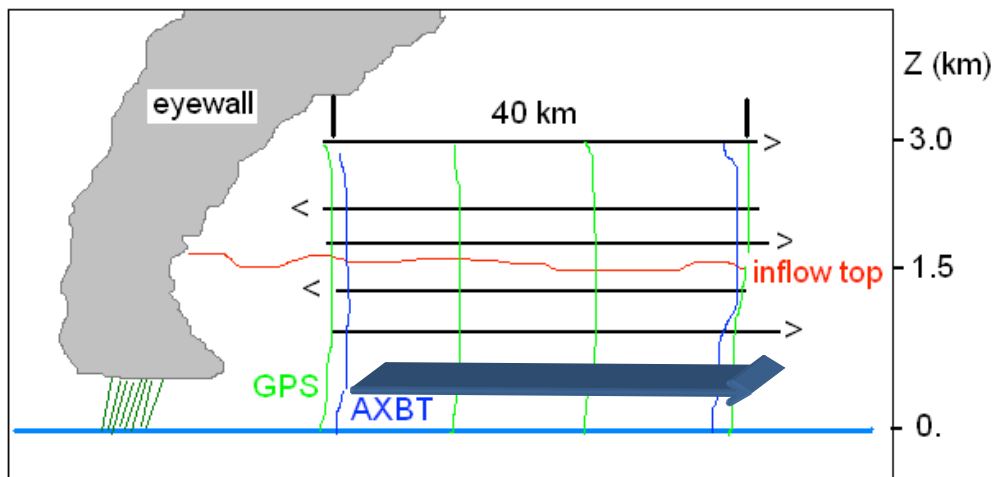


Figure 5-4. (From HFP Boundary Layer Entrainment Module) Vertical cross-section of the stepped-descent module. P3 pattern is in black, low altitude Coyote UAS in heavy blue.

Module/Option 3: Enhanced Boundary Layer Inflow Experiment-

This module builds upon the existing ‘Boundary Layer Inflow Module’ under the ‘TC in Shear Experiment’. As in Module 2 the P-3 pattern remains unchanged. At the IP the Coyote is released and slowly step descends down to 100m as it spirals inward (See Figure 5-5 below). Once at 100m the UAS step ascends up to an altitude just above the inflow layer (~1.5km). Then again descends to 100m. This process continues until eyewall penetration occurs at 500m. Once in the eyewall the UAS step descends in 50M increments every 5 minutes until it reaches 50m and maintains altitude until battery failure.

This module extends work originally conducted by Cione et al in 2000. It also expands the capabilities associated with the original BLI experiment by providing continuous (vs. instantaneous) data at altitudes, radii and azimuths not previously sampled by GPS sonde deployments. In addition, these UAS data will help capture additional vertical variability associated with the inflow layer as a function of radius from the storm center. Once in the eyewall, UAS observations will provide wind and thermodynamic data utilizing a highly unique step descent eyewall orbiting sampling strategy.

Depending on storm conditions and other factors, it may be possible to combine portions of UAS Modules 2 and 3 into one UAS mission.

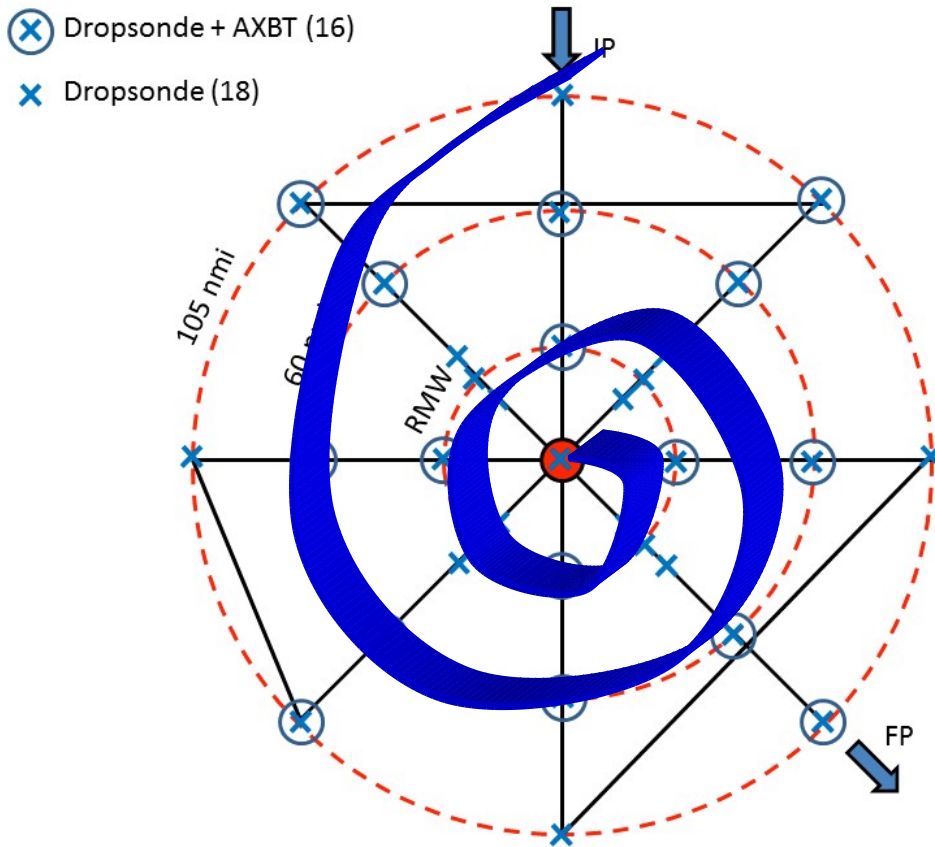


Figure 5-5. Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. 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. Projected Coyote UAS spiral inflow pattern (in heavy blue) is overlaid.

6. SFMR High-Incidence Angle Measurements Module

Principal Investigator(s): Heather Holbach (FSU) and Dr. Mark Bourassa (FSU)

HRD Point of Contact: Eric Uhlhorn

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

Motivation: Surface winds in a tropical cyclone are essential for determining its intensity. Currently the Stepped-Frequency Microwave Radiometer (SFMR) is used for obtaining surface wind measurements. Due to poor knowledge about sea surface microwave emission at large incidence angles and high wind speeds, SFMR winds are only retrieved when the antenna is pointed directly downward from the aircraft. Understanding the relationship between the SFMR measured brightness temperatures, which are used to obtain a surface wind speed, and the ocean surface wave field at off-nadir incidence angles would potentially allow for the retrieval of wind speed measurements when the aircraft is in turns. It is hypothesized that at off-nadir incidence angles the distribution of foam on the ocean surface from breaking waves impacts the SFMR measurements differently than at nadir. Therefore, by analyzing the excess brightness temperature at various wind speeds and locations within the tropical cyclone environment at off-nadir incidence angles, the relationship between the ocean surface characteristics and the SFMR measurements will be quantified.

Objective: Determine the relationship between the SFMR measured surface brightness temperature and the ocean surface wave field characteristics.

Module overview: These modules are designed to obtain SFMR measurements in various locations of the tropical cyclone environment for several different wind speeds during constant banked aircraft turns at several different roll angles. A full pattern for each module consists of three complete circles for each specified roll angle (Figure 6-1). It is important to maintain a constant roll angle. A dropwindsonde and AXBT pair should be released either at the beginning of the pattern. The wide swath radar altimeter (WSRA) should also be obtaining measurements during the pattern for analysis of the ocean surface characteristics. It is ideal to fly these modules in rain-free areas as to reduce the impact of the atmospheric emission on the SFMR measurements. Coordinating measurements with HiRAD and WindSat overpasses would also be ideal if possible.

Modules:

1. Zero wind, high incidence angle response
 - o This module is designed to determine the antenna pattern corrections and possible impacts of sun glint
 - o Fly circles at roll angles of 15, 30, 45, and 60 degrees
2. Moderate wind response (~15 m/s, 30 kts)
 - o This module is designed to understand the mixed “phase” (i.e., foam vs roughness contributions to brightness temperature)
 - o Fly circles at roll angles of 15, 30, and 45 degrees
3. Moderate winds (~15 m/s, 30 kts) and substantial swell response
 - o This module is designed to determine the sensitivity to stress
 - o This can be performed on the way to the storm or in different sectors of the storm
 - o Fly circles at roll angles of 15, 30, and 45 degrees
 - o It would be ideal to coincide with a WindSat overpass if cloud free
4. Strong wind response (>30 m/s, 60 kts)
 - o This module should be flown in multiple storm quadrants (motion relative)
 - o Fly circles at roll angles of 15, 30, and 45 degrees

- Other things to consider
 - Possibility for H-pol measurements (i.e., rotate SFMR antenna 90 deg)

Data Analysis: The SFMR data from these flights will be analyzed to determine if a double harmonic oscillation is evident in the excess brightness temperatures as was found in data collected from Hurricane Gustav (2008). The WSRA data will then be used to analyze the differences in the ocean surface characteristics to reveal any possible relationships between the double harmonic oscillation found in the SFMR measurements and the ocean surface characteristics. Wind speed and direction from the dropwindsondes will be used to verify the SFMR wind speed measurements and for the surface wind direction. SST from the AXBTs will be used as input to the brightness temperature algorithm. If coinciding measurements are retrieved from HiRAD it will be possible to do a comparison with the SFMR measurements to gain a further understanding of the SFMR data. If a WindSat overpass coincides with any of the modules then it would be possible to compare the excess brightness temperatures from the SFMR with those from WindSat.

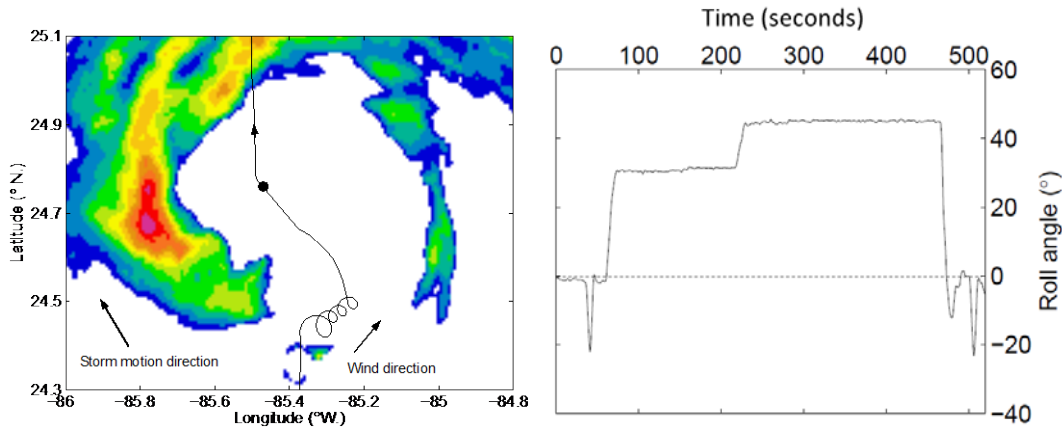


Figure 6-1: Flight pattern for module flown in Hurricane Gustav (2008) in a rain-free portion of the eyewall experiencing approximately 35 ms^{-1} surface winds (left panel). Time series of P-3 roll angle during period of turns in Gustav (right panel).

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.

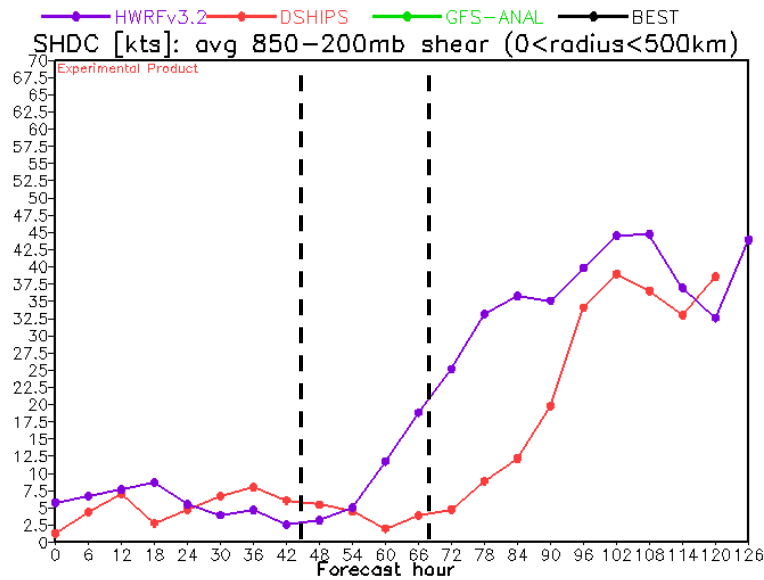


Figure R1

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.

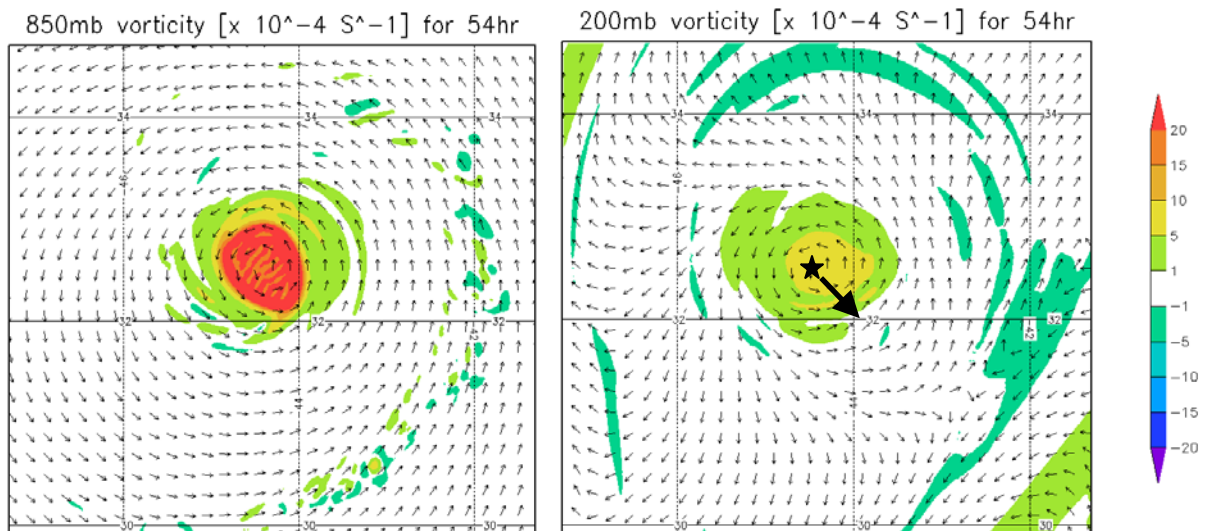


Figure R2

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.

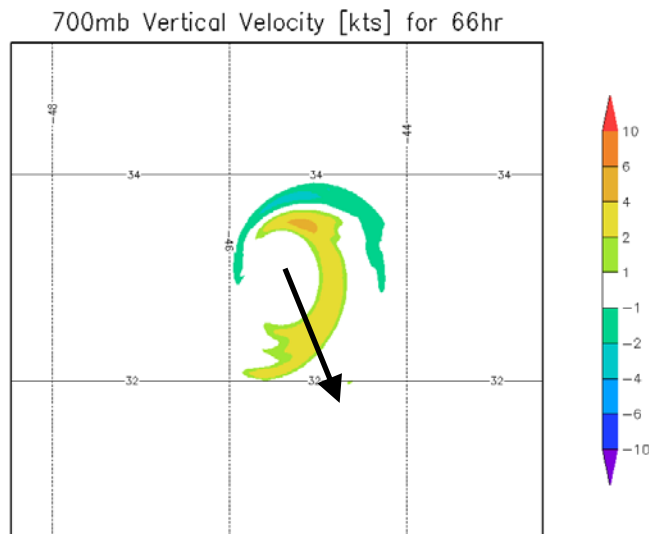


Figure R3

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.

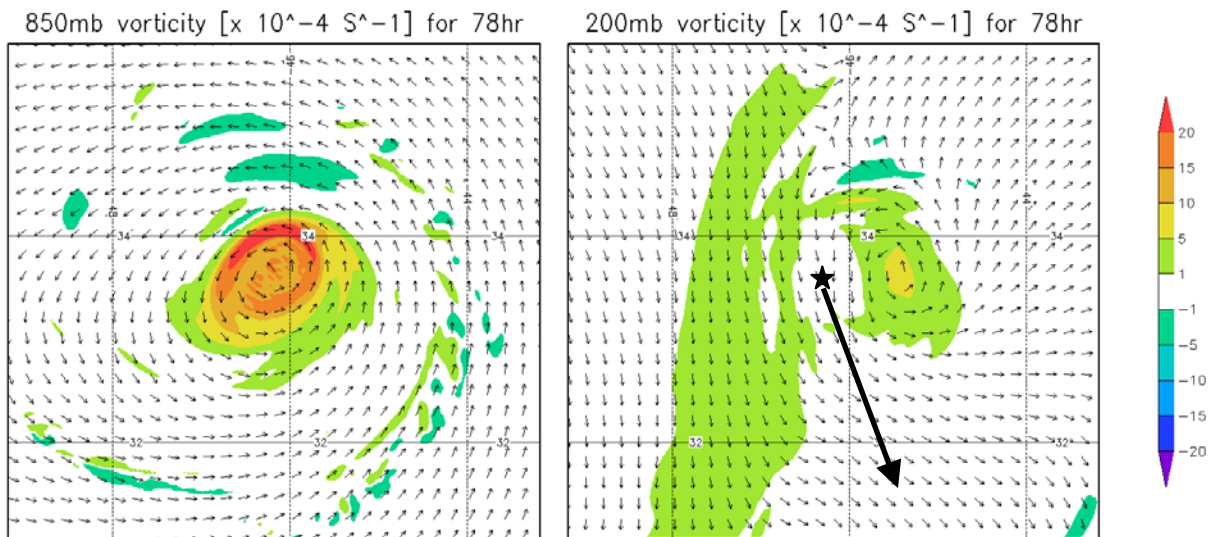


Figure R4

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.

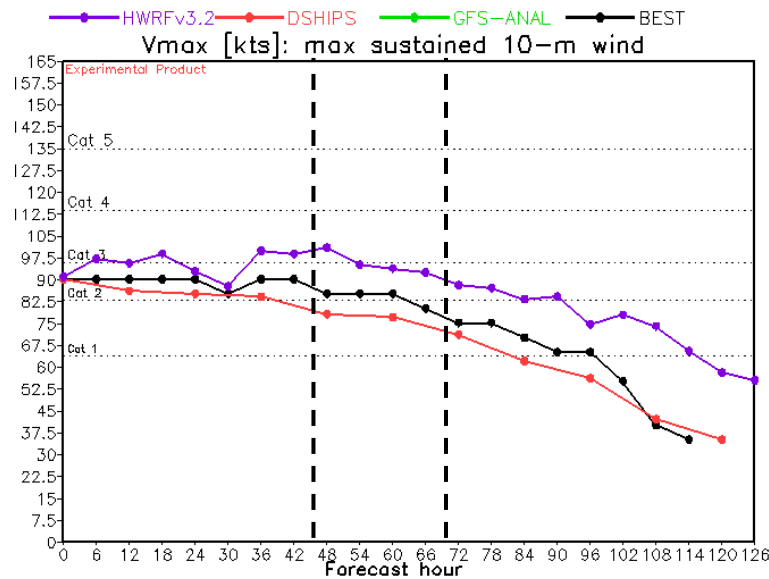


Figure R5

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.

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Tropical Cyclone in Shear Experiment

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

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

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

When to Target: Before a significant increase in environmental vertical wind shear and during the period of maximum vortex tilt. The G-IV should be coordinated with the corresponding P-3 mission.

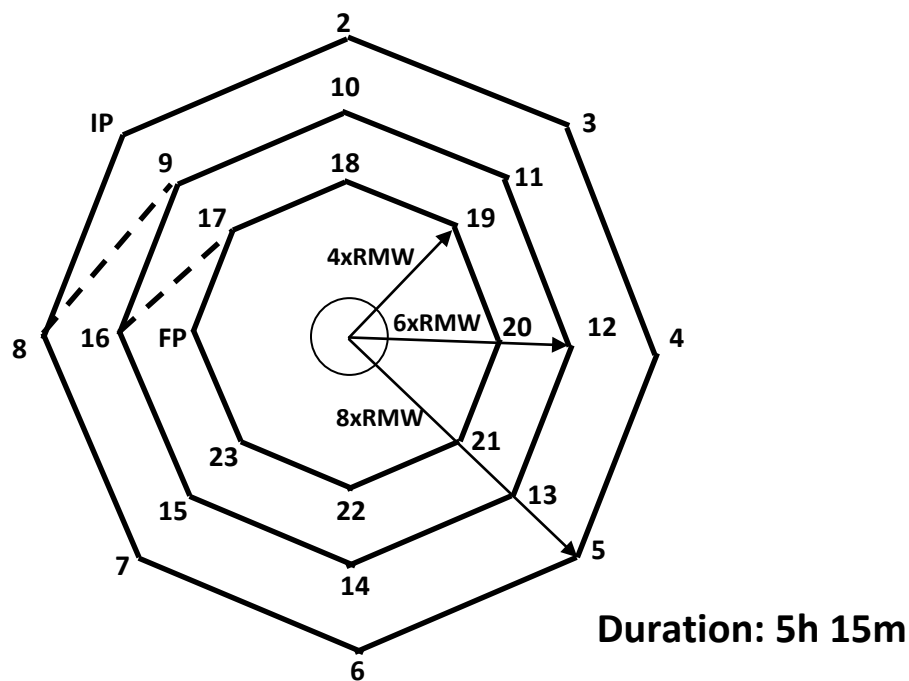


Figure 7-1: G-IV pre-shear outer-core survey pattern

- **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.

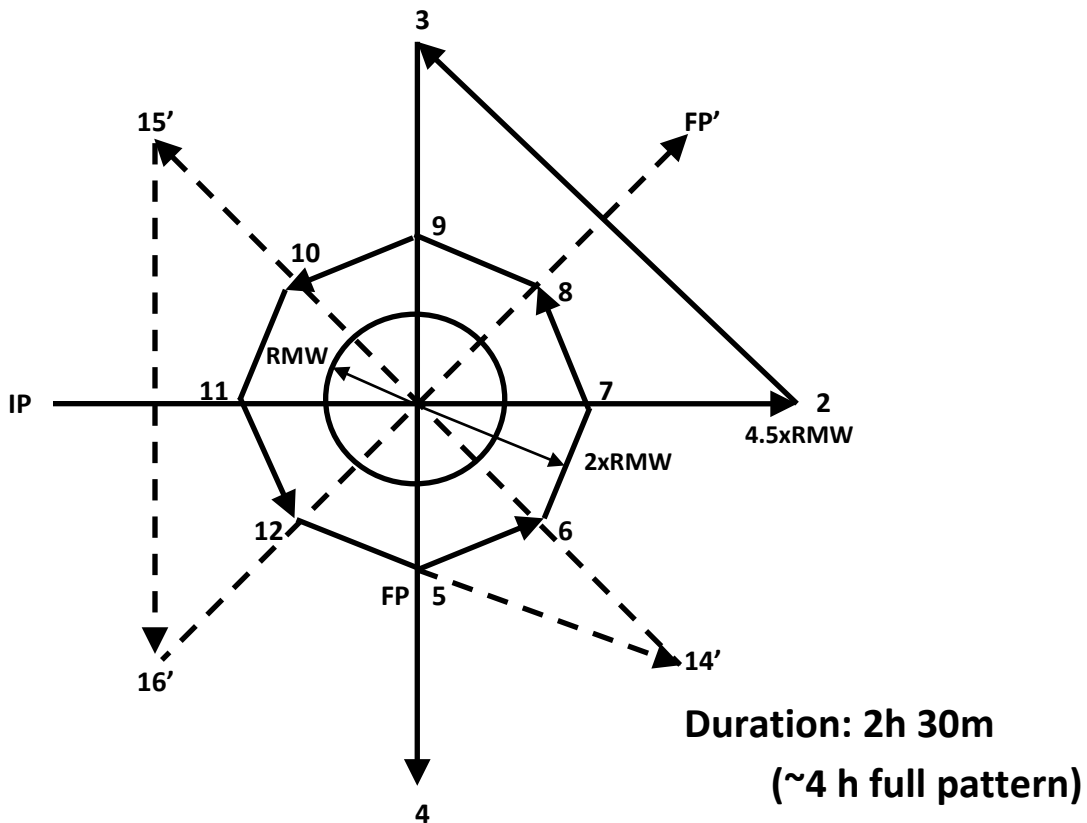


Figure 7-2: P-3 “pre-shear” core-region survey pattern

- **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.

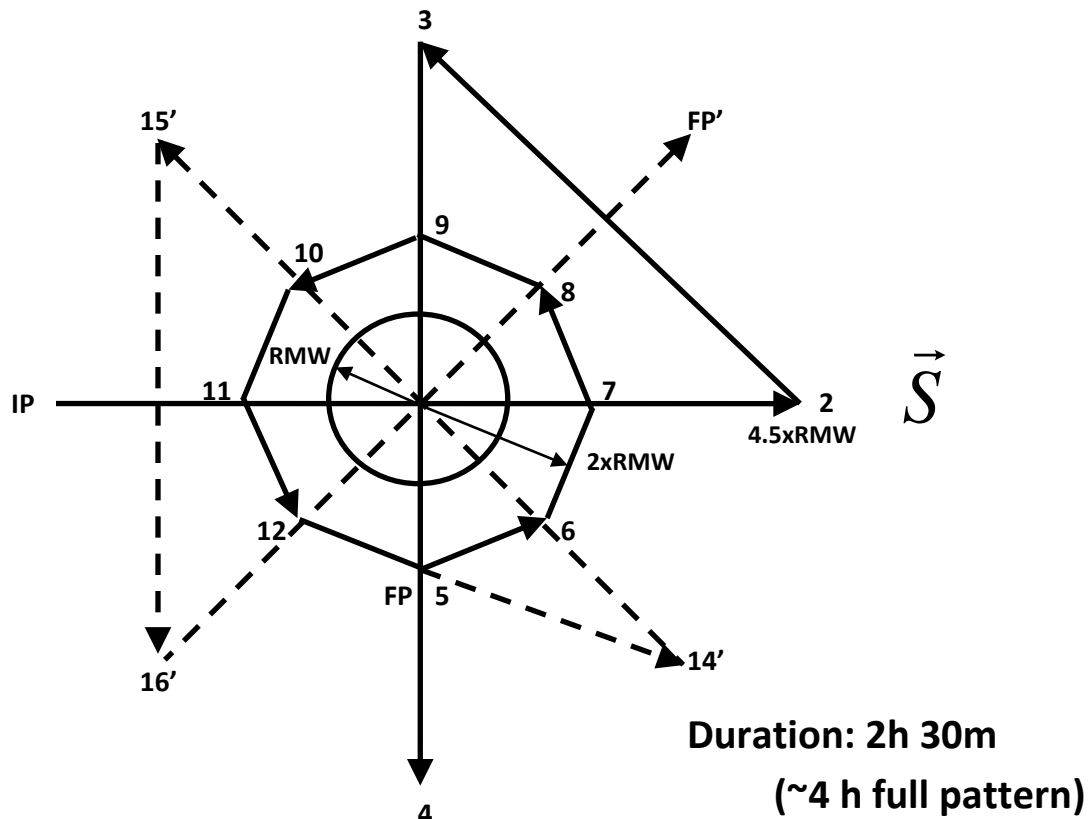


Figure 7-3: P-3 “threshold shear” core-region survey pattern

- **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.

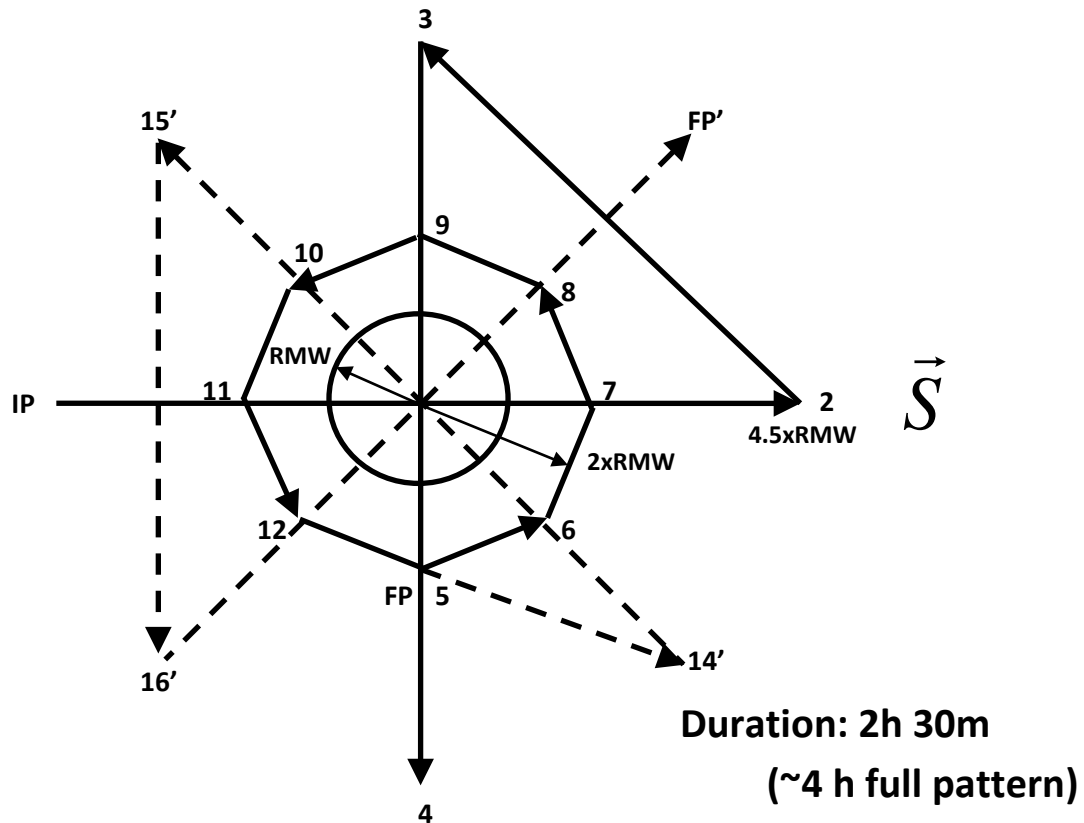


Figure 7-4: P-3 “large tilt” core-region survey pattern

- **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).

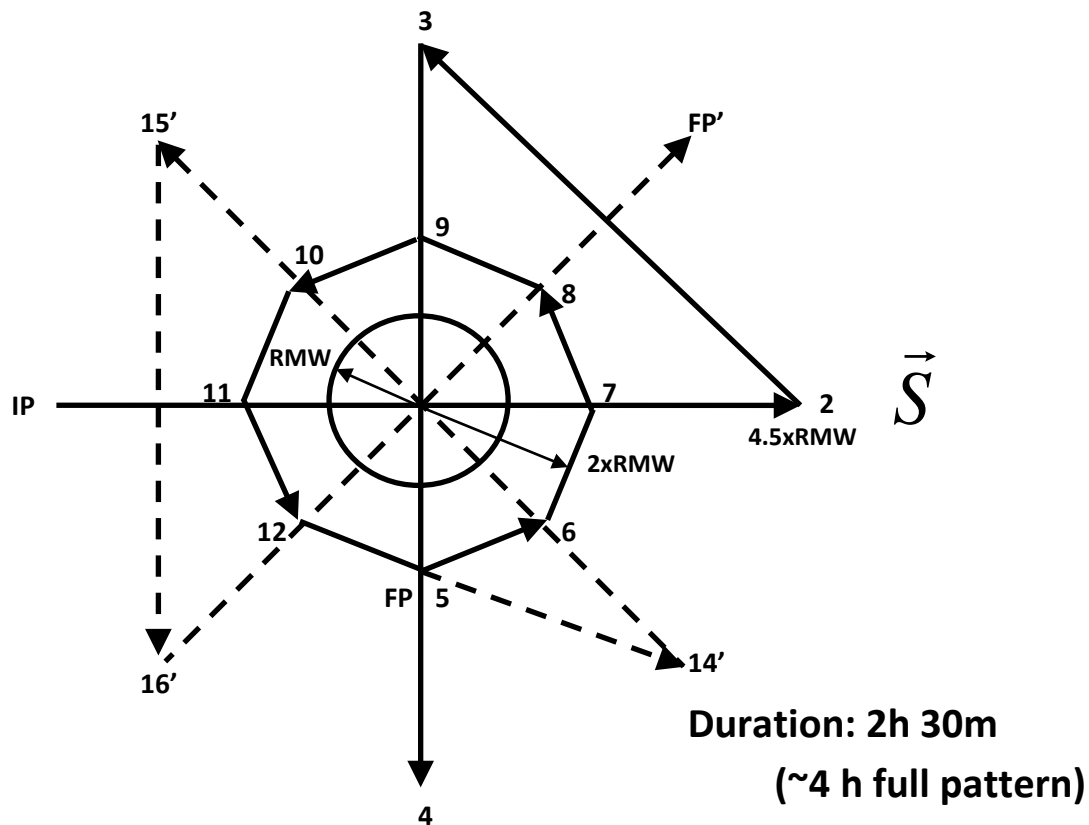


Figure 7-5: P-3 “realignment and recovery” core-region survey pattern

- 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.

Tropical Cyclone in Shear Experiment

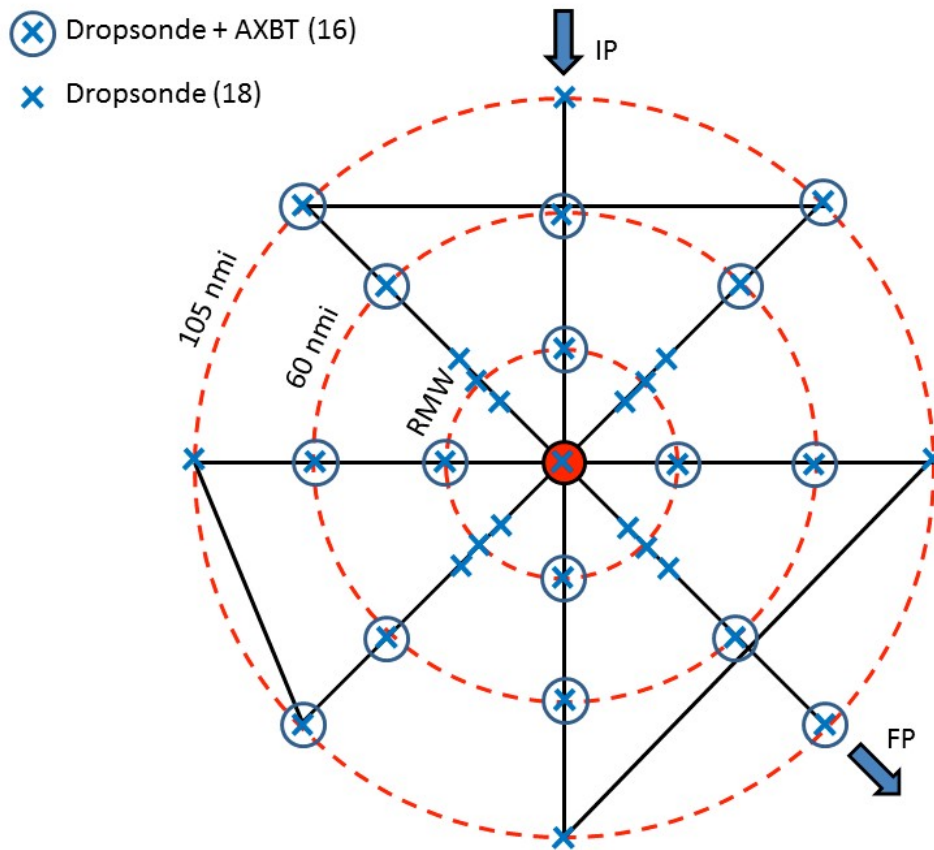


Figure 7-6: Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested.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

Tropical Cyclone in Shear Experiment

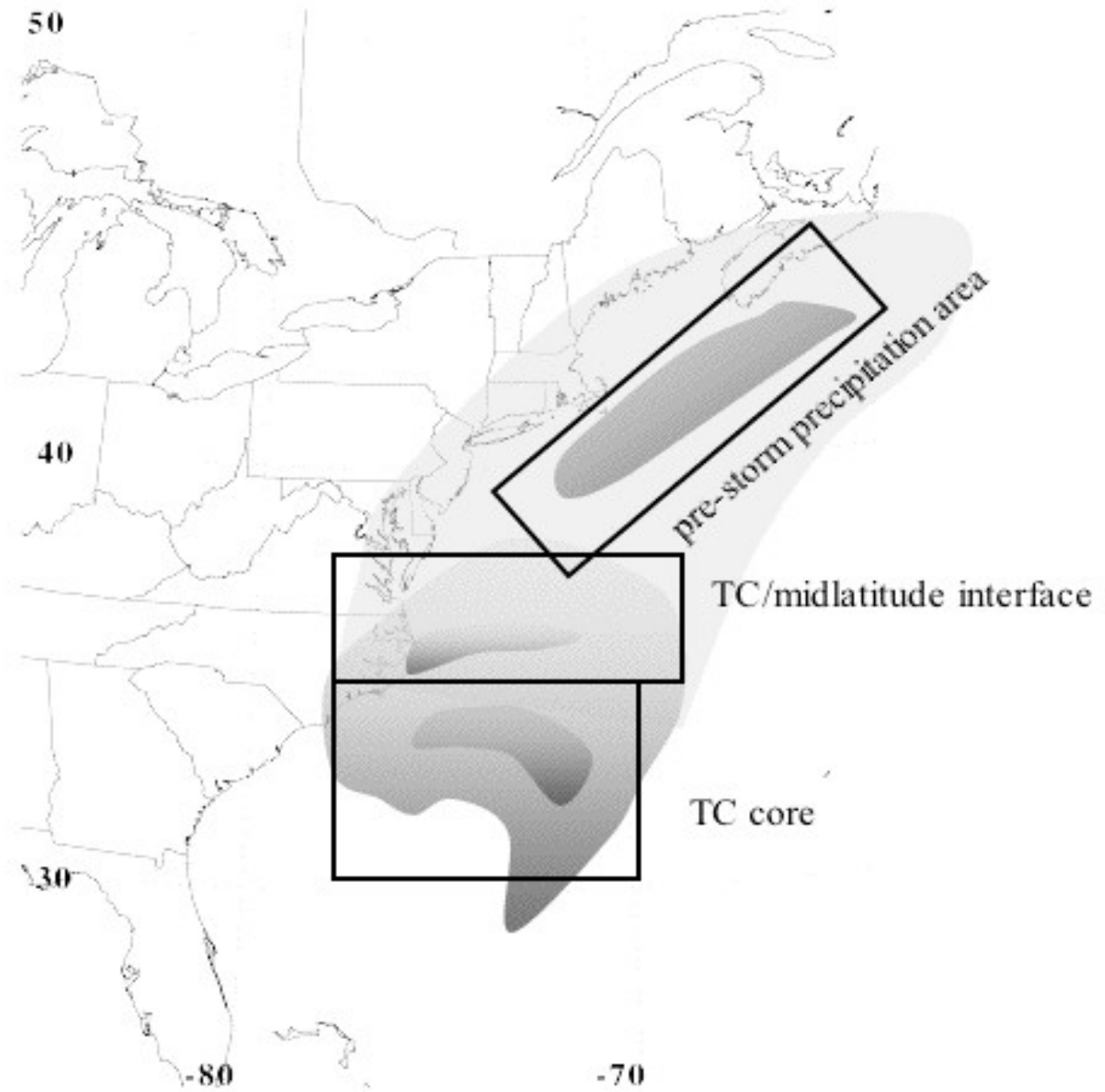


Figure 7-7: Extra-tropical transition module. Schematic of Tropical Cyclone undergoing extra-tropical transition.

Tropical Cyclone in Shear Experiment

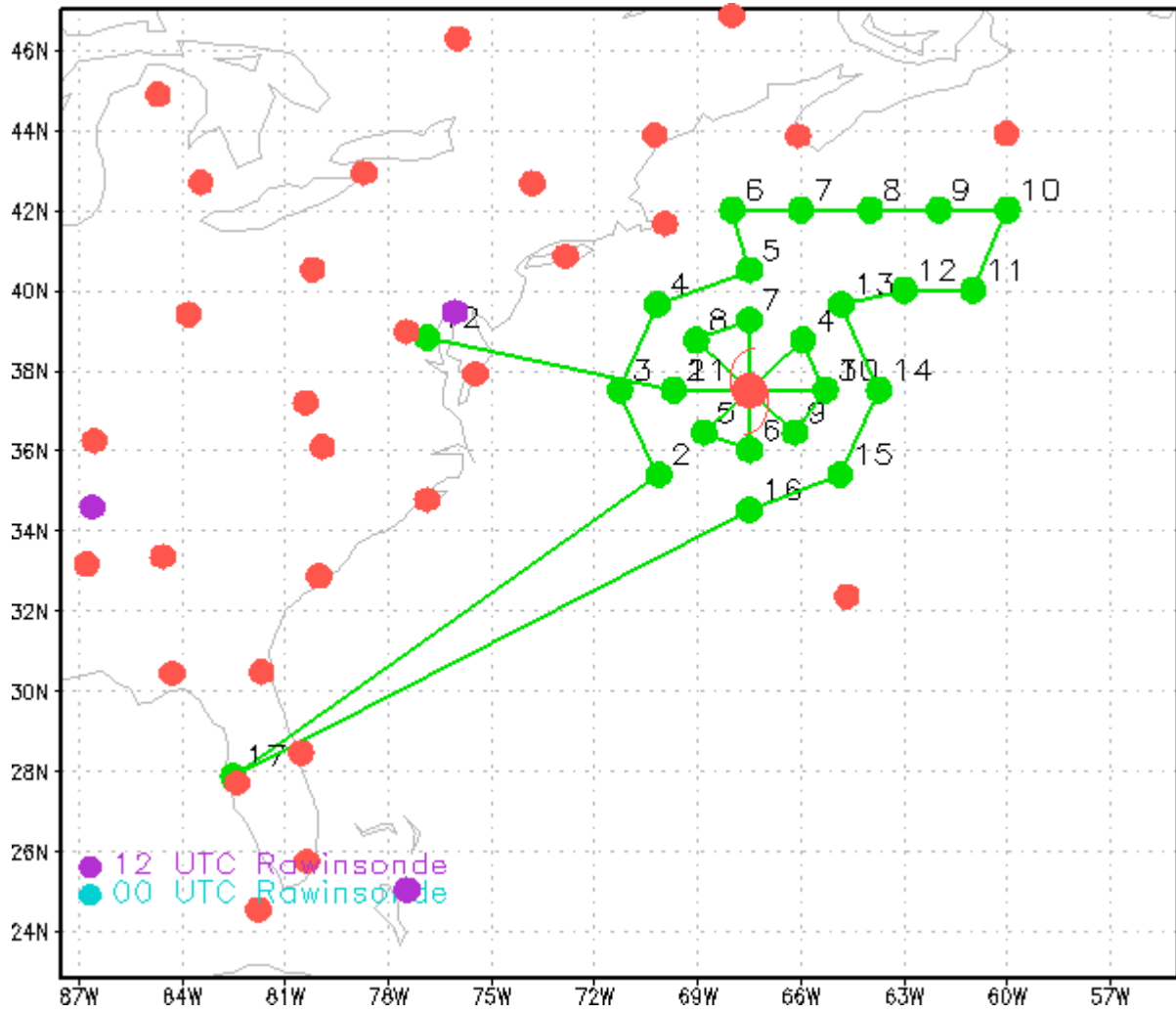


Figure 7-8: Extra-tropical transition module. Proposed flight tracks for G-IV and P3 aircraft.

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. Although the relationships between the TC diurnal cycle and TC structure and intensity are unclear at this time, this phenomenon is may be an important and fundamental TC process;

Objectives:

- The main goal of this experiment is to sample the thermodynamic and kinematic environment of 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;
- 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 ≤400 km) for systems that have exhibited signs of diurnal pulsing in the previous 24 hours;
- Employ the NOAA G-IV jet to sample the temperature, moisture, and winds at the TC cirrus canopy level before, during, and after the time of local sunset;
- Quantify the capabilities of the operational coupled model forecast system to accurately capture thermodynamic (e.g. cirrus canopy cooling at sunset) and kinematic (e.g. enhanced upper-level outflow) characteristics of the TC diurnal cycle and diurnal pulses;

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 cirrus canopy level around sunset each day;
- Data from Caribbean rawinsondes and NASA HS3 Global Hawk GPS dropsondes suggests that are two necessary conditions needed to initiate TC diurnal pulses: a cirrus canopy over an area of deep convection and rapid cooling of the cloud tops (i.e. sunset). These conditions appear create large (~2-5 C) temperature inversions at the cirrus canopy level that may be linked diurnal pulse formation;
- Diurnal pulses may be signatures of outwardly propagating gravity waves, harmonic oscillations of the CDO as it cools near the time of sunset, diurnally-driven changes in inertial stability in the upper-levels (i.e. cirrus canopy) 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

Model Evaluation Component: The TC diurnal cycle may be a fundamental TC process that initiates the formation of TC diurnal pulses near the time of local sunset each day. These TC diurnal pulses radially propagate from the TC inner core and reach peripheral radii (e.g. 300-400 km) the following morning and afternoon. Although the cirrus canopy is typically an under-sampled region of the storm, changes in the thermodynamic structure and outflow patterns in this region of the storm near the time of sunset will be sampled and may be a key component to the formation and evolution of TC diurnal pulses. The predictable propagation of TC diurnal pulses in both space and time each day makes them fairly easy to sample at various radii around the storm. Thermodynamic and kinematic observations will be made of the diurnal pulses from the surface to the cirrus canopy and will include outflow layer sampling, as well as areas of enhanced convergence, moisture, or vertical motions at various levels of the troposphere. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the TC diurnal cycle;

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 $\sim 10 \text{ m s}^{-1}$ 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 $\sim 200 \text{ km}$ at the maximum safe altitude ($\sim 8\text{k}-12\text{k}$ feet) for avoiding graupel. The GPS dropsondes should be dispensed on each leg with a spacing of $\sim 50 \text{ km}$ to provide adequate coverage for sampling the radial gradients of kinematics and thermodynamics. The GPS dropsonde sampling density should be increased to $\sim 20 \text{ km}$ 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 ($\sim 1800-2100 \text{ LST}$) and typically passes the 200 km radius at $\sim 0400-0800 \text{ LST}$ the following morning, optimal P-3 sampling will occur from $\sim 2000-0400 \text{ LST}$ 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 $\sim 175-200 \text{ hPa}/\sim 45,000-41,000 \text{ ft}$) 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 $\sim 0800-1200 \text{ LST}$ ($\sim 1200-1500 \text{ LST}$). Therefore, the optimal G-IV sampling will occur from $\sim 0800-1500$

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.

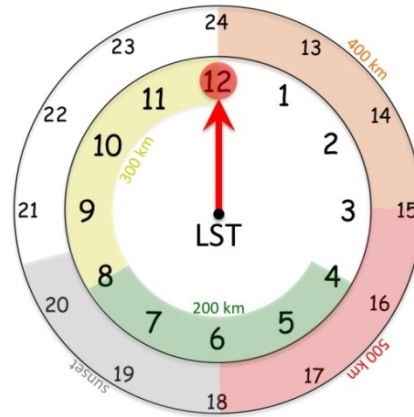


Figure 8-1: Conceptual 24-hr TC diurnal pulsing clock that outlines the lifecycle of cool rings propagating from the TC inner core. For example, the pulse forms at local sunset (~1800-2030 LST, gray shading) and begins to propagate away from the inner core, passing the 200 km radius at ~0400-0800 LST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

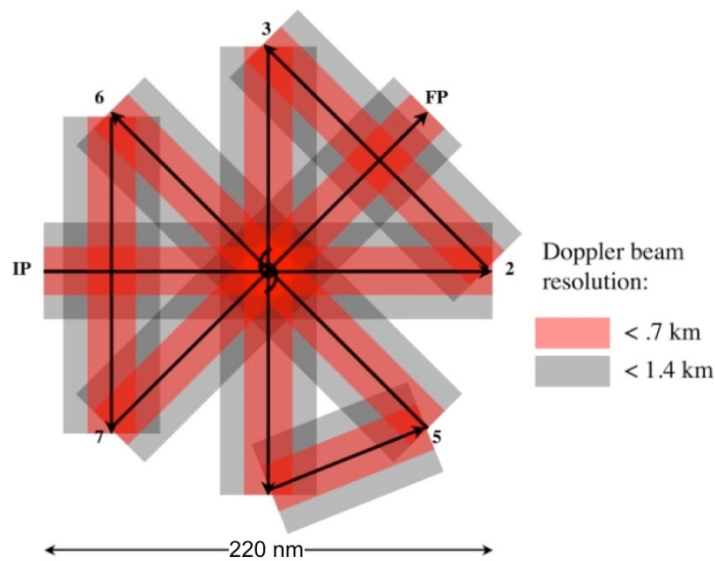


Figure 8-2: Sample rotated figure-4 flight pattern for TC Diurnal Cycle Experiment mission. The red shading denotes locations where vertical spacing of Doppler beam < 0.7 km, grey shading where vertical spacing < 1.4 km. GPS dropsondes should be released at all turn points (past the turn after the aircraft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

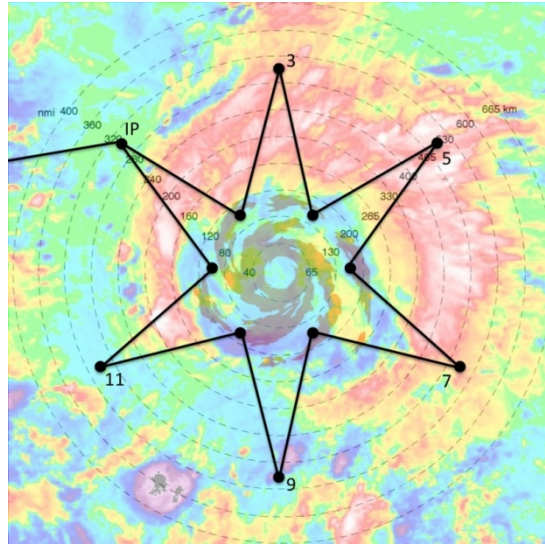


Figure 8-3: Sample G-IV star pattern for the TC Diurnal Cycle Experiment. The endpoints of the pattern will be ~400 km from the storm center, but could be adjusted inward or outward depending in the exact position of the outwardly propagating diurnal pulse cool ring. The pattern is overlaid on a sample 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.

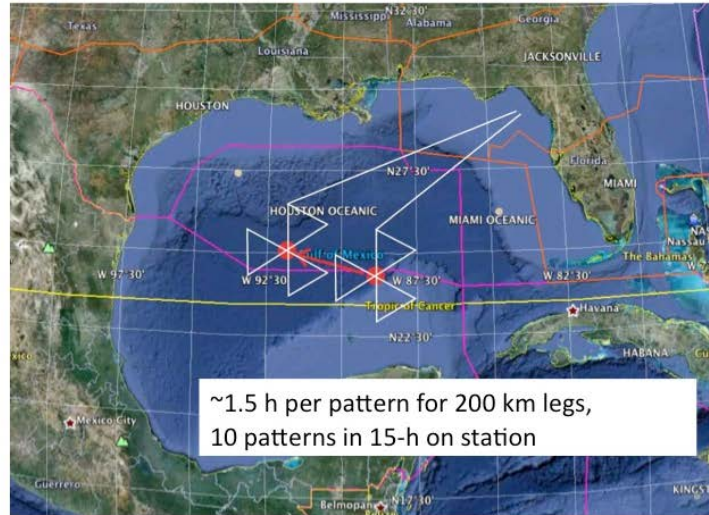
Coordination with Supplemental Aircraft

NASA will be conducting its Hurricane Severe Storm Sentinel (HS3) mission from Aug – Sep 2014. This field campaign 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

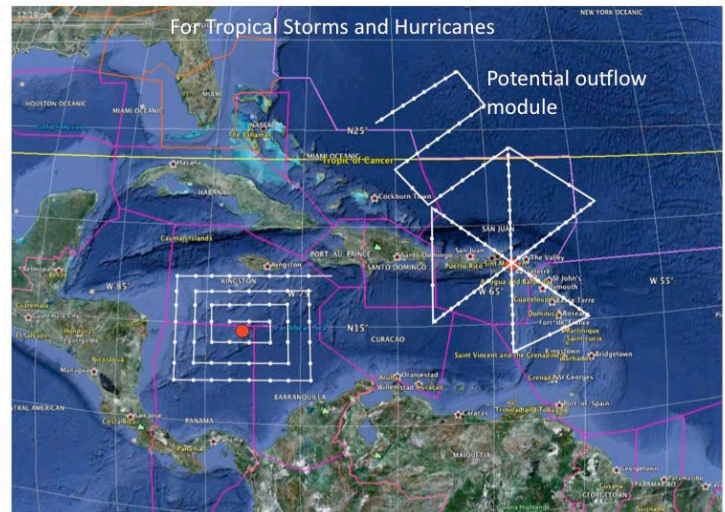


Figure 8-4: Sample flight pattern for the (top) over-storm and (bottom) environmental Global Hawk aircraft for TCs located in the Gulf of Mexico, Caribbean, and western North Atlantic.

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 2014 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.

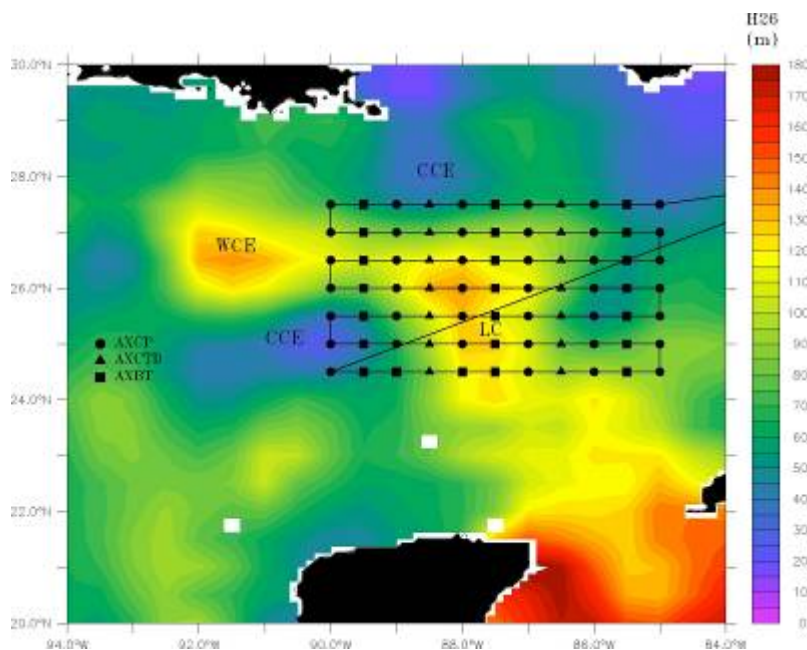


Figure 9-1: Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at KMCF.

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 AXBT 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.

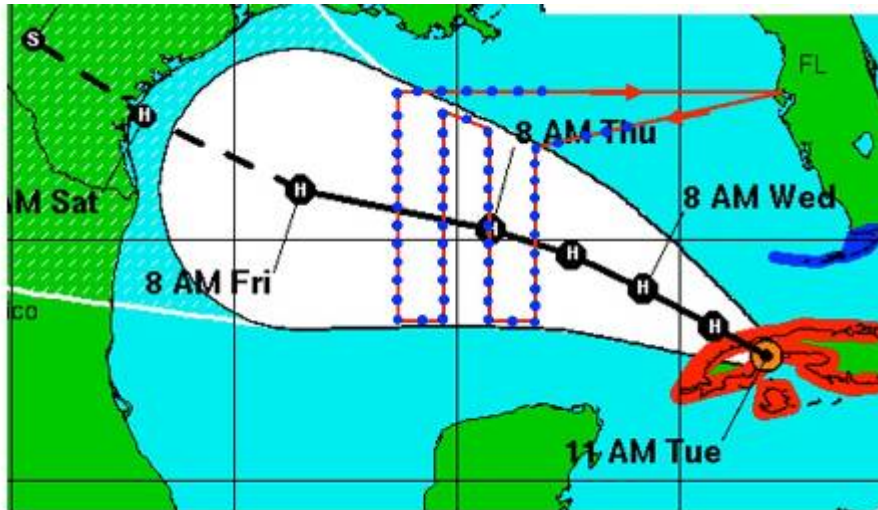


Figure 9-2: Track-dependent AXBT/AXCTD ocean survey. As for the Loop Current survey, a total of 60-80 probes would be deployed on a grid (blue dots).

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.

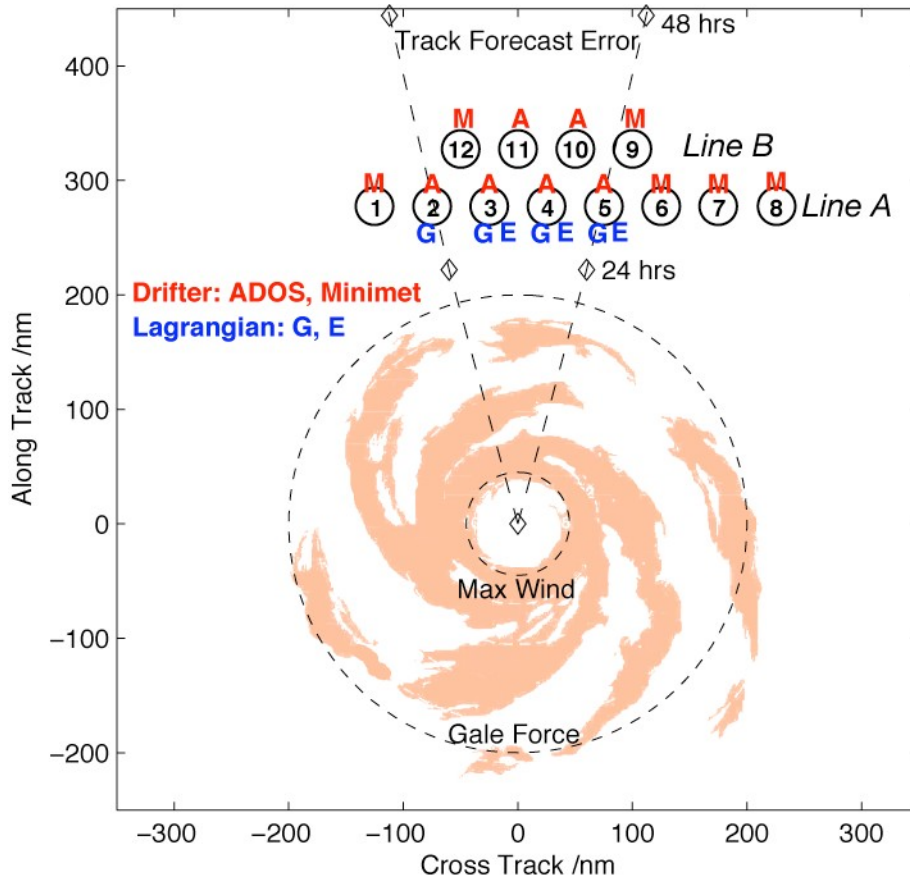
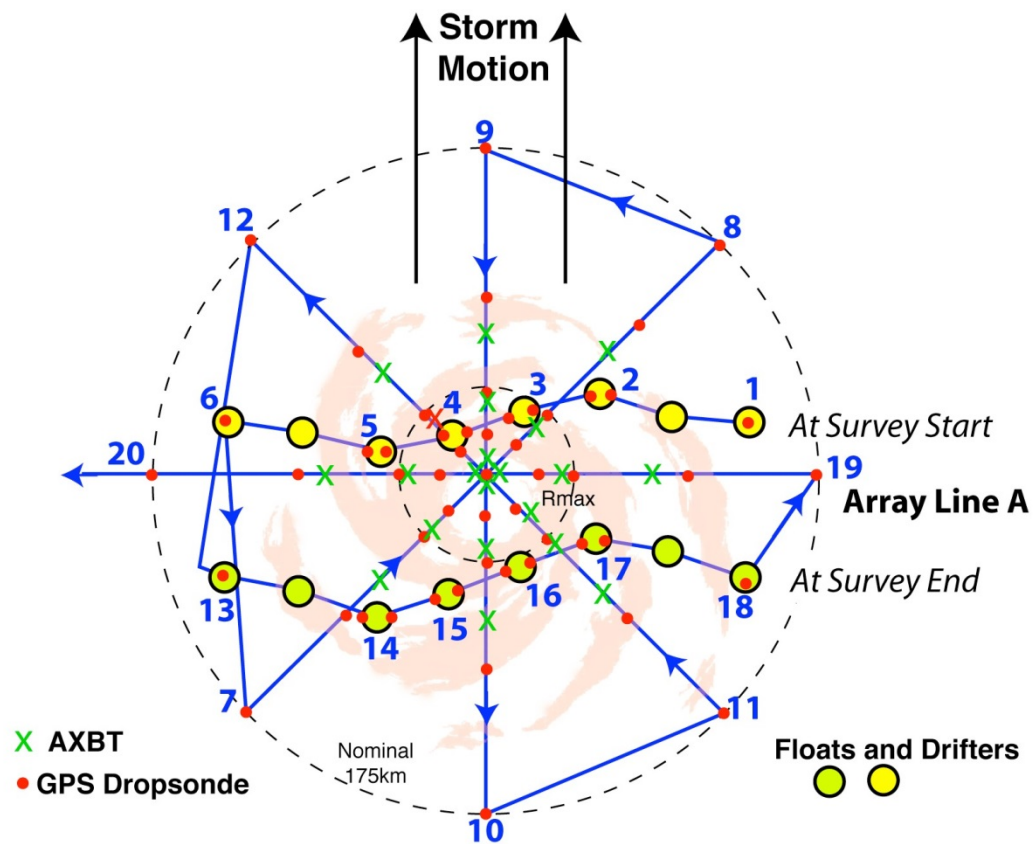


Figure 9-3: Drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of ADOS thermistor chain (A) and minimet (M) drifters. Gas (G) 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.

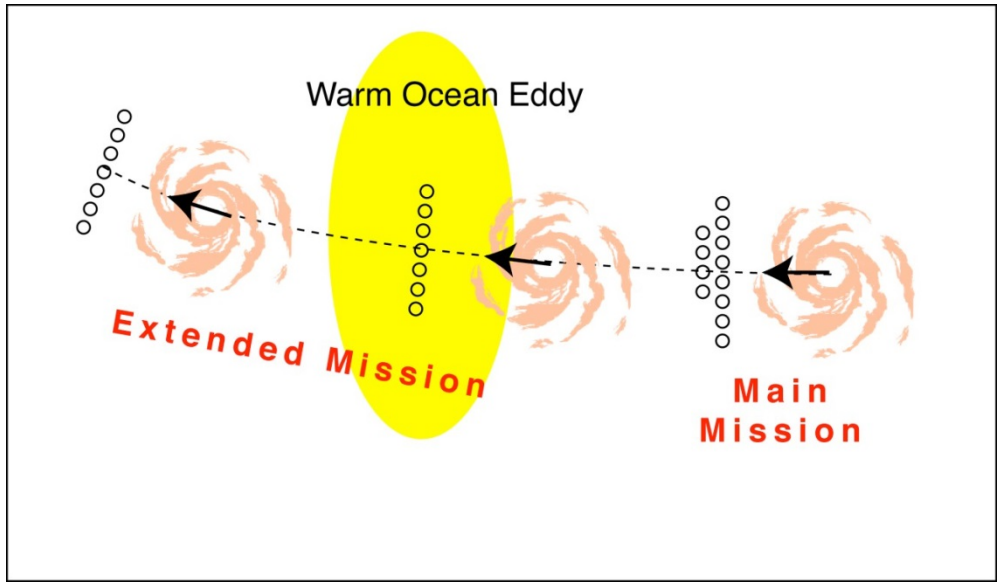


Figure 9-5: Extended Mission. Two additional drifter arrays will be deployed along the storm track.

10. Convective Burst Module

Principal Investigator(s): Robert Rogers, Altug Aksoy

Objective: To sample the wind, temperature, and moisture fields within and around an area of deep convection at high time frequency and to utilize them in high-resolution data assimilation experiments.

What to Target: An area of vigorous, deep convection occurring within the circulation of a tropical cyclone (tropical depression or stronger).

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

This is a stand-alone module that takes 1-2 h 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 (convective bursts) and the nearby environment to examine their role in tropical cyclone genesis and intensity change. 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 sample the convective area (Fig. 10-1). The sampling pattern will be either a circumnavigation (when sampling a burst within a TC of tropical depression strength or less or well-removed from the radius of maximum wind of a tropical storm or stronger) or a series of inbound/outbound radial penetrations, or bowtie patterns (when sampling a burst within the radius of maximum wind of a tropical storm or hurricane).

The high-resolution data collected in this module is planned to be embedded within the typical Hurricane Ensemble Data Assimilation System (HEDAS) framework to carry out storm-scale data assimilation that focuses specifically on the high-resolution analysis of the identified intense convective region. With current technology, a smaller domain with 1-km grid spacing will be nested within the HEDAS 3-km analysis domain, where the data will be assimilated for the duration of its collection (1-2 hours, at 5-10 min intervals). This is a typical setup that has been traditionally used in continental storm-scale radar data assimilation applications and has been shown to be effective to obtain realistic storm structures in analyses and short-range forecasts. With such high-resolution analyses, we hope to be able to obtain fully three-dimensional model representations of the observed convective regions for more detailed investigation, as well as investigate their short-range predictability. In an observing system experiment (OSE) mode, various assimilation experiments can also be devised to investigate hypothetical scenarios for how an observed convective region could interact with the surrounding vortex and impact its evolution.

For circumnavigation patterns, the aircraft should fly a series of straight legs just outside of the main convection, with every effort made to fly the aircraft level for optimal Doppler radar sampling. The tail radar should optimally 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, dropwindsonde 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. When a high-altitude (i.e., above the flight-level of the P-3) aircraft is present, efforts should be made to coordinate this portion of the pattern with the high-altitude aircraft, so that the two aircraft are as close to vertically-stacked as possible. The P-3 should perform as many circumnavigations (or partial ones) of the convective burst as time permits within the 1-2 h window.

For bowtie (radial penetration) patterns, the tail radar should be operated in F/AST full-scan mode. Dropsondes should be released ~10-20 km apart on all passes. Repeat penetrations as long as time permits within the 1-2 h window. When a high-altitude aircraft is present, efforts should be made to coordinate the pattern with the high-altitude aircraft, so that the two aircraft are as close to vertically-stacked as possible.

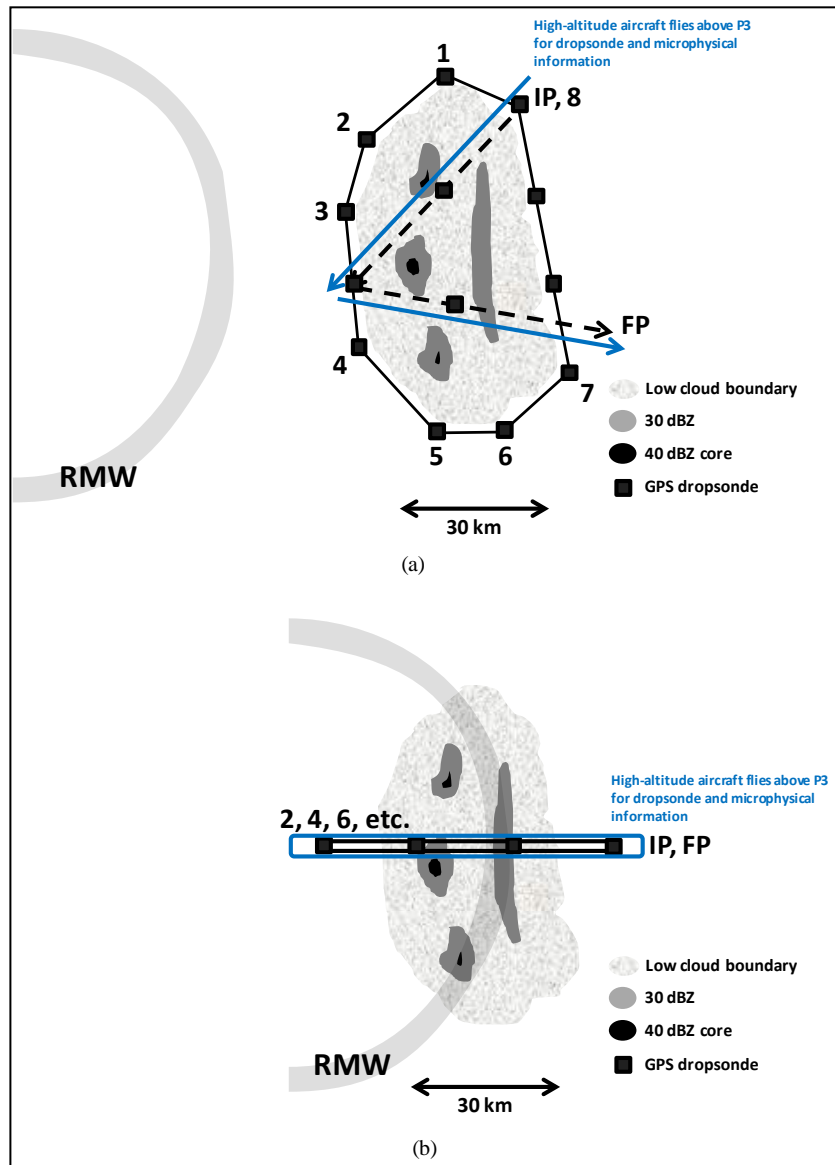


Figure 10-1: P-3 Convective burst module. (a) circumnavigation for when burst is well outside RMW or within a TC of tropical depression strength or less; (b) bowtie pattern for when burst is within or near RMW of tropical storm or hurricane.

- **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 when burst is outside RMW or in weak system. Then fly convective crossing (6-7-FP). Repeat circumnavigation (time permitting). 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. Repeated radial penetration (i.e. bowtie) when burst is inside or near RMW of tropical storm or hurricane.
- **Instrumentation:** Set airborne Doppler radar to scan F/AST on all legs.

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 \leq 48 h) while both statistical/dynamical and 3-D numerical models will be used for the longer time ranges (i.e. beyond 48 h). The datasets collected from this experiment will enable a quantification of the capabilities of the operational coupled model forecast system to adequately distinguish the environmental, vortex and convective-scale structures of tropical cyclones that undergo RI from those that do not.

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

Model Evaluation Component: Recent analyses of airborne Doppler and dropsonde data have shown statistically-significant differences in both the environmental and the inner-core structures of TC's that undergo RI from those that remain steady-state. Such structures include the inner- and outer-core vorticity field, inflow depth and strength, and number and radial distribution of convective bursts. The data collected as a part of this experiment will span scales ranging from the environmental down to the convective and PBL scale. It will enable an evaluation of various features of the operational modeling system, including the sufficiency (or lack thereof) of the horizontal resolution, and the microphysical and planetary boundary layer parameterization schemes.

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.

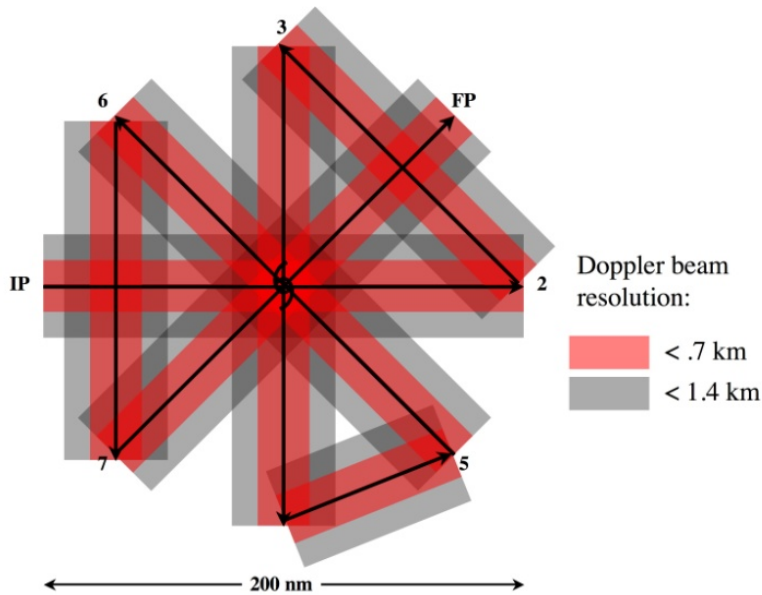


Figure 11-1: Sample rotated figure-4 flight pattern for RAPX mission. The red shading denotes locations where vertical spacing of Doppler beam $< 0.7 \text{ km}$, grey shading where vertical spacing $< 1.4 \text{ km}$. GPS dropsondes should be released at all turn points (past the turn after the aircraft 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.

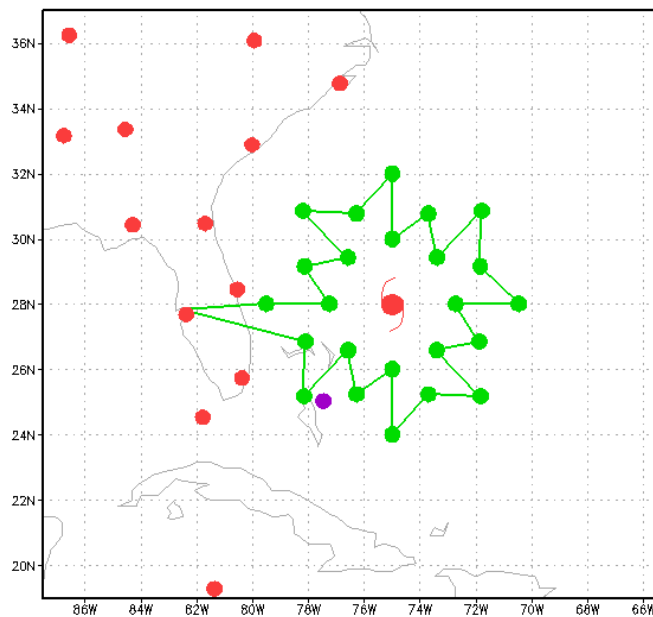


Figure 11-2a: A sample G-IV flight pattern for the RAPX mission. The green dots denote the desired dropsonde locations at 220, 330, and 440 km radius from the storm center. Note that the end points of each leg can be rounded slightly as required for aircraft flight considerations. The flight pattern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

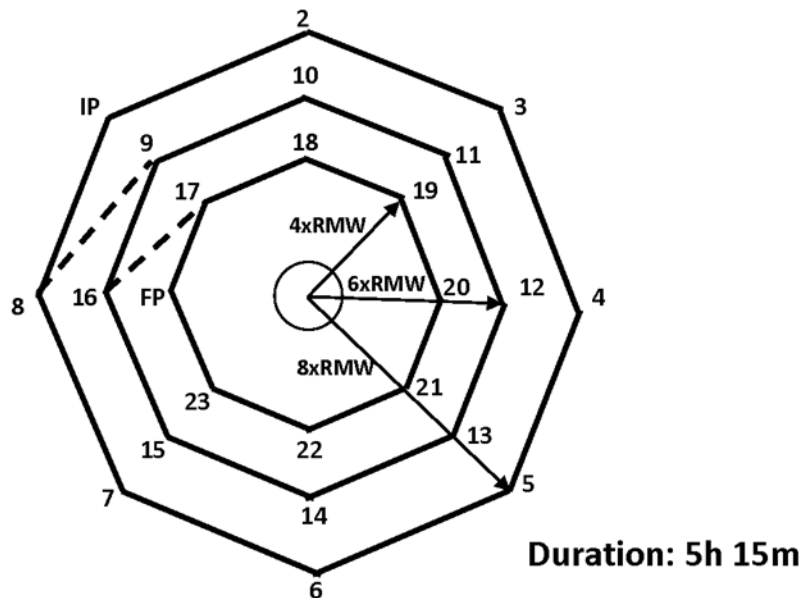


Figure 2b: G-IV outer-core survey pattern

- 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.

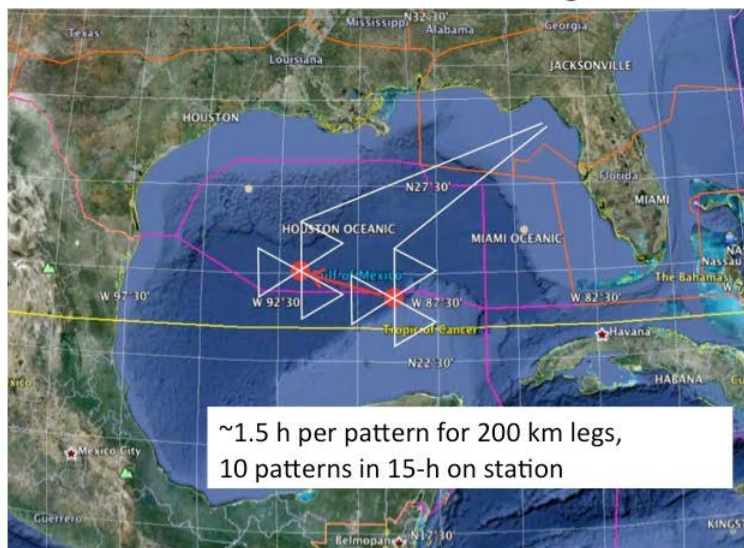
Coordination with Supplemental Aircraft

NASA will be conducting their Hurricane Severe Storm Sentinel (HS3) mission from Aug. –Sept. 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



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, Peter Dodge, Eric Uhlhorn, Jun Zhang

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.

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 2014 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 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 changes in ocean wave action in shallow waters, change in surface roughness, drier and cooler inflow from the land, and topographical impacts. 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 models (such as the Kaplan/DeMaria model) and numerical models like HWRF.

HRD has developed a real-time surface-wind analysis system to aid NHC in the preparation of warnings and advisories in TCs. In the past, the wind analyses produced using the HRD analysis package have been used both for post-storm damage assessment by emergency management officials and by researchers seeking to validate their model analyses and forecasts. However, these wind analyses also have the potential to be used to initialize real-time storm surge models.

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 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 site 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 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. Deploying dropwindsondes near the coast will augment the Doppler data, 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.
- Collect observations that will aid in the evaluation of the current operational coupled model forecast system's ability to predict the three-dimensional structure of tropical cyclones both at the time of landfall as well as after the cyclone has moved inland.

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 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.

Model Evaluation Component:

Recent tropical cyclones (e.g. Irene (2011), Sandy (2012)) have produced over-land wind gusts that have often exceeded the values that might otherwise be expected based upon both the model predicted and observed maximum sustained wind. Thus, it is hypothesized that the collection of landfalling datasets such as those proposed for this experiment will help researchers evaluate the capability of the current operational coupled-model forecast system to accurately predict both the maximum sustained wind and wind gusts of landfalling tropical cyclones.

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 for systems that are expected to be close to major hurricane intensity at the time of landfall. In addition, specific landfall flights will only be requested if the mobile observing systems are also deployed. These additional observations are particularly important for documenting the inland decay of a major hurricane.

The aircraft must have working lower fuselage and tail radars. HRD should have access to a workstation 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 within 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 $> 25 \text{ ms}^{-1}$. 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 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 HRD wind-analysis system 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 could then be combined to produce analyses of surface wind speed and provided to forecasters and/or emergency manager in real-time. The quality-controlled data will also be available for assimilation into models such as HWRF and to validate surface wind analyses.

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 of this pattern for a hurricane 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 be 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 just after the storm has moved 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.

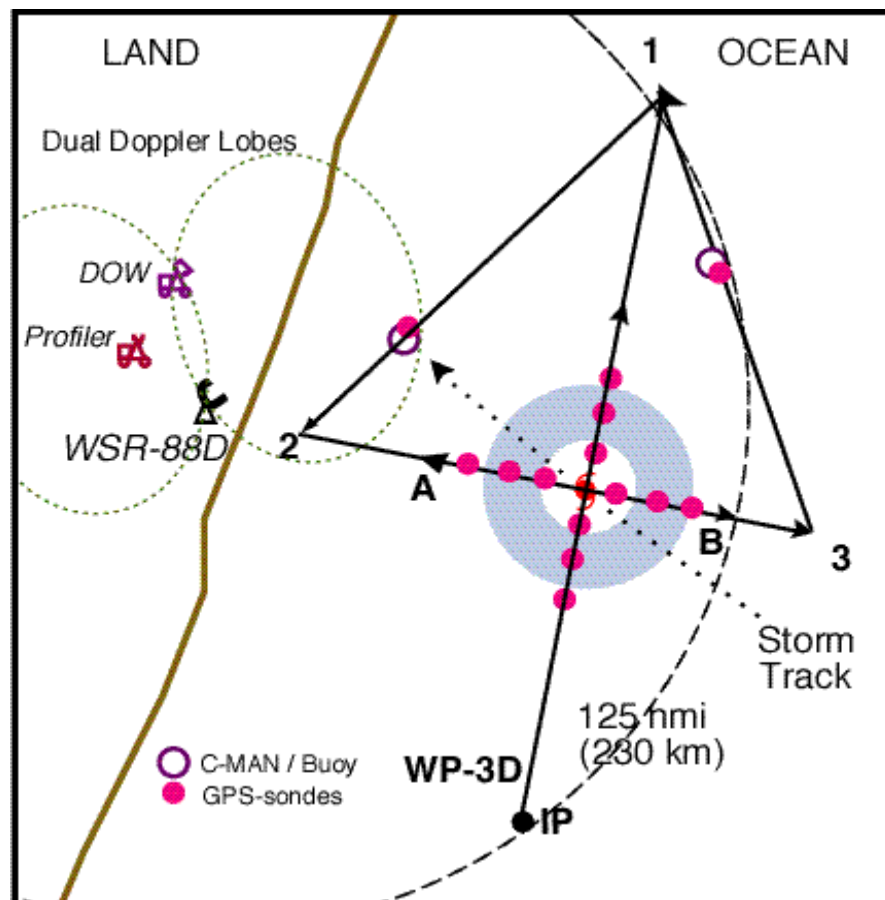


Figure 12-1: Real-time module.

- 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.
- Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

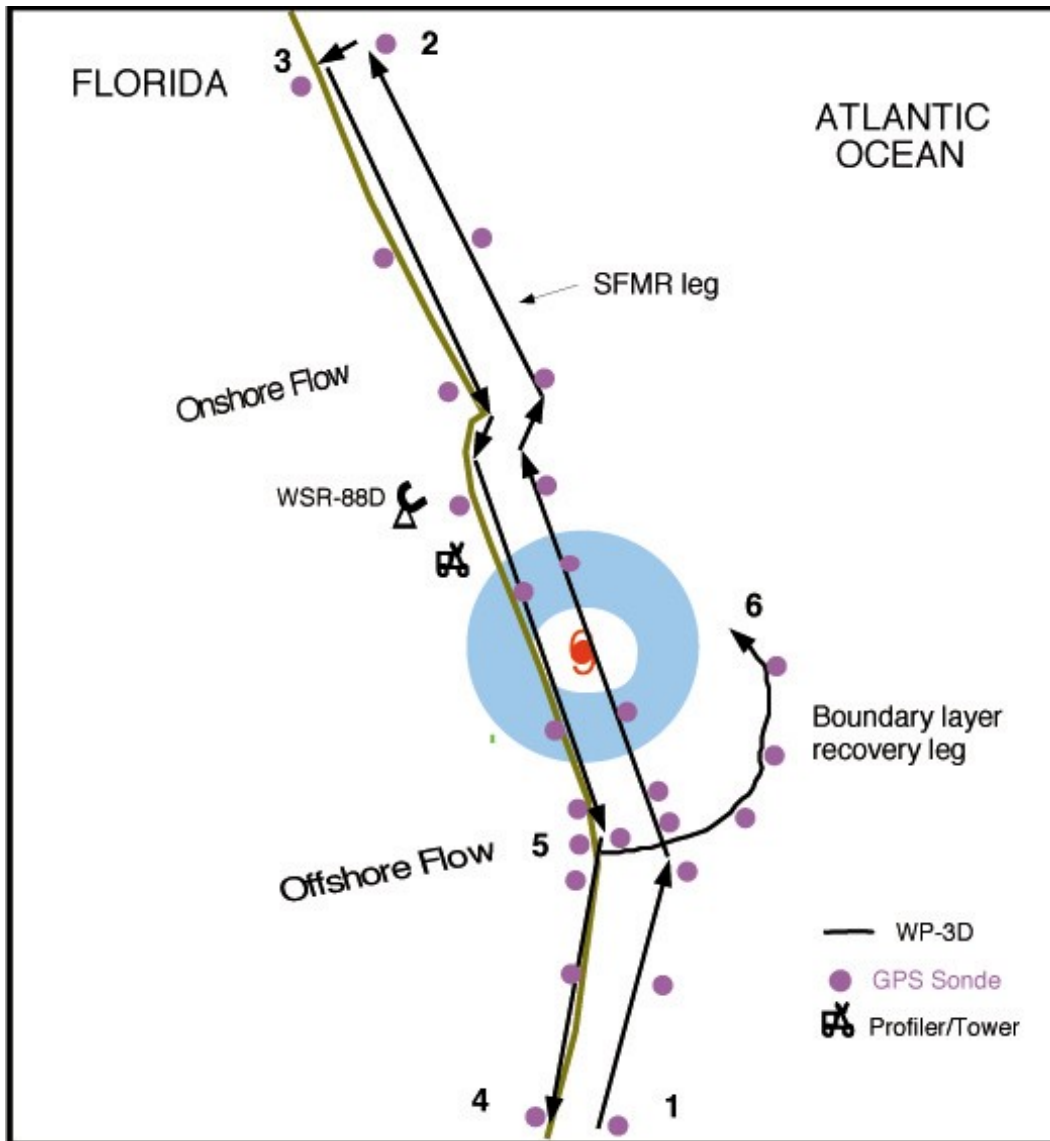


Figure 12-2: Coastal Survey pattern.

- 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 and 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 in mid-level dry layers (e.g. the SAL) that are hypothesized to be a necessary ingredient for the formation of strong downdrafts and subsequent outflow boundaries & arc clouds;
- 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 and how these features may limit short-term intensification;
- Target observations ahead of and behind arc cloud features to sample the horizontal gradients of temperature, moisture, and winds (e.g. outflow) from ~600 hPa to the surface;
- Quantify the capabilities of the operational coupled model forecast system to accurately capture and represent both mid-level dry air (e.g. the SAL) and thermodynamic and kinematic gradients across arc cloud features through direct comparison to observations as well as high-resolution analyses provided by HRD's state-of-the-art Hurricane Ensemble Data Assimilation System (HEDAS);

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

Model Evaluation Component: Arc clouds in the periphery of TCs represent the leading edge of large outflow boundaries that bring cool, dry air and enhanced outflow into the lower levels of the atmosphere. These rarely observed environments are formed in the presence of precipitation falling through mid-level dry air and are hypothesized to limit short-term TC intensification. Thermodynamic and kinematic observations that are collected during this module will be used to evaluate the robustness of the operational coupled model forecast system to represent the SAL and arc cloud environments. Data assimilation (DA) provides a natural platform to compare model output to observations by accounting for the underlying uncertainties of observations and model in a statistical framework. Normalization of model-observation differences by the total expected uncertainty allows for the identification of areas where lack of model performance is statistically the most significant. Furthermore, the high-resolution, three-dimensional analyses that DA produces provide the best estimate of the SAL structure within the modeling framework. Such analyses can be directly compared to operational model output to understand how well the SAL structure is represented in operational models and the consequences for subsequent model forecasts.

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.

Option #1: G-IV aircraft. 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.

Option #2: WP-3D aircraft: 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 flight 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.

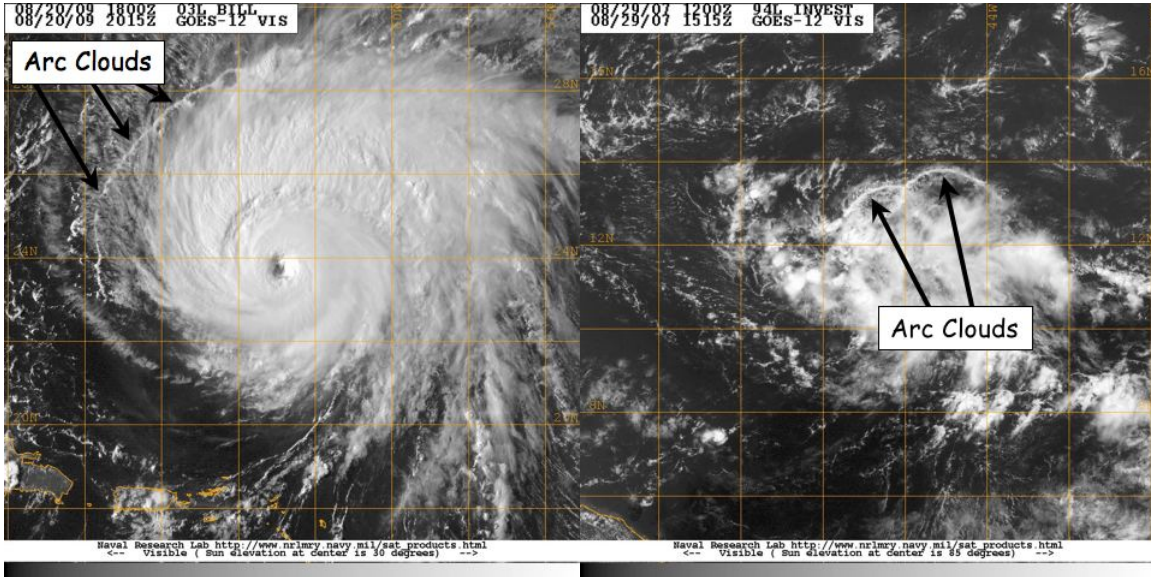


Figure 13-1: GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2009 Hurricane Bill and (right) 2007 Pre-Tropical Depression Felix.

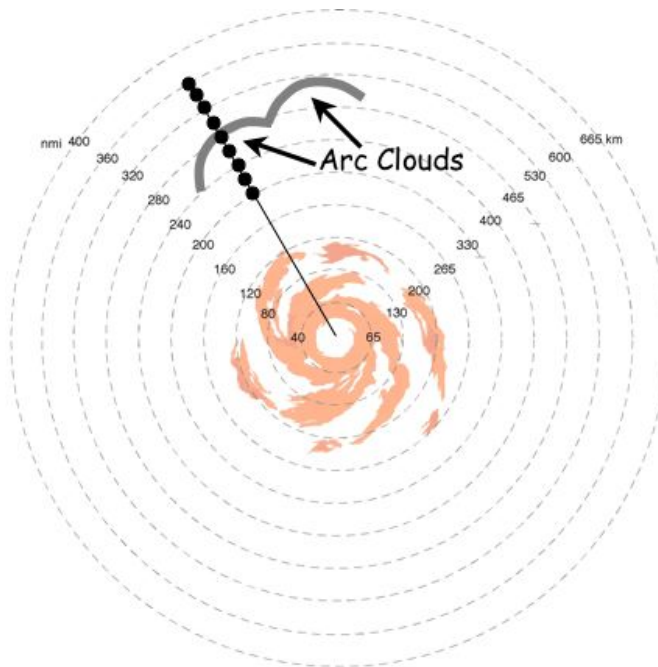


Figure 13-2: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the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

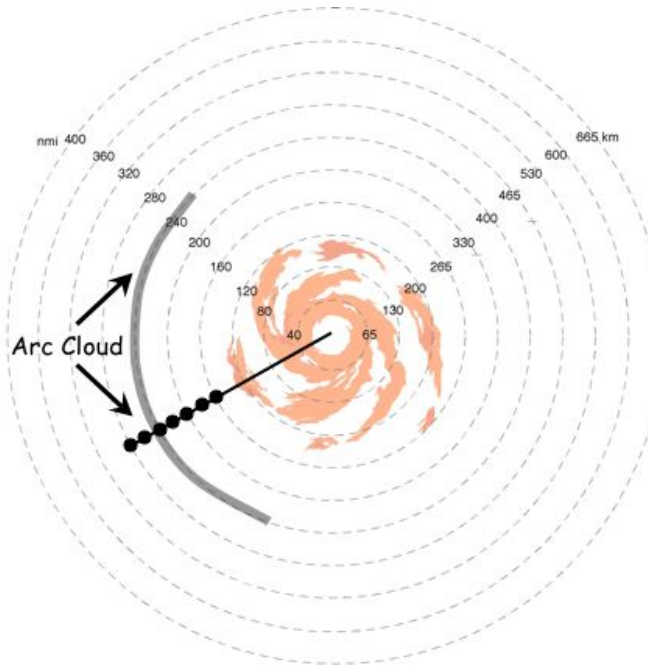


Figure 13-3: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the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

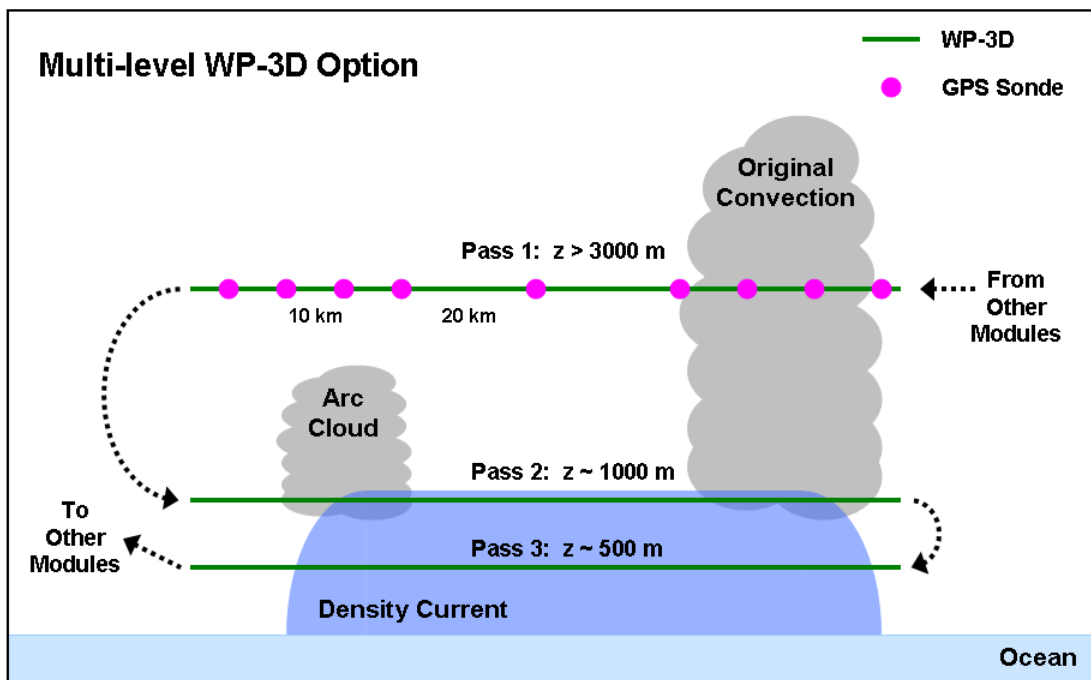


Figure 13-4: The WP-3D flight track for the multi-level option. Azimuth and length of initial midlevel pass with GPS dropsonde sequence will be dictated by the pre-determined flight plan. Lengths of the low-level

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

Program Significance: Tropical cyclones interact with the ocean through the boundary layer. An improved knowledge of mechanisms underlying air-sea exchange across the boundary layer is essential for interpreting dynamical and thermodynamical processes, and hence for the development of models with realistic prognostic capabilities forecasting or simulating tropical cyclones. 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 (Zhang 2010). The experiment is designed to estimate these fluxes 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

- Directly measure turbulent fluxes near the top of the inflow layer;
- Determine the air-sea fluxes both as a residual to an energy budget and via the bulk aerodynamic formulae;
- Quantify the capabilities of the operational hurricane models to accurately capture and represent the turbulent fluxes near the top of the boundary layer.

Model Evaluation Component: Turbulent fluxes are the key boundary layer conditions for numerical models. How energy is transported in the hurricane boundary layer is crucial to the hurricane maintenance and intensification. Observations that are collected during this experiment module will be used to evaluate the robustness of the operational coupled model forecast system (e.g. HWRF) to represent turbulent fluxes and energy budget in the inflow layer.

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 content 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 1,500 ft (500 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 scatters 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).

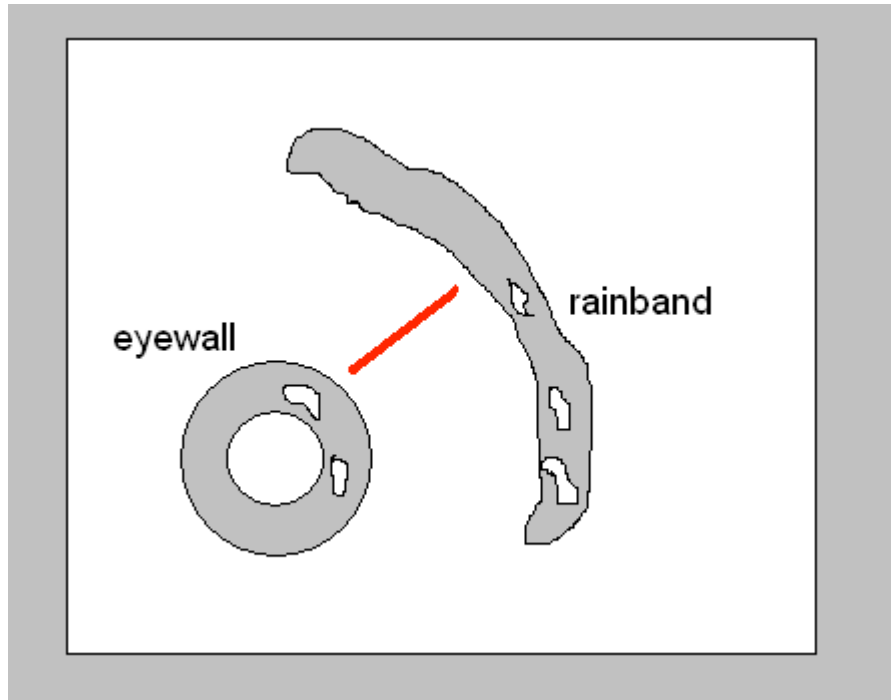


Figure 14-1: Plan view of the preferred location for the stepped-descent module. Red line shows aircraft track.

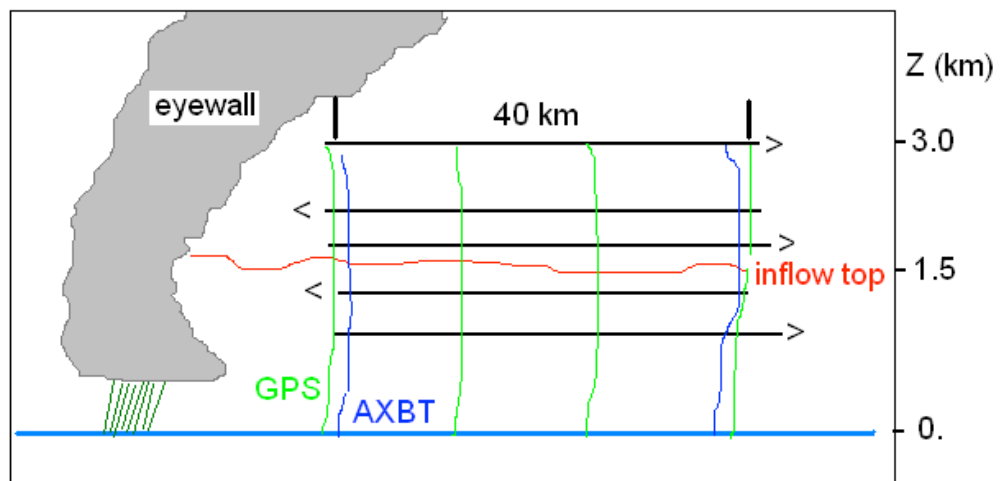


Figure 14-2: Vertical cross-section of the stepped-descent module.

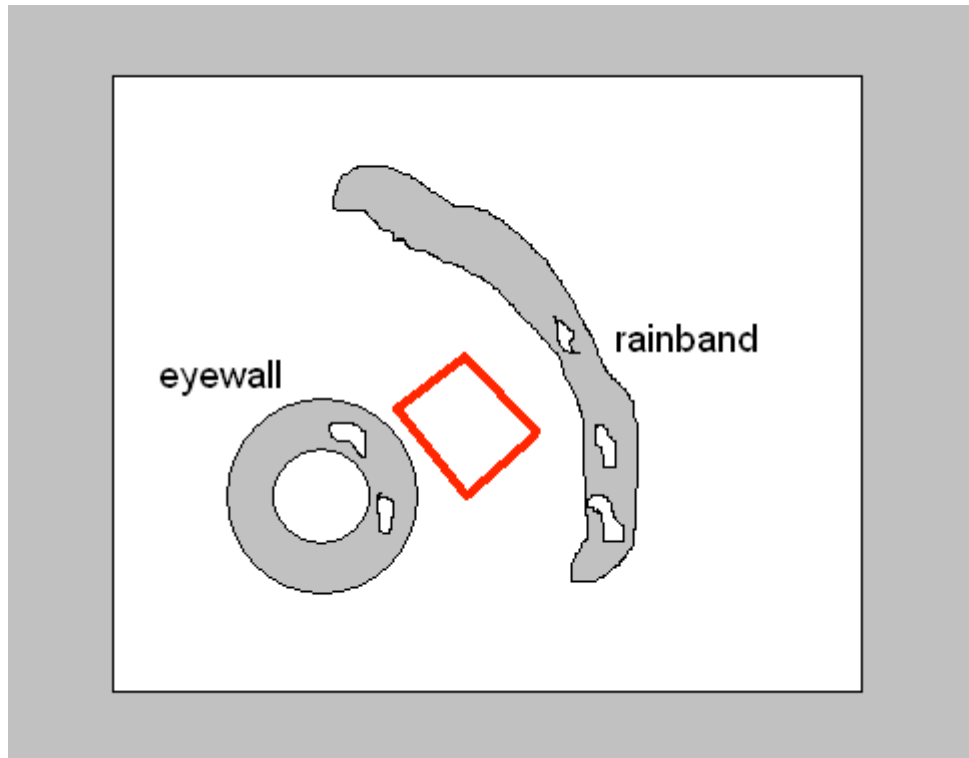


Figure 14-3: Box module used to calculate divergence if no scatterers exist in the volume.

References:

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15. Offshore Wind Module

HRD Point of Contact: Shirley Murillo

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, 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, wave heights and spectrum, 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 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 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.

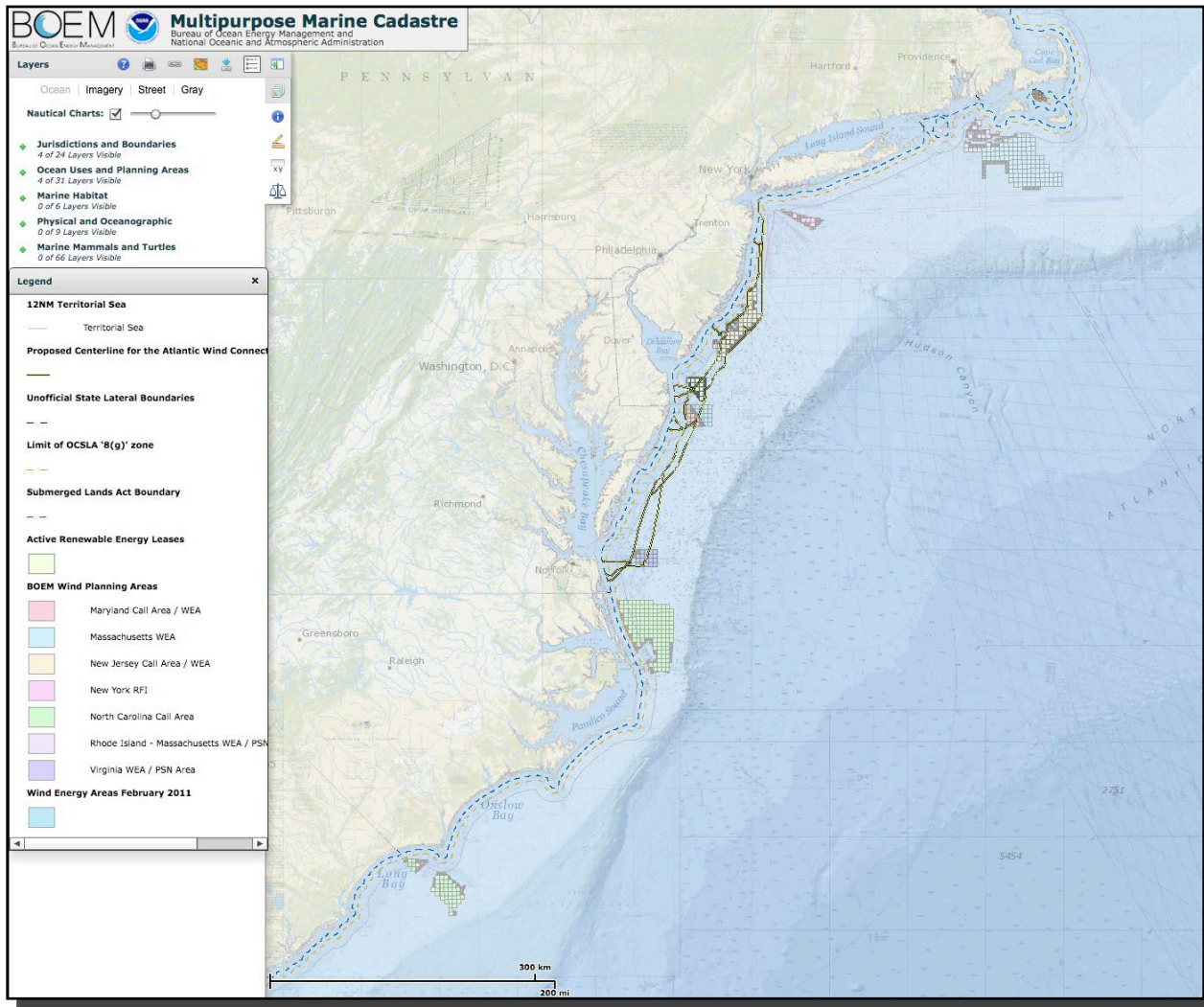


Figure 15-1: Potential offshore wind farm and Atlantic Wind Connection subsurface transmission line locations in federal waters off the U. S. Atlantic coast. Additional areas include state waters off Maine, Nantucket Sound MA, Block Island RI, Atlantic City NJ, Virginia Beach VA, and near Port Isabel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

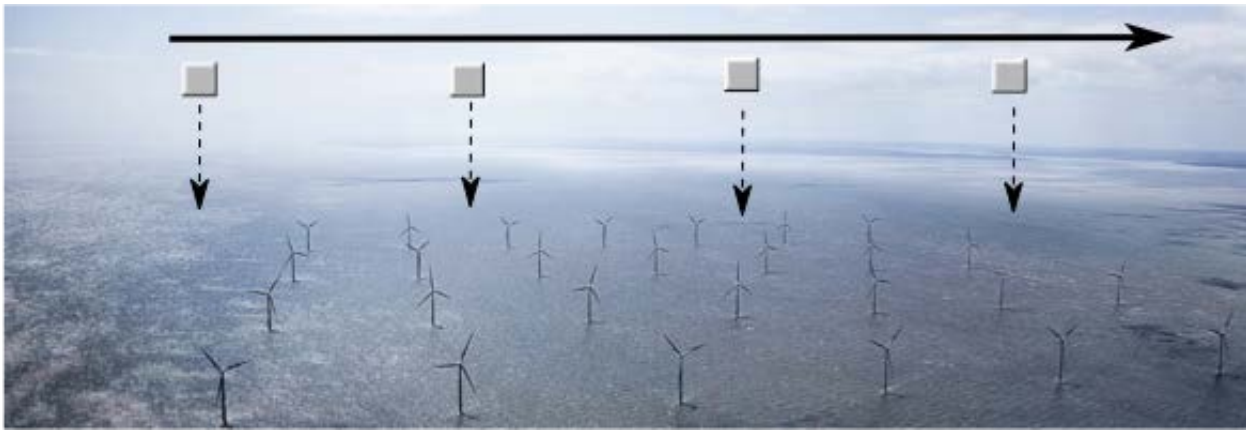
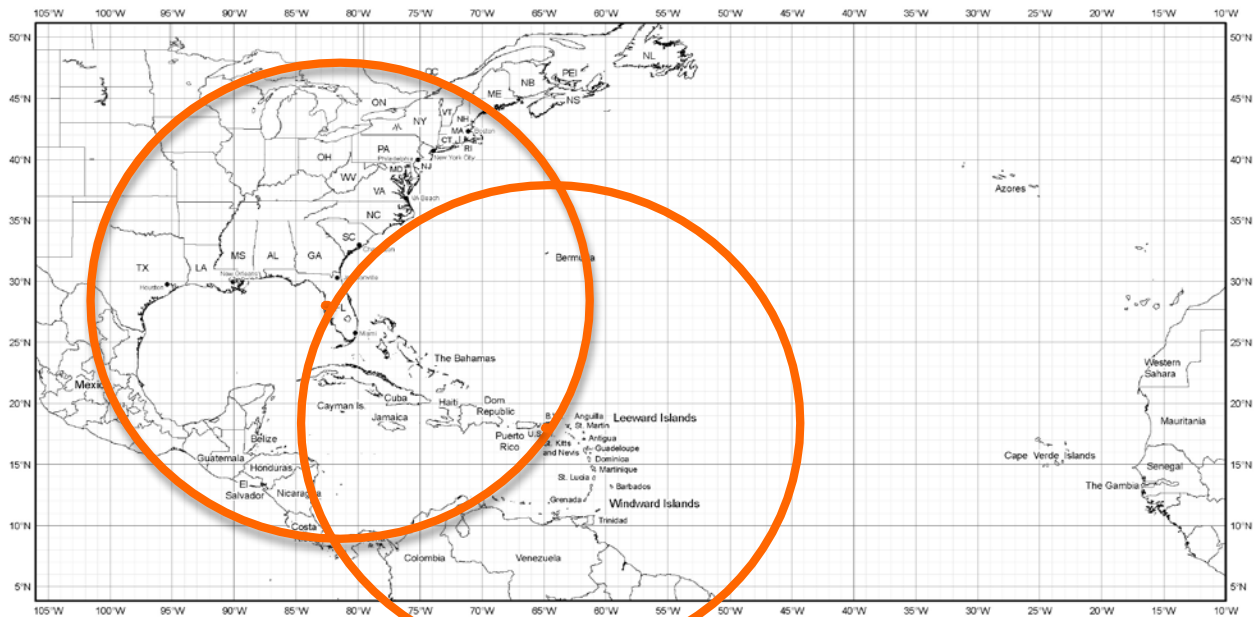


Figure 15-2: Schematic of piggyback pattern showing hypothetical wind farm fly-by with expendable launches at a 2-4 km interval. No U.S. wind farms are yet in operation. (Dong Energy Gunfleet Sands 1 farm off SE England)

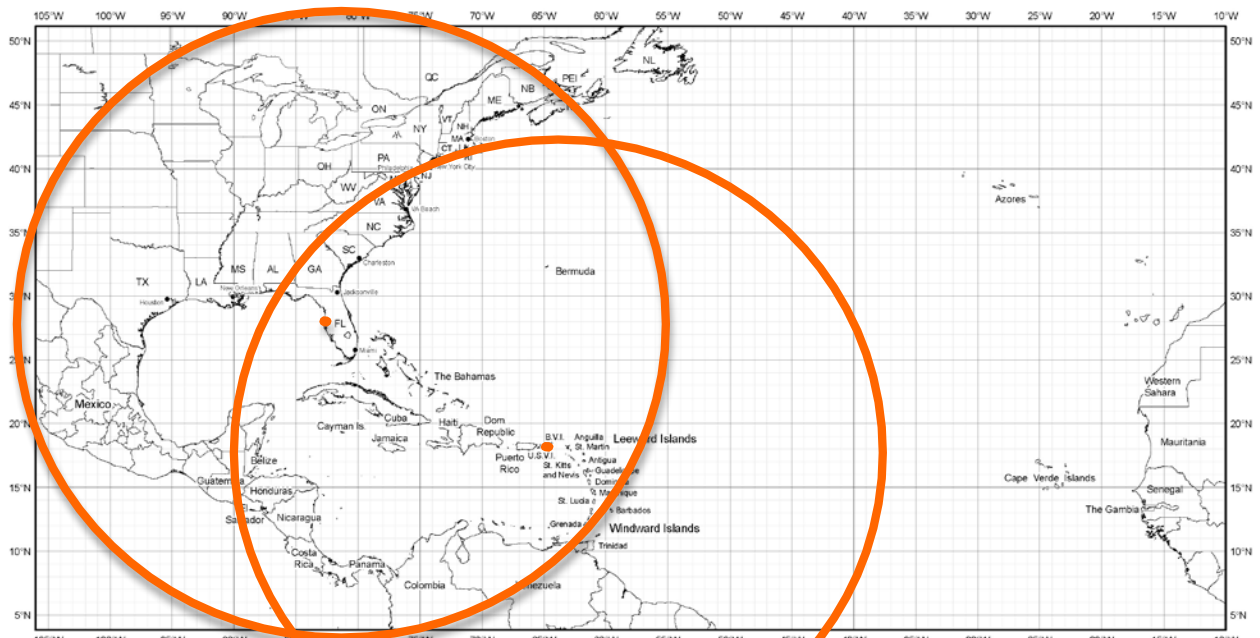
Table 15-2: Expendables (Ex) and aircraft (A/C) measurement systems required for conducting offshore wind experiment

Observing system	Measurement	Number	Type
GPS sonde	Pressure, Temperature, Humidity, Velocity	4-10	Ex
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.