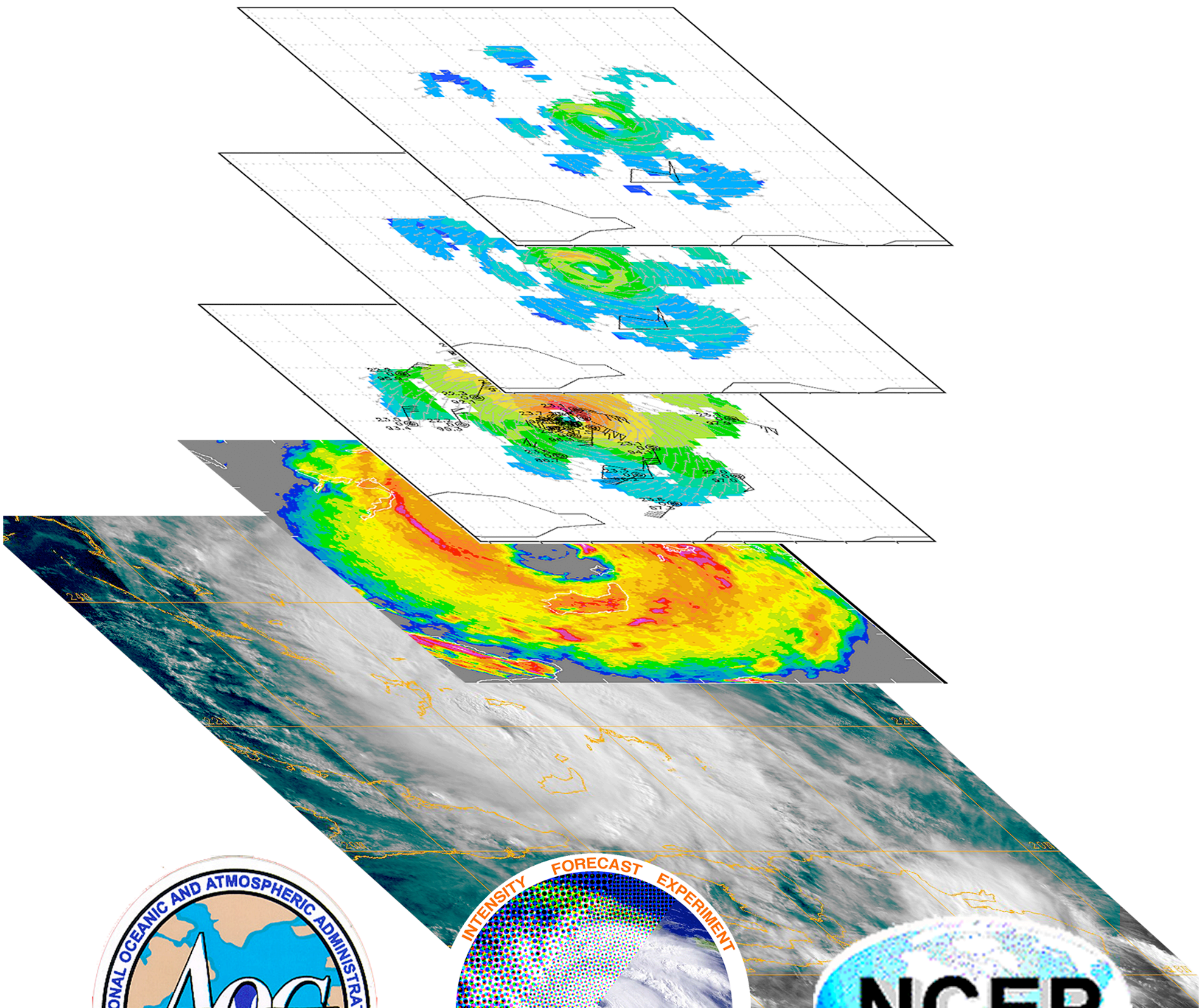
Hurricane Field Program 2012



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

INTENSITY FORECAST EXPERIMENT
IFEX
EMC - NHC -HRD

NCEP

2012 Hurricane Field Program Plan

Hurricane Research Division
National Oceanographic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
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31 May 2012

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INTRODUCTION

National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
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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 TC model, HWRF, is run at 9 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 it 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, each one corresponding to which IFEX goal they most directly address (note that many experiments address multiple IFEX goals). The flight patterns that comprise these various experiments 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 experiment or operational mission follows, including descriptions of the scientific and details of the associated flight patterns.

In this document reference is made to either "experiments" or "modules." For this discussion, "experiments" refer to when research scientists (i.e., from HRD) set the flight pattern for the entire mission. Operational needs take priority in this scenario. "Modules" refer to short patterns that can be flown as a part of larger experiments (either operationally- or research-tasked). 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*

(1) 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 a major hurricane. The definition is meant 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 is: 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.

(1a) 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.

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

(2) NESDIS Ocean Winds and Rain Experiment: This will be executed by NESDIS and aims to improve understanding of microwave scatterometer retrievals of the ocean surface wind and to test new remote sensing techniques. The NESDIS/Center for Satellite Research and Applications in conjunction with the University of Massachusetts (UMASS) Microwave Remote Sensing Laboratory and AOC have been conducting flights as part this experiment for the past several years. Collecting the raw data allows spectral processing to be done which will allow the rain and surface contributions in the AWRAP data to be decoupled. This is critical in understanding the impacts of rain on the measurements, and thus, the ocean surface wind vector retrievals.

(3) Gale UAS Module: This is a single-aircraft module whose primary objective 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.

(4) 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.

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

(5) East Pacific Decay Experiment: The observational objective is to obtain SST and flight-level, surface, and profile wind observations in tropical cyclones over several days during the decay process over cold water.

(6) 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.

(7) Saharan Air Layer Experiment: This is a multi-option, multi-aircraft experiment which uses dropwindsondes launched from the NOAA G-IV and NOAA P-3 to examine the thermodynamic and kinematic structure of the SAL and its potential impact on TC genesis and intensity change. The dropwindsonde release points will be selected using real-time GOES SAL tracking imagery from UW-CIMSS and mosaics of SSM/I total precipitable water from the Naval Research Laboratory. Specific effort will be made to gather atmospheric information within the SAL as well as regions of high moisture gradients across its boundaries and the region of its embedded mid-level easterly jet. The goals are to better understand and predict how the SAL dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change and to assess how well these components of the SAL are being represented in forecast models.

(8) Extra-tropical Transition Experiment: 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.

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

(10) Rapid Intensity Change Experiment: 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).

(11) Tropical Cyclone/AEW 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.

(12) Tropical Cyclone Landfall and Inland Decay Experiment: 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. An accurate description of the TC surface wind field is important for warning, preparedness, and recovery efforts.

(13) Tropical Cyclone Eye Mixing Module: The objective is to directly observe the kinematic and thermodynamic structures of eyewall mesovortices for the first time.

(14) Eyewall Sampling and Intensity Change Module**:** This is a single-aircraft dual-option (1 circle or concentric circles) experiment designed to study both the thermodynamics and kinematics of inflow into the hurricane eyewall, including estimates of radial fluxes of mass, moisture and energy, from just below flight level to the surface. Multi-circle flight plans may allow estimates of surface fluxes of moisture, energy or momentum from residuals.

(15) Air Sea Surface Flux Module: This is a single-aircraft module to get information on the bulk exchange coefficients that are important for understanding the air-sea exchanges of heat and momentum. This module that was executed during the CBLAST field campaign calls for a high frequency of dropwindsonde deployments through the eyewall region. A second module would be to fly pie shape wedges that originate in the eye and extend outward just beyond the eyewall.

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

(17) 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.

(18) Aerosol/Cloud Droplet Measurement Module: This is a single-aircraft module designed to detect the size of the aerosol particles and the activation spectrum in the hurricane environment to determine their impact on the low altitude cloud droplet layer, whose droplets coalesce into larger precipitation particles. The need for this data is to help the numerical modelers improve model physics to obtain better precipitation forecasts, both as rain rate and mass concentration. An additional goal is to determine the possible impacts of pollutant aerosol entrainment into the hurricane cloud structure, as pollutant loading has been theorized to be a mitigating factor in the intensity of the eyewall and rainband convection.

OPERATIONS

1. Locations

Starting on 01 June, N42RF and Gulfstream IV-SP (N49RF) aircraft will be available for possible missions with two flight crews available for back to back mission on N42RF. Operations for both 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 30 September 2012.

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 are to receive primary notification at each decision or notification point are shown in Figs. A-1, A-2, and A-3 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 operations on a non-interference basis with tasked operational missions from 01 June to 31 October 2012. Also, the G-IV aircraft should be available, on a non-interference basis with tasked operational missions from 01 June to 31 October 2012.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of the 2012 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 2012 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 with 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 principle 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 2012 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, on 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

1. P-3 Three-Dimensional Doppler Winds Experiment

Principal Investigators: John Gamache and Vijay Tallapragada (EMC)

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

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

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

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

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

Links to IFEX: The Three-Dimensional Doppler Winds 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. 1-1); ii) the box-spiral pattern (Figs. 1-2 and 1-3); iii) the rotating figure-4 pattern (Fig. 1-4); iv) the butterfly pattern that consists of 3 penetrations across the storm center at 60-degree angles with respect to each other (Fig. 1-5); and v) the single figure-4 (Fig. 1-6). 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. 1-1) 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. 1-2, 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 render 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. 1-4). 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. 1-5) 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. 1-6) 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

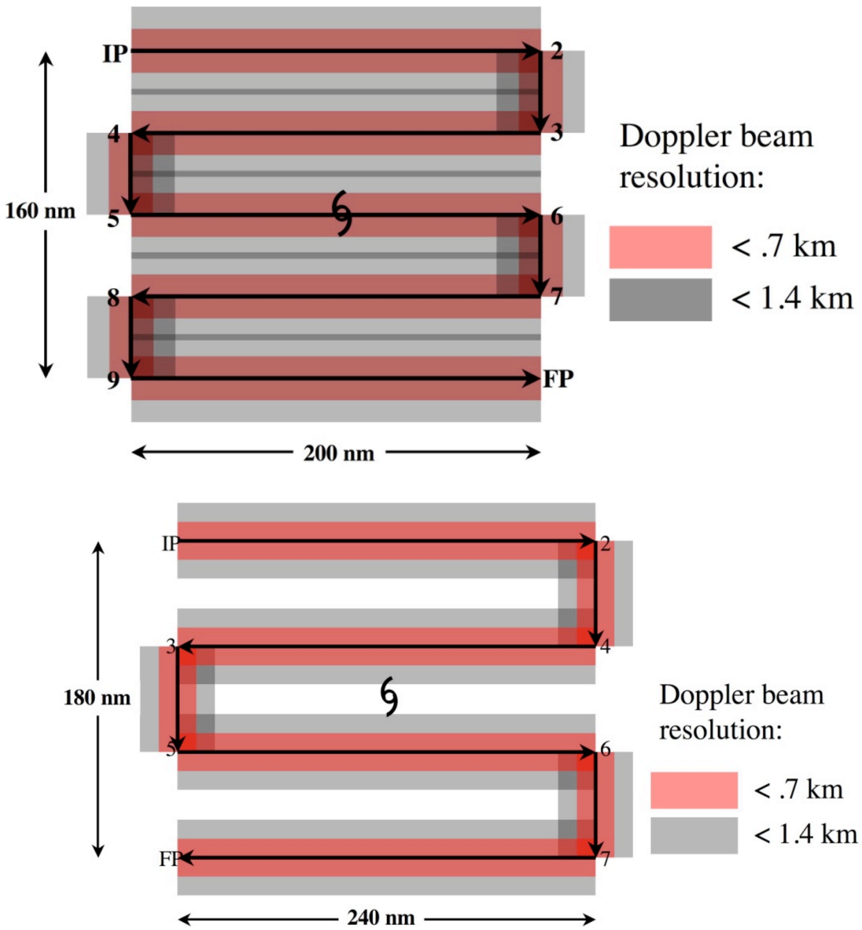

Figure 1-1: Display of Doppler coverage for A (upper panel) and B (lower panel) lawnmower patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately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

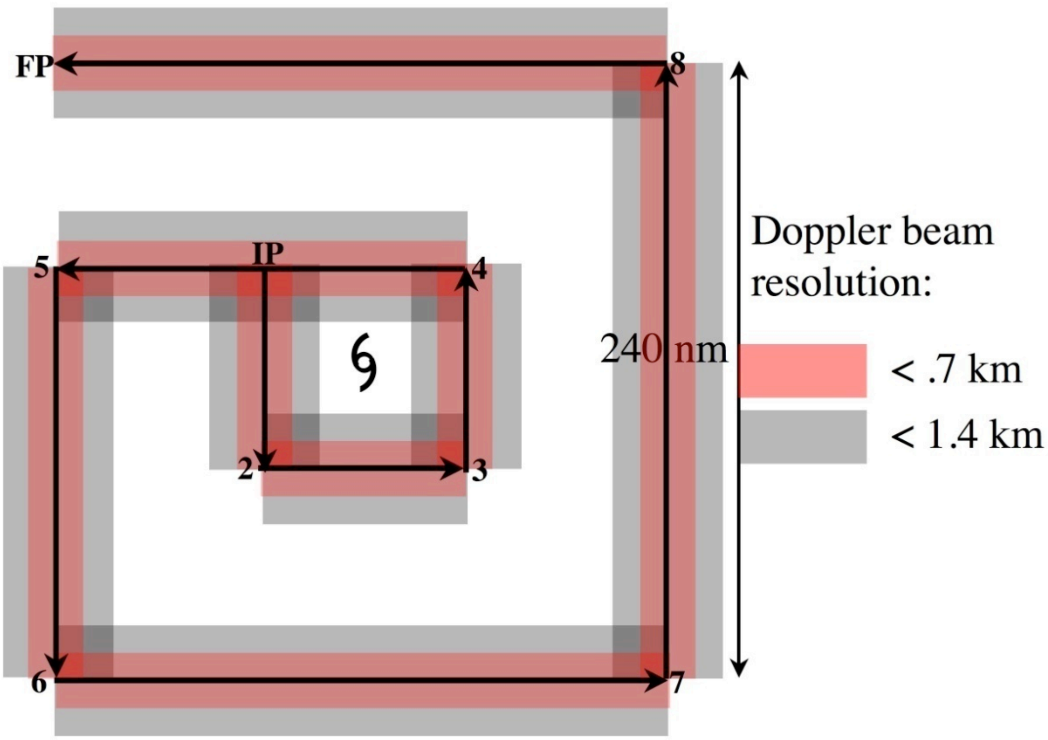

Figure 1-2: Doppler radar coverage for box-spiral pattern A. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately 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.
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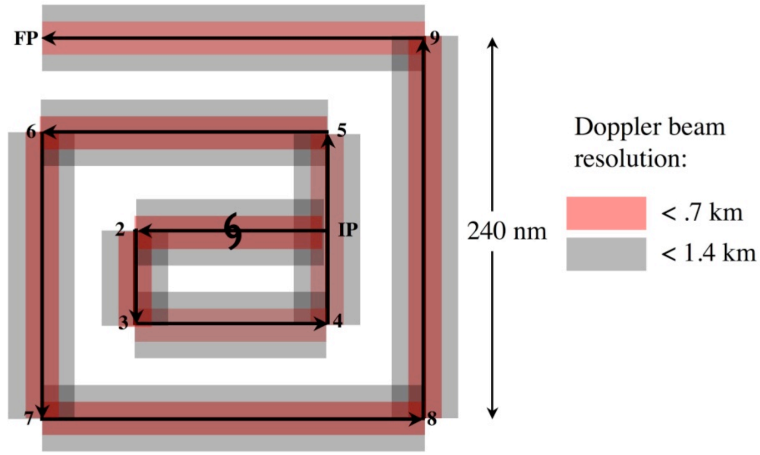
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 UTC operational model analysis times.

P-3 Three-Dimensional Doppler Winds



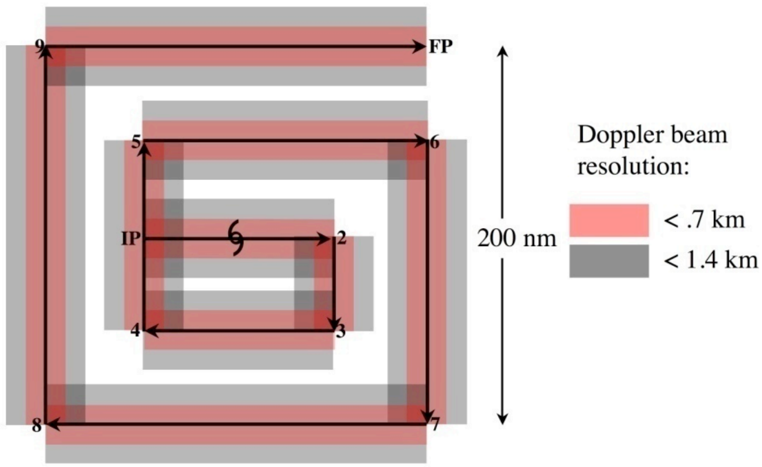
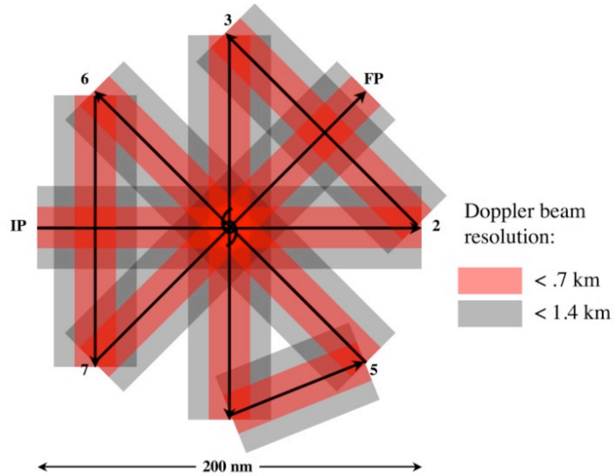


Figure 1-3: Doppler radar coverage for box-spiral pattern with 200- (top) and 240- (bottom) nm legs. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately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



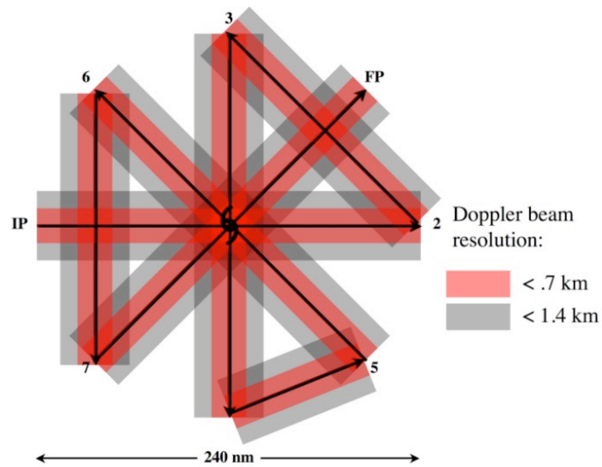


Figure 1-4: Doppler radar coverage for radial extents of 100 (top) and 120 (bottom) nm of the rotating figure-4 patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent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

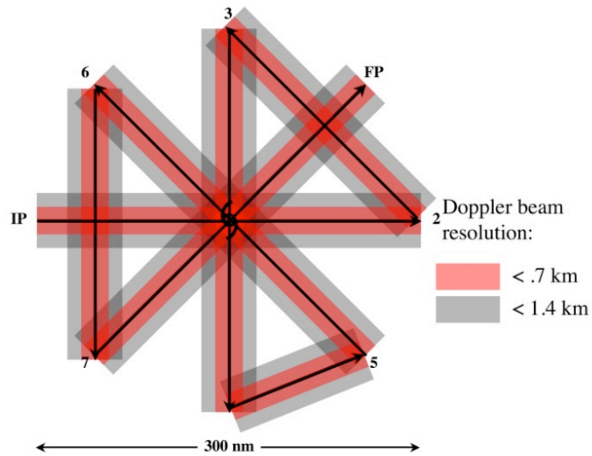


Figure 1-4 (continued): Doppler radar coverage for 150-nm legs for a rotating figure-4. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

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

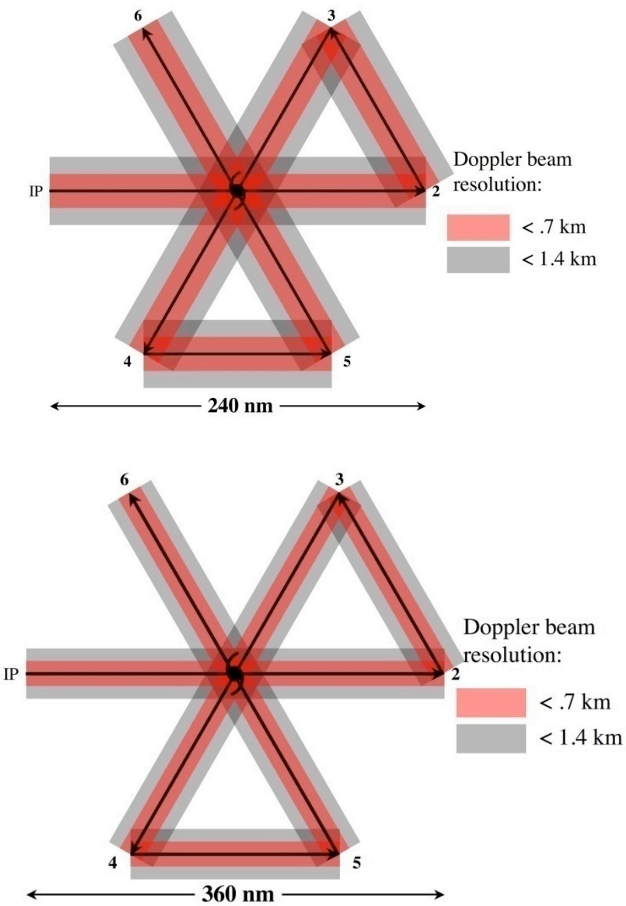


Figure 1-5: Doppler radar coverage for 120- (top) and 180- (bottom) nm legs for the Butterfly pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately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

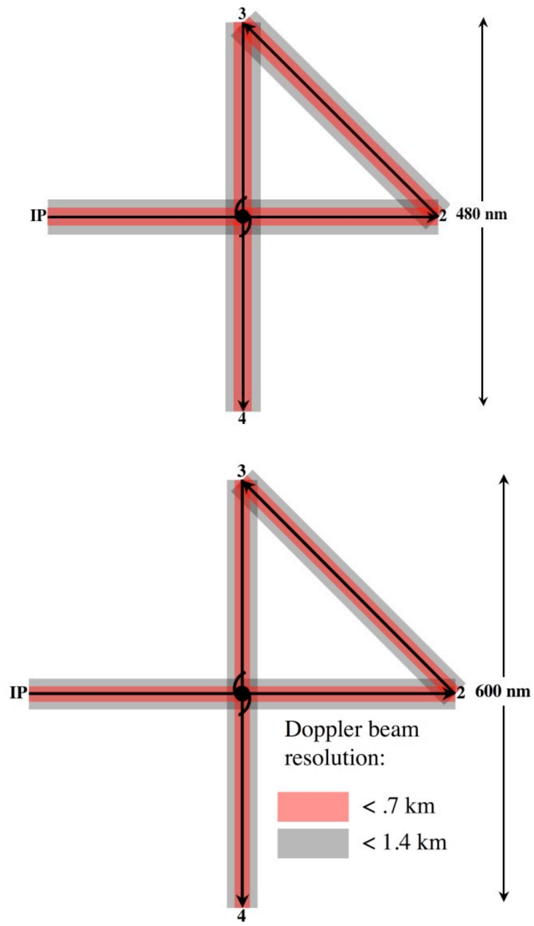


Figure 1-6: Doppler radar coverage for 300-nm legs for a single figure-4 pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from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

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

1a. G-IV Tail Doppler Radar Experiment

Principal Investigator(s): John Gamache, Peter Dodge, Paul Reasor, Sylvie Lorsolo, Altug Aksoy

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 2012, 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 2012 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. 1-1 and 1-2); ii) the rotating figure-4 pattern (Fig. 1-3); iii) the butterfly pattern that consists of 3 penetrations across the storm center at 60-degree angles with respect to each other (Fig. 1-4); iv) the single figure-4 (Fig. 1-5); and v) the surveillance/TDR combination pattern (Fig. 1-6). These patterns provide the maximum flexibility in planning, in which the need for dense date coverage must be balanced against the need to sample the entire vortex.

Square-spiral pattern: As the weak, developing, poorly organized circulations become larger, it will be necessary to spread out the pattern to cover a larger area at the expense of complete Doppler coverage. The pattern, as shown in Figs. 1-1 and 1-2, 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. 1-1 (1-2) 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. 1-3). 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. 1-4) 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. 1-5) 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. 1-6) will be flown to test the ability of the G-IV platform to satisfy both NHC-tasked surveillance requirements (i.e., sampling the TC environment with GPS dropsondes) and the EMC-tasked requirement for tail Doppler radar sampling of the TC core region. The environmental sampling consists of a cyclonic circumnavigation of the TC at a fixed radius of 150 nm. This is followed by core region sampling using a rotating figure-4 pattern out to 75 nm. The duration of this pattern is approximately 6 h. Any orientation of the flight legs may be flown to permit the initial and final points to be closest to the base of operations.

G-IV Tail Doppler Radar Experiment Flight Planning Approach: Ideally, for initial experiments following the NOAA acceptance of the G-IV radar this would entail coordination with a P-3 aircraft conducting a Three-Dimensional Doppler Winds flight when the system is at depression, tropical storm, or hurricane strength. This initial coordination is necessary for 1) comparing and synthesizing storm structure derived from the two radar platforms and 2) the most thorough testing of HEDAS with this new data source. Subsequent flights may relax this requirement for P-3 coordination so as to test the Surveillance/TDR Combination Pattern (Fig. 1-6). It is not anticipated that the Combination Pattern will be flown during NHC tasking of the G-IV in 2012.

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.

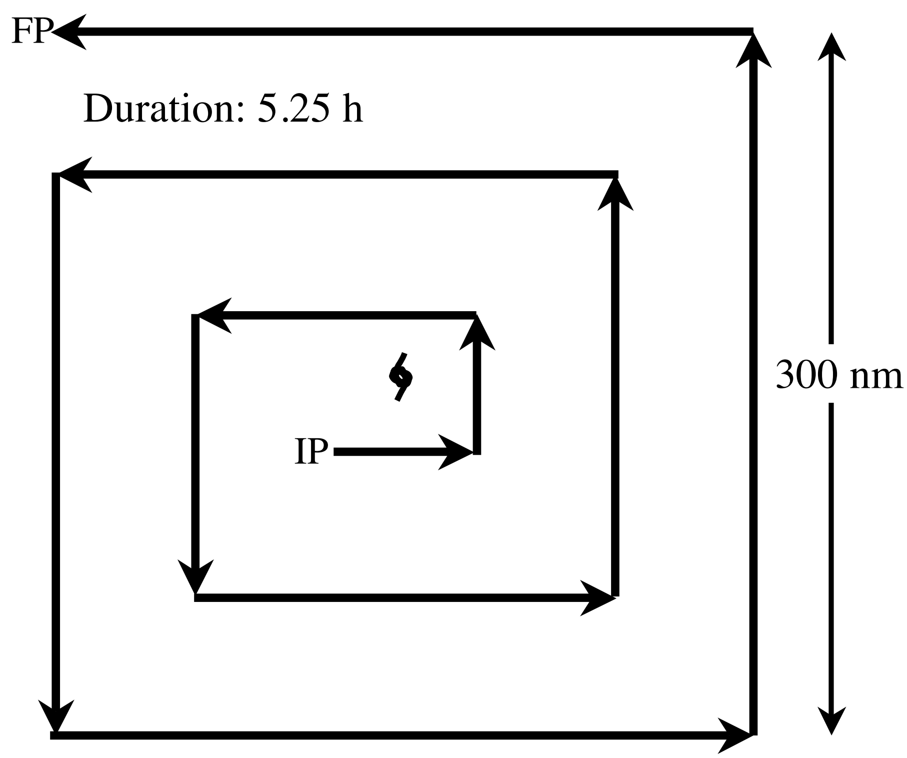


Figure 1-1: G-IV tail Doppler radar pattern – Square Spiral (outward)

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 5.25 hour--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)

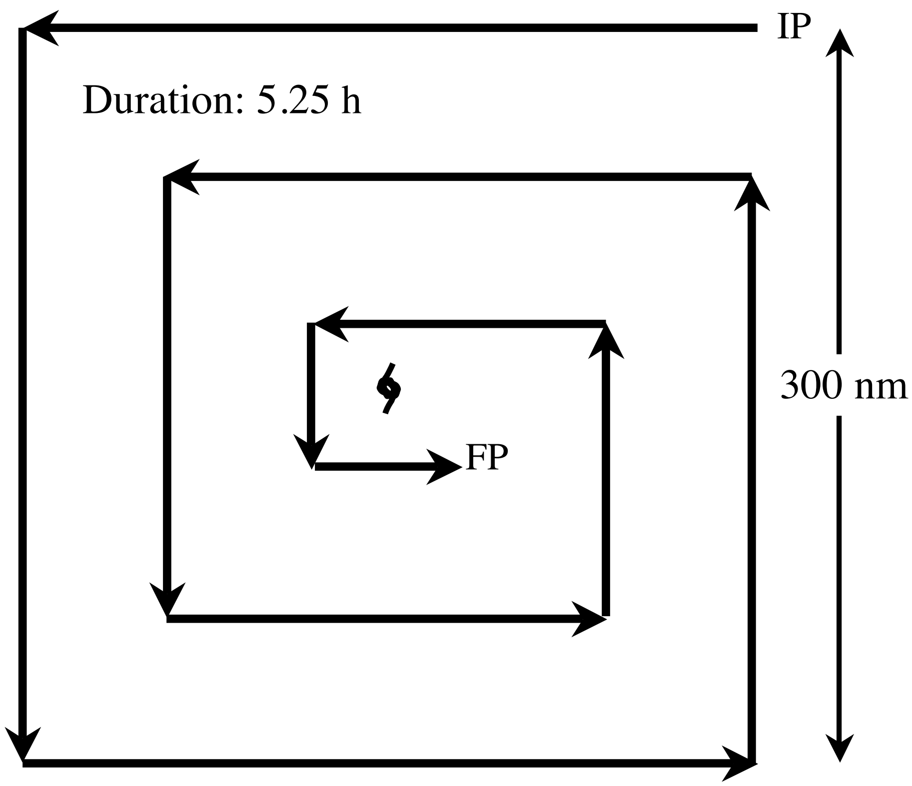


Figure 1-2: G-IV tail Doppler radar pattern – Square Spiral (inward)

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 5.25 hour--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)

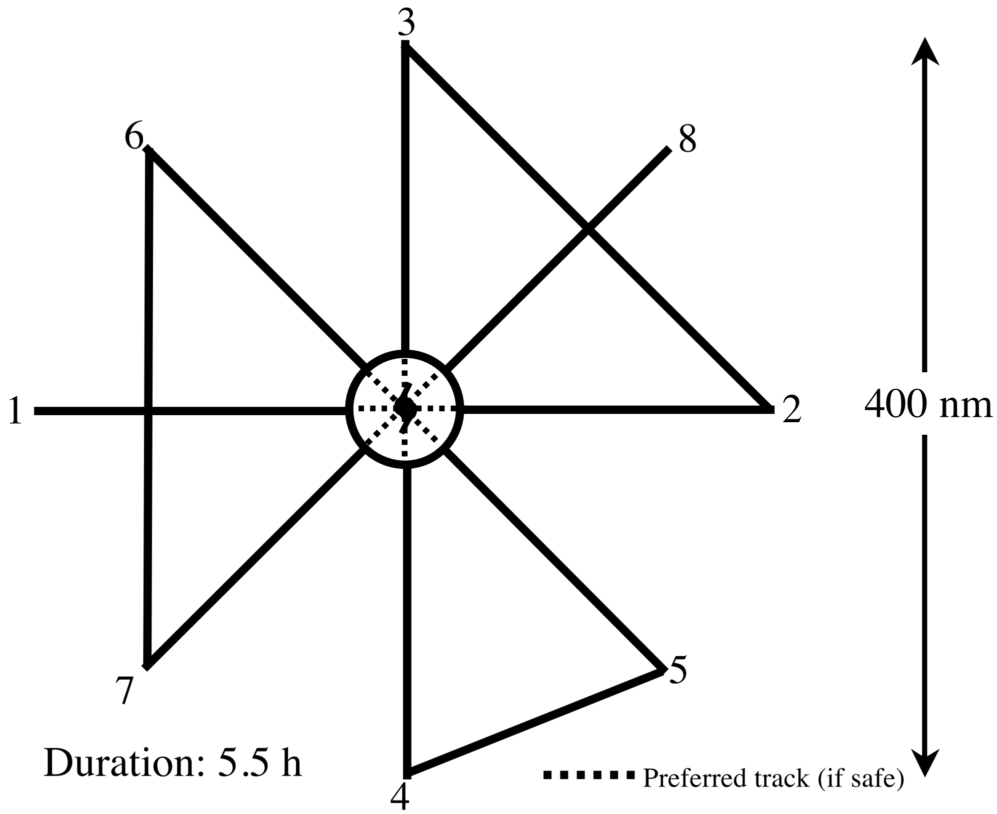


Figure 1-3: G-IV tail Doppler radar pattern – Rotating Figure-4

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: 2190 nm, or 5.5 hours

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)

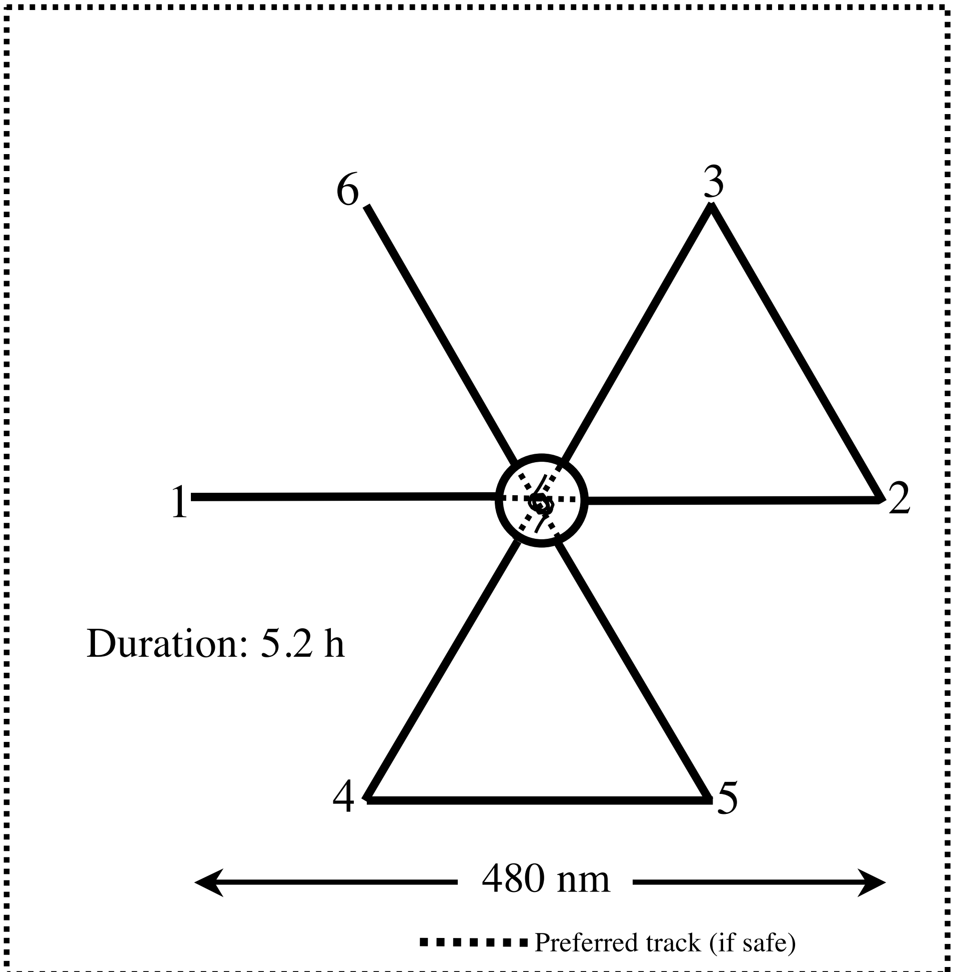


Figure 1-4: G-IV tail Doppler radar pattern – Butterfly

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: 2080 nm, or 5.2 hours

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)

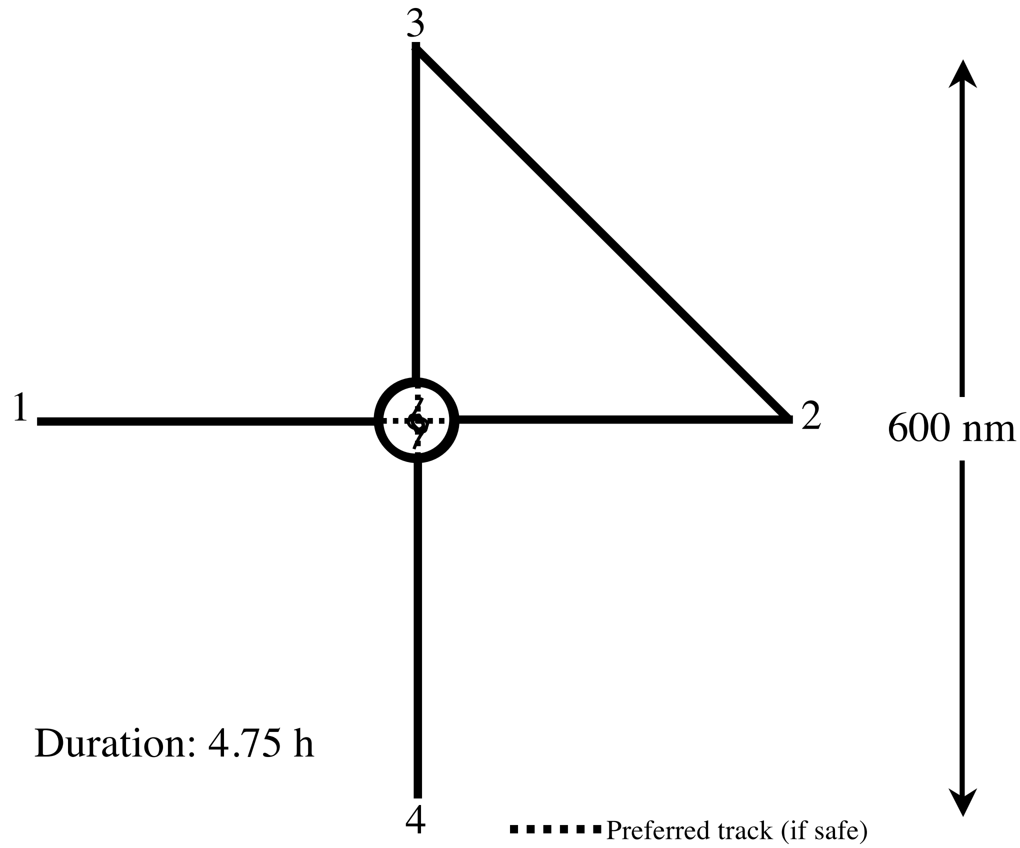


Figure 1-5: G-IV tail Doppler radar pattern – Single Figure-4

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: 1900 nm, or 4.75 hours--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)

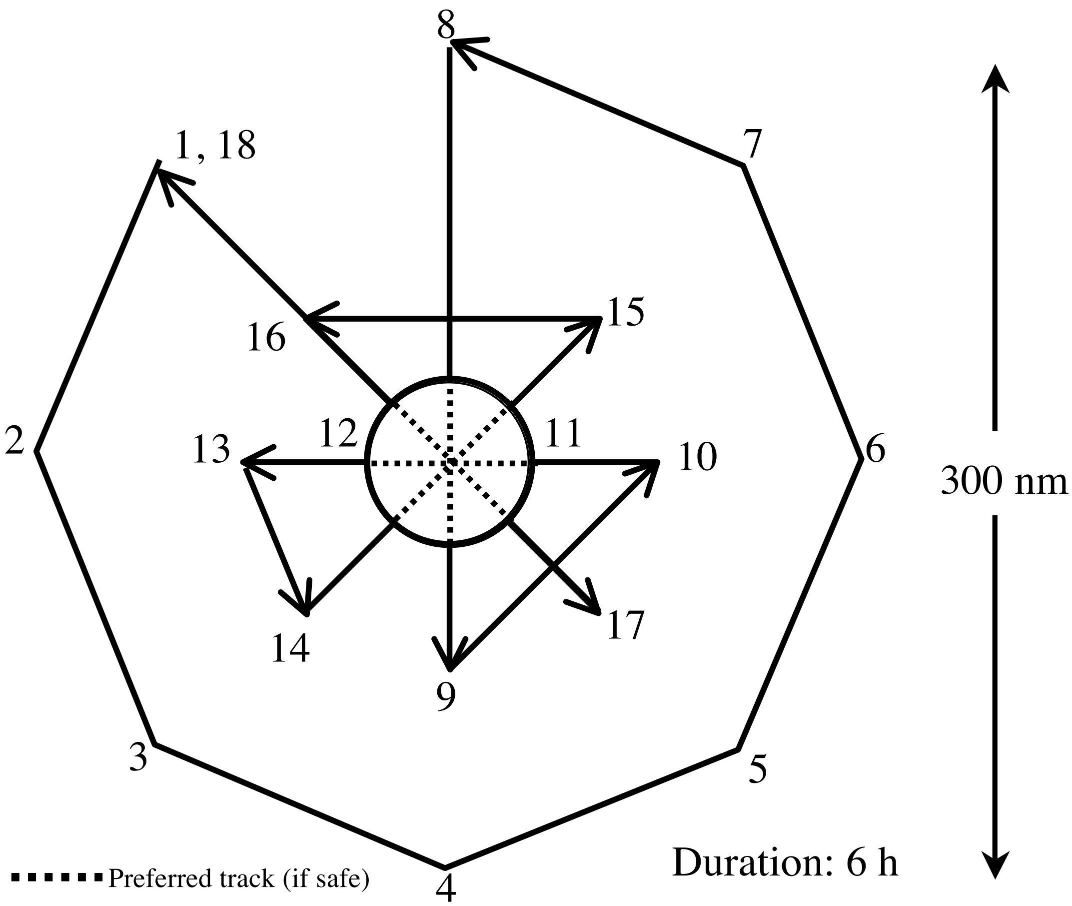


Figure 1-6: G-IV tail Doppler radar pattern – Surveillance/TDR Combination

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: 2350 nm, or about 6 hours

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)

2. The NESDIS Ocean Winds Hurricane Experiment

Principal Investigator: Paul Chang (NESDIS)

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

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

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

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

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

derived wind profiles down to 0 m altitude.

Flight Profiles:

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

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

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

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

3. GALE UAS Eye/Eyewall Module

Principal Investigator: Joe Cione

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

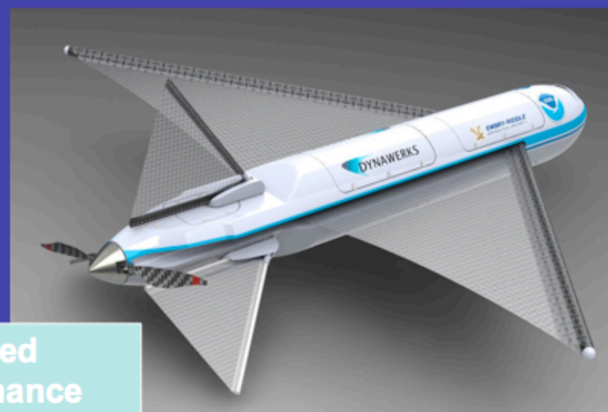
Why UAS?

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

GALE UAS

GALE is an aircraft platform that is currently under development by Embry Riddle Aeronautical University in close cooperation with the Dynawerks Corporation (http://www.dynawerks.com/index.html). The intended deployment vehicle for the GALE is the P-3 Orion. The GALE is a small electric-powered unmanned aircraft with 1-2 hour endurance and is capable of carrying a 1-2lb payload. The GALE can be launched from a P-3 sonobuoy tube in flight, and terrain-permitting, is capable of autonomous landing and recovery. The GALE is supported is capable of supporting multiple aircraft operations. GALE's control station will be onboard the deployment aircraft (i.e. P-3), allowing for in-air command and control after launch. The GALE, when deployed from NOAA's P-3's within a hurricane environment, will 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 will be able to carry a comparable meteorological payload (i.e. lightweight sensors for P, T, RH, V). Unlike the GPS sonde however, the GALE 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, GALE 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. GALE UAS operations also represent a potentially significant upgrade relative to the more traditional "deploy, launch and recover" low altitude UAS hurricane mission plan used in the past. By leveraging existing NOAA manned aircraft assets, GALE operations significantly reduces the need for additional manpower. The GALE 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 GALE UAS are illustrated in Figure 3-1.

Gale UAS



Performance Attribute	Estimated Performance
Mission Weight	8.0 lbm
Cruise Speed	42 kts
Dash Speed	110 kts
Stall Speed	22 kts
Mission Endurance	60 minutes

Figure 3-1. GALE Unmanned Aerial System Specifications.

Relevance to NOAA

In recent years, an increasing number of hurricanes have impacted the United States with devastating results, and many experts expect this trend to continue in the years ahead. In the wake of Katrina (2005), NOAA is being looked at to provide improved and highly accurate hurricane-related forecasts over a longer time window prior to landfall. NOAA is therefore challenged to develop a program that will require applying the best science and technology available to improve hurricane prediction without placing NOAA personnel at increased risk. UAS are an emerging technology in the civil and research arena capable of responding to this need.

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

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

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

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

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

The strength and location of the storm's strongest winds
The radius of maximum winds
The storm's minimum sea level pressure (which in turn may give forecasters advanced warning as it relates to dangerous episodes of rapid intensity change)

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

This HRD field program module is designed to build on the successes and strong momentum from recent UAS missions conducted in 2005 and 2007 as well as successful P3-UAS test flights in 2009. As part of this effort, any UAS data collected will continue to be made available to NOAA's National Hurricane Center in real-time.

Mission Description
The primary objective of this experiment is further demonstrate and utilize the unique capabilities of a low latitude UAS platform in order to better document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. For this purpose, we will be using the GALE UAS. Since the GALE will be deployed from the manned P-3 aircraft, no UAS-specific forward deployment teams will be required. Furthermore, since the GALE is launched using existing AXBT launch infrastructure, no special equipment is required beyond a 'ground' control station GALE operators will have onboard the P-3. The target candidate storm is a mature hurricane with a well- defined eye. Furthermore, since the P-3 will have to operate within the eye, daylight missions will be required so as to maintain P-3 visual contact with the eyewall at all times. This capability will have the dual positive effect of minimizing experimental and safety risks. The immediate focus of this experimental module will be to test the operational capabilities of the GALE UAS within a hurricane environment. Besides maintaining continuous command and control links with the P-3, these flights will test the accuracy of the new MISTSONDE meteorological payload (vs. observations taken from dropsondes released near the UAS). The UAS will be tested to see if it can maintain altitudes according to command. In addition, the GALE UAS will attempt to fly at extreme altitudes (as low as 200 ft) in low (eye) and high (eyewall) wind conditions within hurricane environment. The longer-term goal for this UAS platform is to assist scientists so they can better document and ultimately improve their understanding of the rarely observed tropical cyclone boundary layer. To help accomplish this, the UAS will make detailed observations of PTHU at low altitudes within the hurricane eye and eyewall that will then be

compared with multiple in-situ and remote-sensing observations obtained from manned aircraft (NOAA P-3 and AFRES C-130) and select satellite-based platforms. In addition, a primary objective (but not a 2012 requirement) for this effort will be to provide real-time, near-surface wind observations to the National Hurricane Center in direct support of NOAA operational requirements. These unique data will also be used in a 'post storm' analysis framework in order to potentially assist in the numerical and NHC verification process.

For this experiment, NOAA P-3 flight altitude will be at 10,000 ft at all times. Ideally both modules (~1.5h each) would be conducted on the same manned mission. The eye-only module would be conducted first, followed by the eye-eyewall UAS module. The P-3 flight pattern is identical for both eye and eye-eyewall UAS modules. GPS dropsonde and AXBT drop locations are also identical for each UAS module. AXBT and GPS drop locations are explicitly illustrated in the flight plan below. UAS deployment on leg 3-4 is also identical for both modules. UAS operational altitude will be entirely below 5,000 ft. UAS motor will not be activated until an altitude of 5,000 ft is met. The UAS will be conducting a controlled, spiral glide (un-powered) decent from 10,000 ft to 5,000 ft.

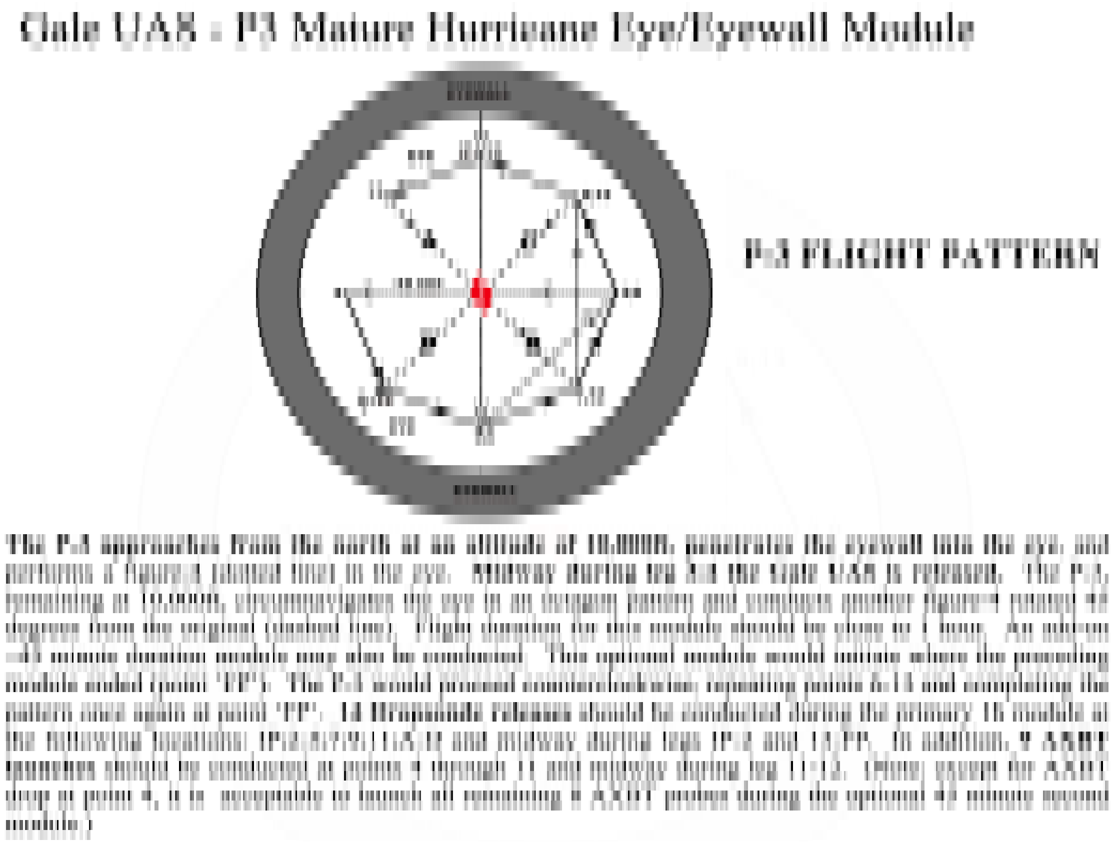
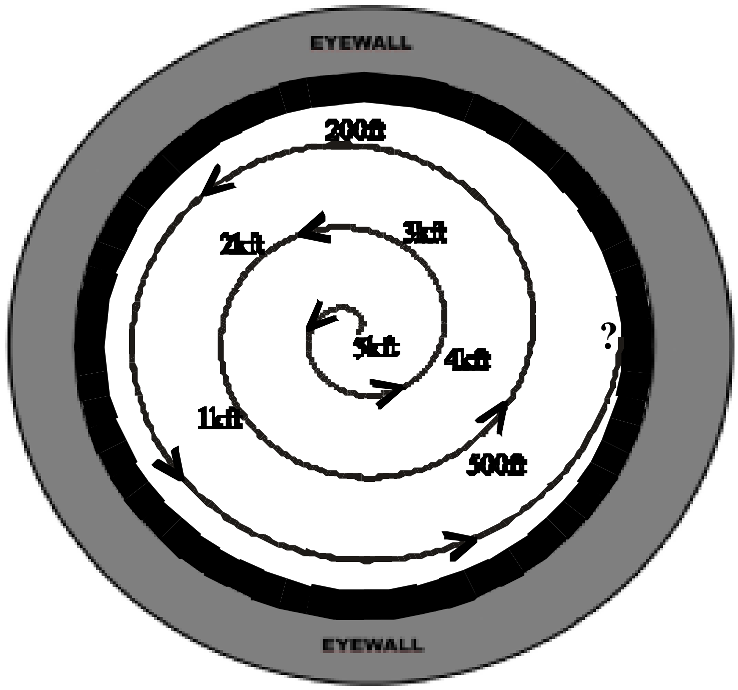


Figure 3-2a. P-3 Pattern for GALE UAS eyewall/eye module.



Midway during P-3 leg 3-4, the Gale USA is released at 10,000 ft altitude. The Gale UAS proceeds to glide (unpowered) in a downward counterclockwise spiral to an altitude of 5,000 ft. **At 5,000 ft the UAS motor is started and the Gale continues its counterclockwise descent in 1000 ft increments.** At each interval (4kft, 3fkt, 2kft, 1kft), the UAS maintains altitude for 3 minutes prior continuing its counterclockwise, radially expanding with decreasing altitude, spiral descent. After 3 minutes at 1,000 ft, the Gale descends to 500 ft and remains at this for 3 minutes. **The UAS continues to descend in 100 ft increments down to 200 ft, maintaining altitude for 3 minutes at each level.** The remainder of the flight is conducted at 200 ft until battery power is fully expended and the UAS reaches the ocean surface. (Note: If full descent to 200 ft 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 an attempted YAS eye-eyewall penetration, Gale should ascend from 200 ft to a (minimum) altitude for 500 ft.)

Figure 3-2b. GALE UAS pattern (eye only).

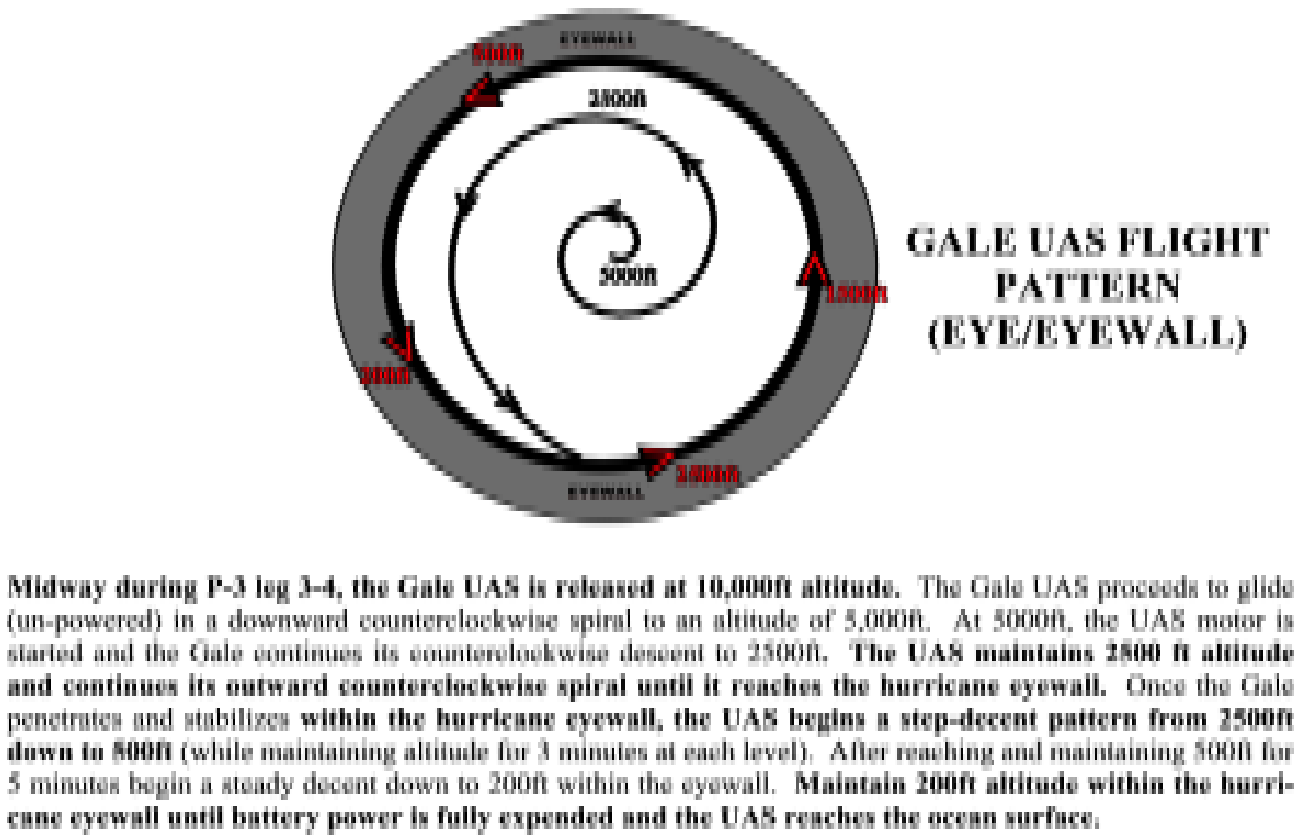


Figure 3-2c. GALE UAS pattern (eye/eyewall).

4. TC-Ocean Interaction Experiment

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

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 2012 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 lead 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. 4-1).

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. 4-1). 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.

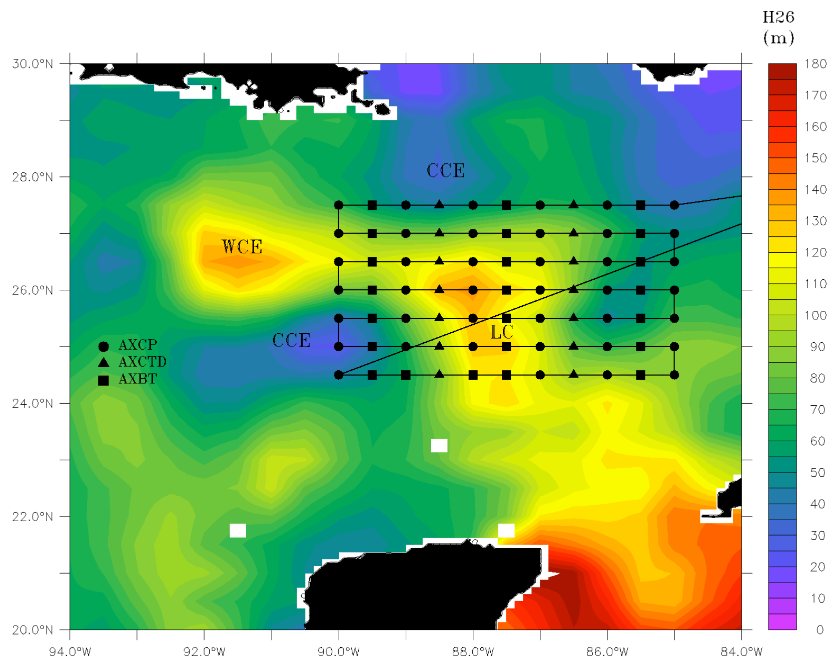


Figure 4-1: Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at KMCF.

Track-dependent survey. For situations that arise in which a TC is forecast to travel outside of the immediate Loop Current region, a pre- and post-storm ocean survey focused on the official track forecast is necessary. The pre-storm mission consists of deploying AXBTs/AXCTDs on a regularly spaced grid, considering the uncertainty associated with the track forecast. A follow-on post-storm mission would then be executed in the same general area as the pre-storm grid, possibly adjusting for the actual storm motion. Figure 4-2 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.

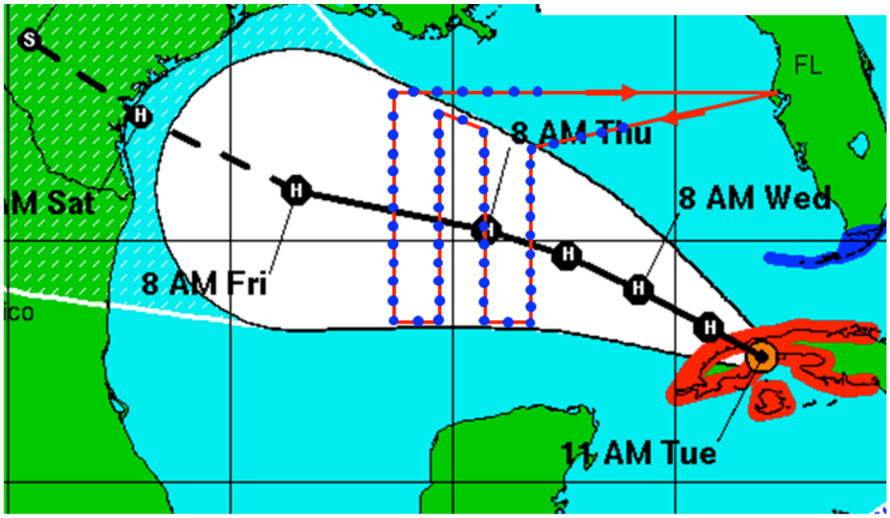


Figure 4-2: Track-dependent AXBT/AXCTD ocean survey. As for the Loop Current survey, a total of 60-80 probes would be deployed on a grid (blue dots).

Coordinated float/drifter deployment overflights:

Measurements will be made using arrays of profiling and Lagrangian floats and 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 will measure SST, surface pressure and wind speed and direction. Thermistor chain Autonomous Drifting Ocean Station (ADOS) drifters add ocean temperature measurements to 150m. All drifter data is reported in real time through the Global Telecommunications System (GTS). 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. E-M APEX Lagrangian floats will measure temperature, salinity and velocity profiles to 200m. Profile data will be reported in real time on GTS.

Substantial resources for this work will be funded by external sources. 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.

Main Mission description:
P-3 flights will be conducted in collaboration with operational float and drifter deployments by WC-130J aircraft operated by the AFRES Command (AFRC) 53rd Weather Reconnaissance Squadron. The P-3 surveys will provide information on the storm and sea-surface structure over the float and drifter array.

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. Rick Lumpkin (PhOD) will be the primary point of contact for coordination with the 53rd WRS and CARCAH.

Flights:
Coordinated float/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 4-3 shows the 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. The Lagrangian floats and 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.

Day 2. P-3 In-storm mission- Figure 4-4 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. 4-5). The extended arrays will consist entirely of thermistor chain and minimet drifters, with 7 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.

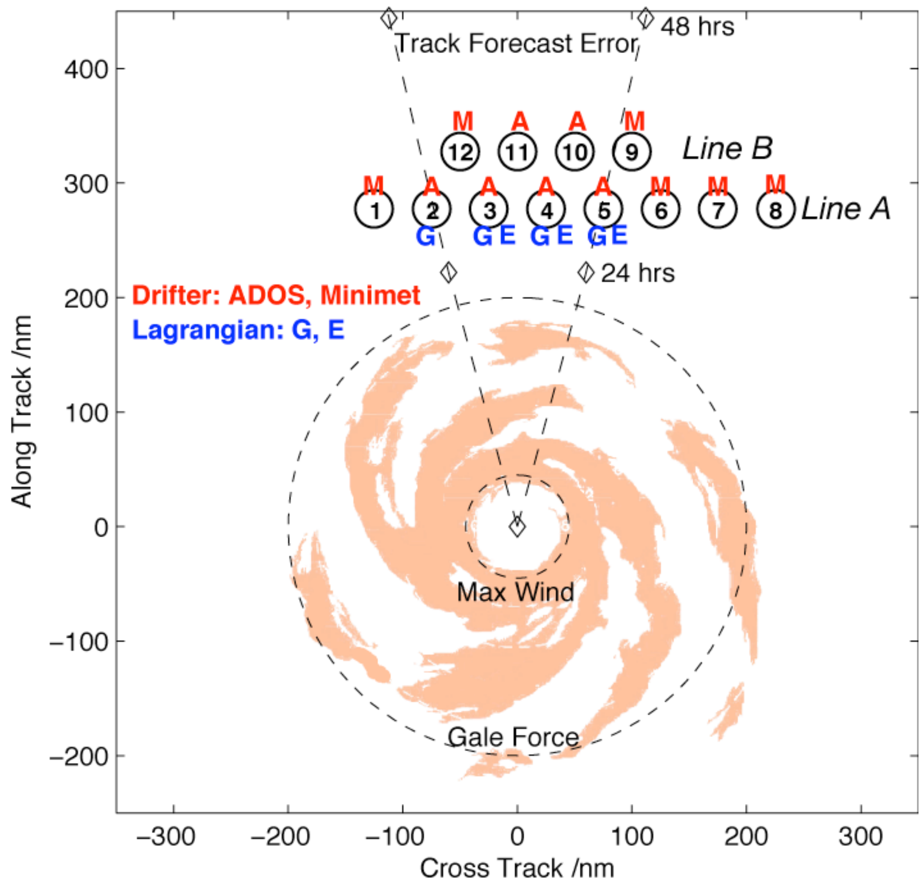
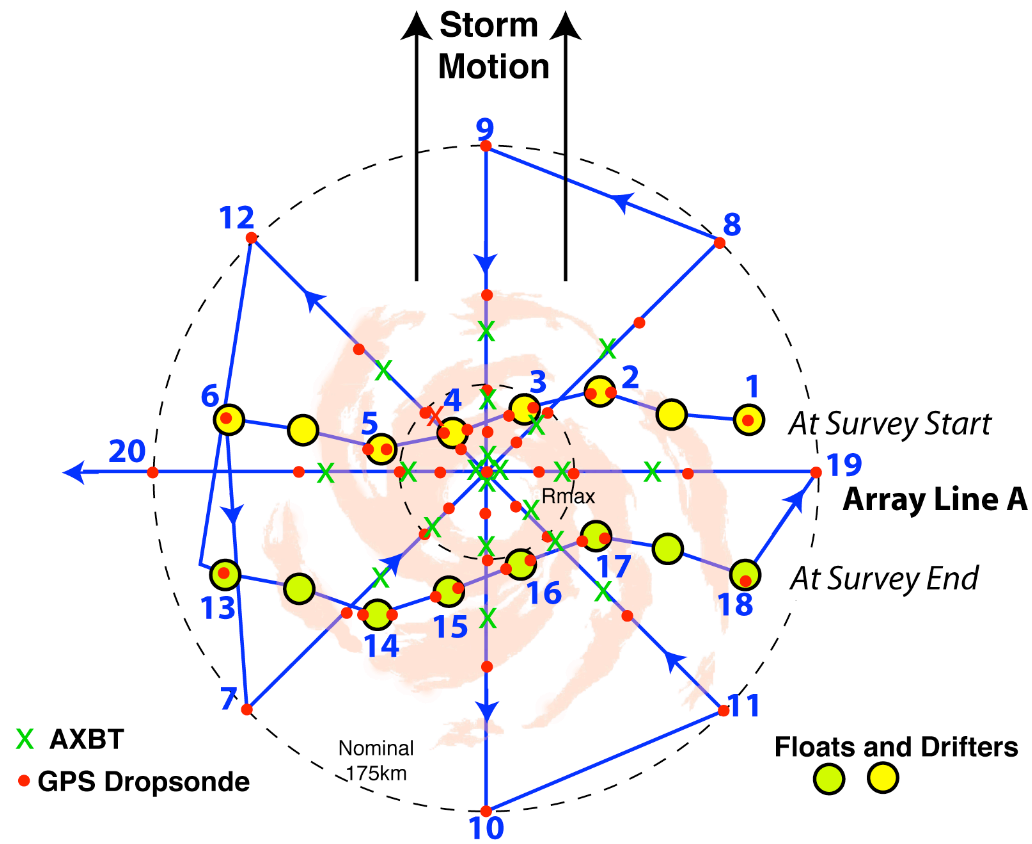


Figure 4-3: Float and drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of a mix of ADOS thermistor chain (A) and minimet (M) drifters and gas (G) and EM (E) Lagrangian floats. 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 4-4: 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.

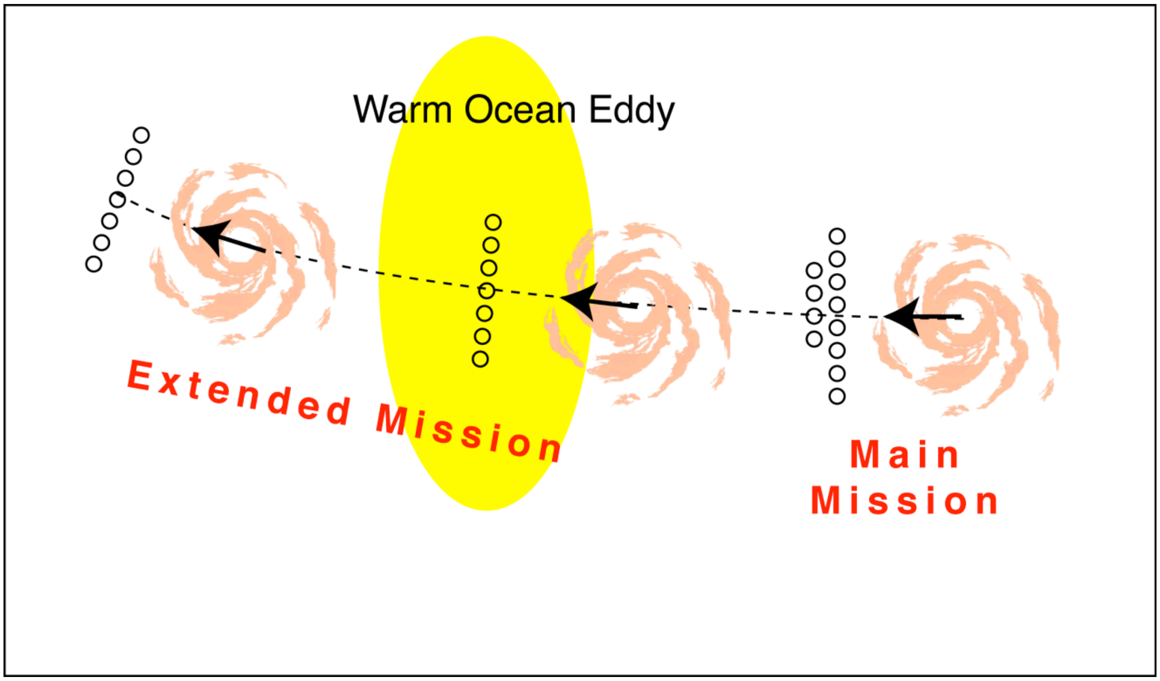


Figure 4-5: Extended Mission. Two additional drifter arrays will be deployed along the storm track.

5. East Pacific Decay Experiment

Principle Investigators: Ed Rappaport/James Franklin (NHC)

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

Experiment Objectives:
The observational objective is to obtain SST and flight-level, surface, and profile wind observations in tropical cyclones over several days during the decay process over cold water. Observations must be sufficient to obtain a reliable estimate of the cyclone's maximum sustained surface wind.

Links to Operations:
In-situ observations are rarely, if ever, available in eastern North Pacific tropical cyclones decaying over cooler waters. The intensity of these systems is typically estimated by the Dvorak technique, supplemented by scatterometer observations, however, there is some evidence that the Dvorak technique overestimates the intensity of weakening systems, thus overstating the hazard to marine interests. The purpose of this experiment is to obtain in-situ observations of decaying tropical cyclones to better calibrate existing methods of estimating tropical cyclone intensity over cold water.

Mission Description:
The flight strategy is to obtain two standard (105 n mi radius) alpha patterns (rotated) on each of 3 flights over a 3-4 day period. Each flight requires the SFMR, 18 AXBTs for measuring SST, and about 10 dropsondes. AXBTs are to be deployed at turn points, mid-radial points, and in combination with dropsondes at the maximum wind. Drops would be made at the corner points of one alpha pattern and in the max wind band of two of the four penetrations of each alpha pattern. In addition, a center drop would be made during each penetration to provide surface pressure. If the storm were too far away to do two, one alpha pattern would be acceptable. SFMR is critical for the success of the mission, but should it fail or be otherwise unavailable a mission could be conducted with a significantly enhanced number of dropsondes.

Three flights would occur over a 3-4 day period. First flight is in a hurricane just prior to reaching the SST gradient. Second flight is in or just beyond the gradient (presumably now TC is a TS), and last flight is over the cold water as the TS is decaying toward TD status. Depending on forward speed, flights would occur on consecutive days, or perhaps there would be a down day. Flights would likely take off at the same time of day each day, but no particular take off time is required. If possible, flight levels should be constant over the course of the flights - 850 mb is the preferred level.

No real-time transmission of data is required, although it is presumed that the HDOBs would be transmitted as a matter of course. Transmission of dropwindsonde data is desired, but not required.

6. Experiment: TC Diurnal Cycle Experiment

Principle Investigator: Jason Dunion

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;

Program Significance:

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

Objectives:

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

Hypotheses:

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

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 cool rings appears to be remarkably predictable: after its initial formation in the inner core region, it propagates outward at ~10 m s^{-1} and reaches peripheral radii (e.g. 200-500 km) at very specific times of day (local time). Therefore, a conceptual clock describing the evolution of this phenomenon has been developed. Figure 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. 2) in the inner-core with leg lengths of ~120-180 km at the maximum safe altitude (~8k-12k feet) for avoiding graupel. The GPS dropsondes should be dispensed on each leg with a spacing of ~50 km to provide adequate coverage for sampling the radial gradients of kinematics and thermodynamics. The GPS dropsonde sampling density should be increased to ~20 km just ahead of, within, and behind the cool ring that will be identified in real-time using the UW-CIMSS/HRD Diurnal Pulsing satellite imagery. Since the cool ring begins forming around local sunset (~1800-2030 LST) and typically passes the 200 km radius at ~0400-0800 LST the following morning, optimal P-3 sampling will occur from ~2000-0400 LST so that the aircraft can adequately sample the formation (just after sunset) and early-stage (inner core out to 200 km) propagation of the cool ring. The P-3 may also fly an arc cloud module or convective burst module as opportunities present. The execution of these optional modules will be at the discretion of the LPS.

The NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) GPS dropsonde drop points will be based on a star pattern selected using real-time information from the UW-CIMSS/HRD diurnal pulsing satellite imagery (Fig. 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. 3, yellow to pink shading) and will be determined by the LPS during the mission. Since the cool ring typically passes the TC outer radii (e.g. 300-400 km) later in the morning and early afternoon, the optimal G-IV sampling will occur slightly later than the optimal P-3 sampling. The diurnal cycle conceptual clock (Fig. 1) indicates that the cool ring passes the 300 (400) km radius at ~0800-1200 LST (~1200-1500 LST). Therefore, the optimal G-IV sampling will occur from ~0800-1500 LST and will target the later stages of the diurnal cycle cool ring evolution. The G-IV may also fly an arc cloud module as opportunities present. The execution of this optional module will be at the discretion of the LPS.

When possible, TC Diurnal Cycle Experiment missions will be coordinated with the HRD Tropical Cyclone Genesis Experiment (GenEx) 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.

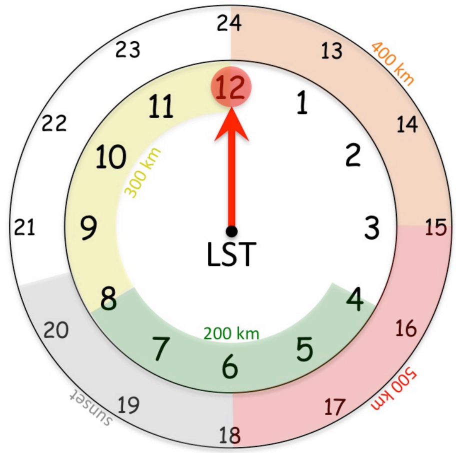


Figure. 6-1. Conceptual 24-hr TC diurnal pulsing clock that outlines the lifecycle of cool rings propagating from the TC inner core. For example, the pulse forms at local sunset (~1800-2030 LST, gray shading) and begins to propagate away form the inner core, passing the 200 km radius at ~0400-0800 LST (green shading) the following morning. It eventually reaches the 400 km radius at ~1200-1500 LST (orange shading) in the early afternoon.

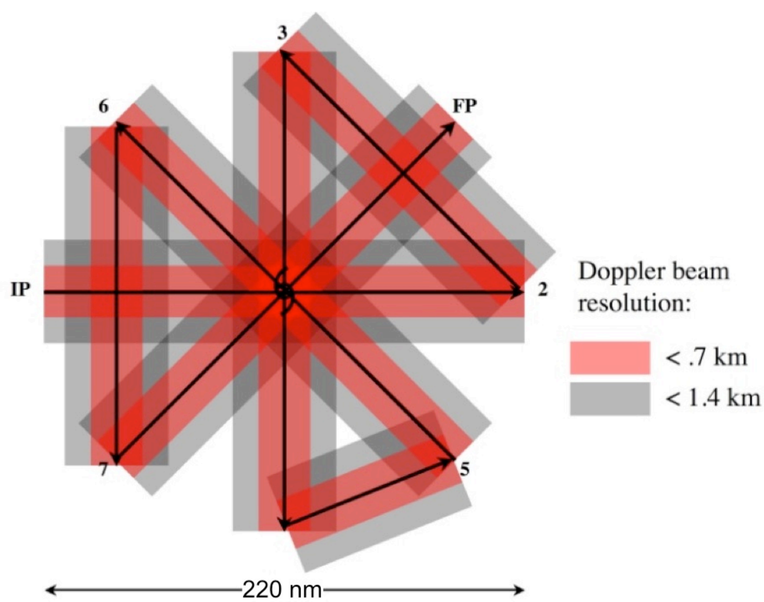


Figure. 6-2. Sample rotated figure-4 flight pattern for TC Diurnal Cycle Experiment mission. The red shading denotes locations where vertical spacing of Doppler beam < 0.7 km, grey shading where vertical spacing < 1.4 km. GPS dropsondes should be released at all turn points (past the turn after the aircraft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

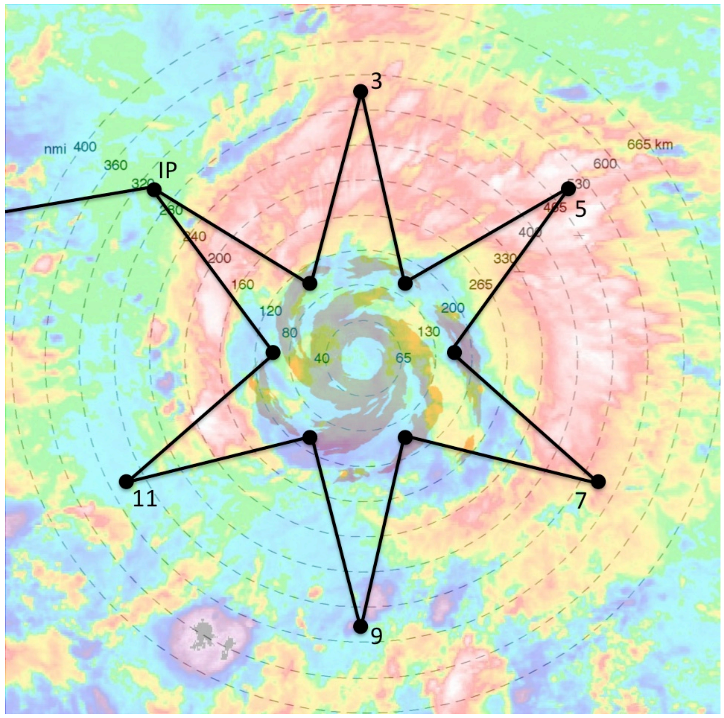


Figure. 6-3. Sample G-IV star pattern for the TC Diurnal Cycle Experiment. The endpoints of the pattern will be ~400 km from the storm center, but could be adjusted inward or outward depending in the exact position of the outwardly propagating diurnal pulse cool ring. The pattern is overlaid on a sample 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 01 Sep – 05 Oct 2012. 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 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. 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. 2. The inner-core GH can fly patterns that are similar in geometry to the NOAA P-3 patterns (Fig. 3). 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.

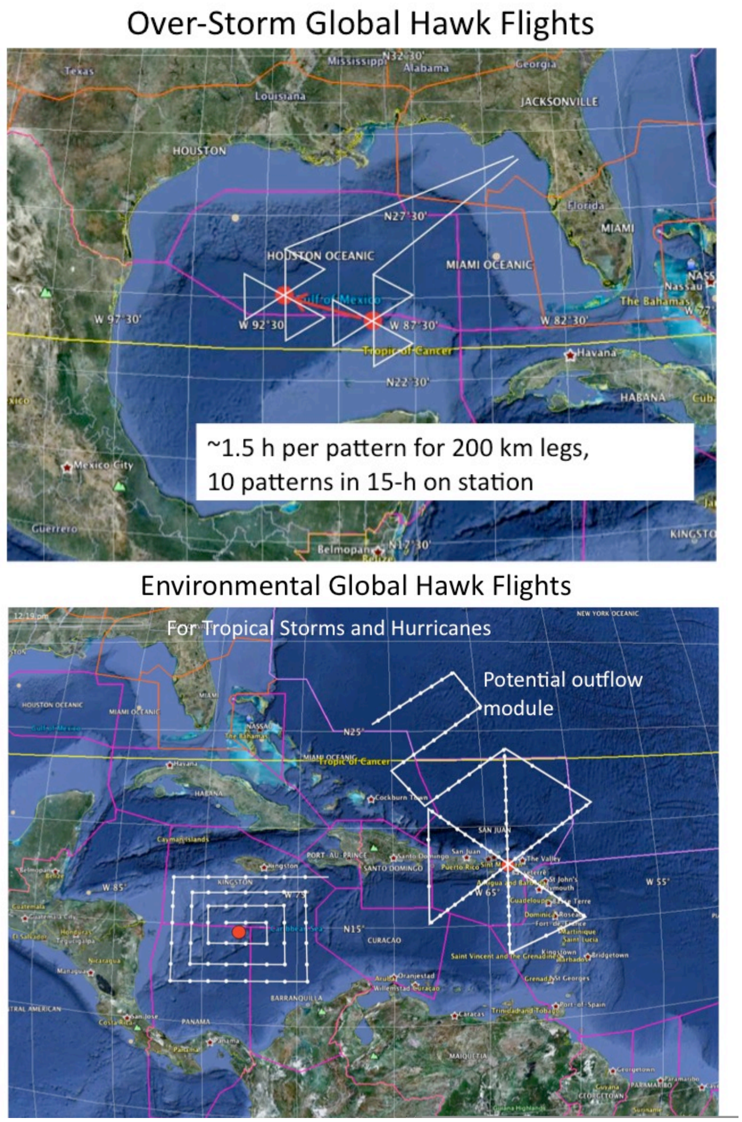


Figure 6-4. Sample flight pattern for the (top) over-storm and (bottom) environmental Global Hawk aircraft for TCs located in the Gulf of Mexico, Caribbean, and western North Atlantic.

7. Saharan Air Layer Experiment (SALEX): Dry Air Entrainment

Principal Investigator: Jason Dunion

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;

Saharan Air Layer Experiment: This is a multi-option, single-aircraft experiment which uses GPS dropsondes launched from the NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) to examine the thermodynamic and kinematic structure of the Saharan Air Layer (SAL) and mid-latitude dry air intrusions (MLDAIs) and their potential intrusion into/impact on tropical cyclone (TC) genesis and intensity change. The GPS dropsonde drop points will be selected using real-time GOES SAL tracking imagery from UW-CIMSS, mosaics of microwave-derived total precipitable water from the Naval Research Laboratory and the UW-CIMSS MIMIC TPW product. GOES 6-hr infrared brightness temperature difference imagery will also be used to track "cool rings" in the cloud top region of the storm (Fig. 7-1). These cool rings have been noted to propagate outward from the inner 100-200 km of the storm and appear to be associated with the formation of arc clouds several hours later (400-600 km form the storm center). Arc clouds signify that a dry air-TC/AEW interaction has occurred and will be targeted as opportunities present (see SALEX Arc Cloud Module). Infrared "cool rings" will be monitored in the context of low TPW (<45 mm) positioned upshear of the storm. When an expanding infrared "cool ring" becomes collocated with these upshear dry air locations, arc cloud formation appears to be favored. Specific effort will be made to gather atmospheric information within the SAL as well as regions of high moisture gradients across its boundaries and the region of its embedded mid-level easterly jet. The goals of this experiment are to better understand and predict how SAL and MLDAI dry air, the SAL mid-level easterly jet, and suspended mineral dust in the SAL affect Atlantic TC intensity change and to assess how well these components are being represented in forecast models.

Program Significance: The SAL has been investigated fairly extensively during the past several decades, buts its role in influencing Atlantic TCs has not been thoroughly examined. The SAL is characterized by a well-mixed layer that originates over the arid regions of the Sahara and often extends up to ~500 hPa (~19,000 ft) over the African continent. This air mass is extremely warm and dry, with temperatures that are markedly warmer (~0.5-5.0°C in the central/western North Atlantic and ~5-10°C in the eastern North Atlantic) than a typical moist tropical sounding. Additionally, the RH (mixing ratio) in the SAL is ~45-55% (~25-35% RH, ~1.5-3.5 g kg^{-1}) drier than a typical moist tropical sounding from 500-700 hPa. The SAL is often associated with a 20-50 kt mid-level easterly jet centered near 600-800 hPa (~14,500-6,500 ft) and concentrated along its southern boundary.

SAL outbreaks typically move westward off the western coast of North Africa every 3-5 days during the summer months. There are several characteristics of these frequent outbreaks that can act to suppress Atlantic TC formation:

1) The SAL (and MLDAIs) contains **dry, stable air** that can diminish local convection by promoting convectively driven downdrafts in the TC environment;

2) The SAL contains a **mid-level easterly jet** that can significantly increase the local vertical wind shear. The low-level circulations of TCs under the influence of this jet tend to race out ahead of their mid and upper-level convection, decoupling the storm and weakening it;

3) **Mineral dust** suspended within the SAL absorbs solar energy and subsequently releases longwave infrared energy. These thermal emissions act to warm the SAL and can re-enforce the tropical

inversion that already exists in the tropical North Atlantic. This warming helps to stabilize the environment and also limits vertical mixing through the SAL, allowing it to maintain its distinctive low humidity for extended periods of time (several days) and over long distances (1000s of km). Recent studies also suggest that mineral dust may impact the formation of clouds in both the ambient tropical and tropical cyclone environments. Data from previous studies have indicated that the particle size of the SAL's suspended mineral typically ranges from 0.4 - 40 μm;

Objectives: The main objectives of SALEX Dry Air Entrainment are to:

- Better understand how the SAL's (and MLDAIs) dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change;
- Include the moisture information from the GPS dropsondes in operational parallel runs of the NOAA Global Forecast System (GFS) model. The impact of this data on the GFS (and GFDL) initial/forecast humidity fields and its forecasts of TC track and intensity will be assessed;
- Investigate the representation of the SAL's temperature structure, low- to mid-level dry air, and embedded easterly jet in the GFS, GFDL, and HWRF-X models compared to GPS dropsonde data;
- Investigate how the TC environment becomes modified when substantial arc clouds are present. Improve the predictability of arc cloud events;
- Investigate the relationship between vertical distributions of dust detected by the DWL and temperature profiles/anomalies captured by collocated GPS dropsonde (pending P-3 DWL availability);

Mission Description: The NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) GPS dropsonde drop points will be based on a flight pattern selected using information from the UW-CIMSS/HRD GOES SAL tracking product, mosaics of microwave-derived TPW from NRL Monterey, the UW-CIMSS MIMIC TPW product, and "cool rings" identified in 6-hr infrared BT difference imagery (Fig. 7-1). Theoretical trajectory analysis suggests that the front left and rear left quadrants of a TC/AEW are the favored entry points for mid-level dry air intrusions (Fig. 7-2). TPW imagery (≤45 mm) and this basic trajectory theory will be used to monitor the progress of dry air intrusions around the TC-AEW circulation. Specific effort will be made to gather atmospheric information within the SAL (and MLDAIs), the transitional environment (regions with high gradients of humidity) across its boundaries, its embedded mid-level easterly jet, and the immediate surrounding moist tropical environment. When possible, SALEX missions will be coordinated with the HRD Tropical Cyclone Genesis Experiment (GenEx). This coordination will involve the WP-3D and G-IV and be executed on a case-by-case basis. Additionally, HRD's Saharan Dust Microphysics Module and/or Arc Cloud Module should be conducted during SALEX should opportunities present. The following SAL-TC/AEW interaction scenario is the ideal candidate for SALEX missions:

Single TC located along the southern edge of a SAL outbreak (or MLDAI, Fig. 7-3). Depending on the proximity of these two features, the SAL's (or MLDAI's) mid-level dry air may be wrapping into the TC's low-level circulation (western semicircle). The G-IV **IP** will preferably (but not necessarily) be west of the TC (preferably west of the SAL's (or MLDAI's) leading edge) and the initial portion of the 1st leg (**IP-2**) will focus a GPS dropsonde sequence across the high gradient region of humidity at the SAL's (MLDAI's) leading edge. The spokes of this star pattern (**IP-2/12-FP**, **3-5**, **6-8**, and **9-11**) will include sampling of the environment between ~200-400 nm from the center and will be adjusted according to the storm size. The inner-most portion of the track will be roughly defined by convective areas that are below the flight level (GOES and Meteosat IR brightness temperature values warmer than ~-55ºC). The tangential legs at ~200 nm will observe the variability of possible dry air and shear that has penetrated close to the inner core (**2-3**, **5-6**, **8-9** and **11-12**). These inner tangential legs should be positioned as close to the outer edge of the inner core convection as safety permits. The region east of the storm along the southern edge of the SAL is a favored location for the SAL's mid-level easterly jet. The region will be sampled to observe the moisture gradients and variability of the mid-level easterly jet across this portion of the SAL (**4-5-6**). Intermediate GPS dropsondes will likely be requested along these legs of the mission.

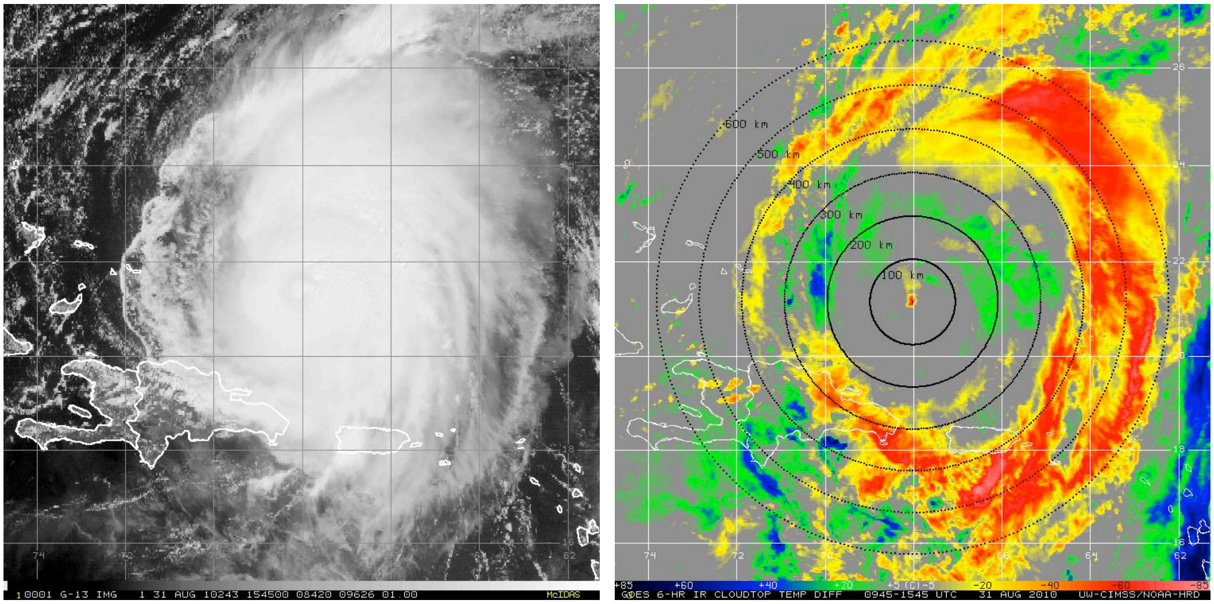


Figure 7-1: (Left) GOES visible and (right) 6-hr infrared brightness temperature (BT) difference imagery for Hurricane Earl on 31 August 2010 1545 UTC. Negative (positive) temperature changes [yellows to reds (greens to blues)] in the BT difference imagery indicate cloudtop temperatures and cirrus clouds that have cooled (warmed) over the past 6 hours.

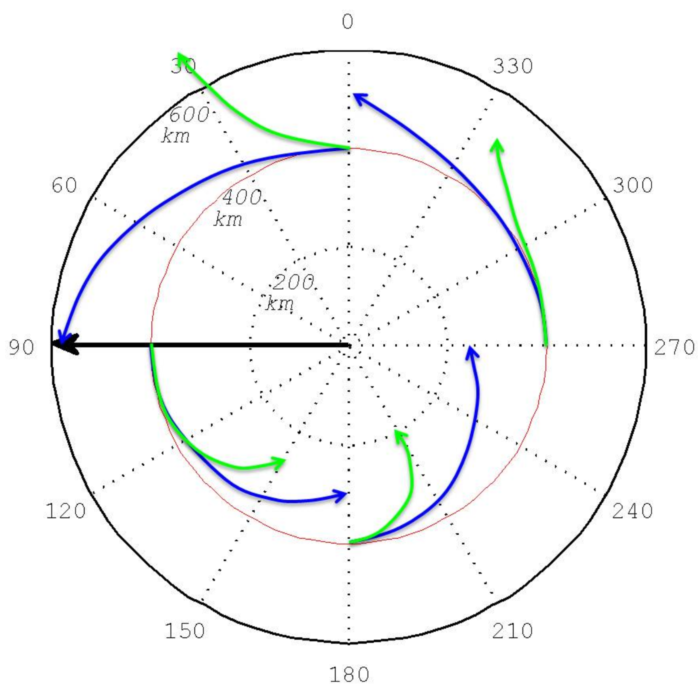


Fig. 7-2: Trajectories for points originating 400 km north, south, west, and east of the storm center based on simple trajectory theory where the radius of curvature of the trajectories relates to the radius of curvature of the streamlines (R_s), the tangential wind speed at the radius of interest, the forward motion of the disturbance (C), and the angle (ϒ) of the storm relative parcel starting position relative to the forward motion of the disturbance. Blue (green) trajectories are calculated from C=V/2 (C=V*2).

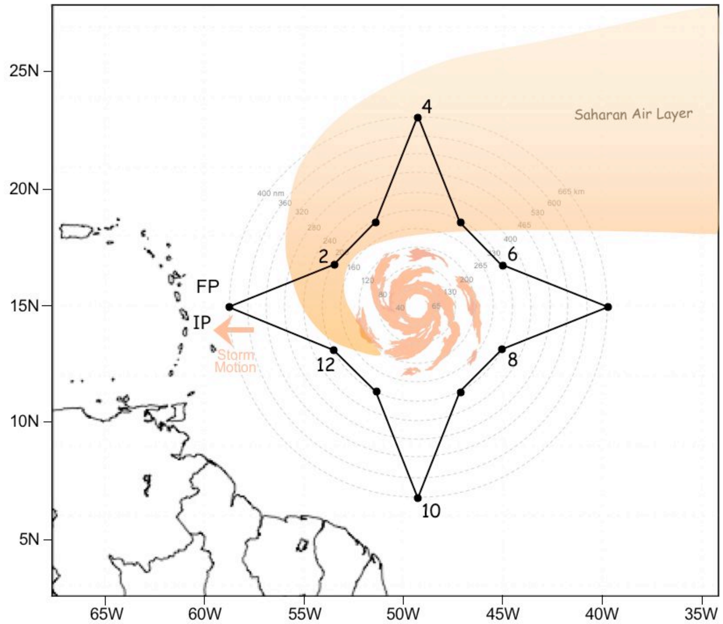


Figure 7-3: Sample G-IV flight track for sampling a dry SAL intrusion around the western semicircle of the storm.

- *Note 1*: During the ferry to the **IP**, the G-IV should climb to ~200 hPa/41,000 ft as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern
- *Note 2*: In order to capture the SAL's (or MLDAI's) horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (**IP-2**, **2-3**, and **4-5-6**) and possible penetration of dry air and vertical wind shear toward the inner core (**IP-2**, **3-5**, **6-8, 9-11** and **12-FP**).
- *Note 3*: The SAL's mid-level easterly jet (~20-50 kt at 600-800 hPa/14,500-6,500 ft) may be evident from GPS dropsondes dropped near the SAL's southern boundary (**2-3-4 and 4-5-6**).

8. Extratropical Transition Experiment

Principal Investigator: Sim Aberson

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

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 $ms\text{-}^{1}$?
- 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. 8-1). 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. 8-2). 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.

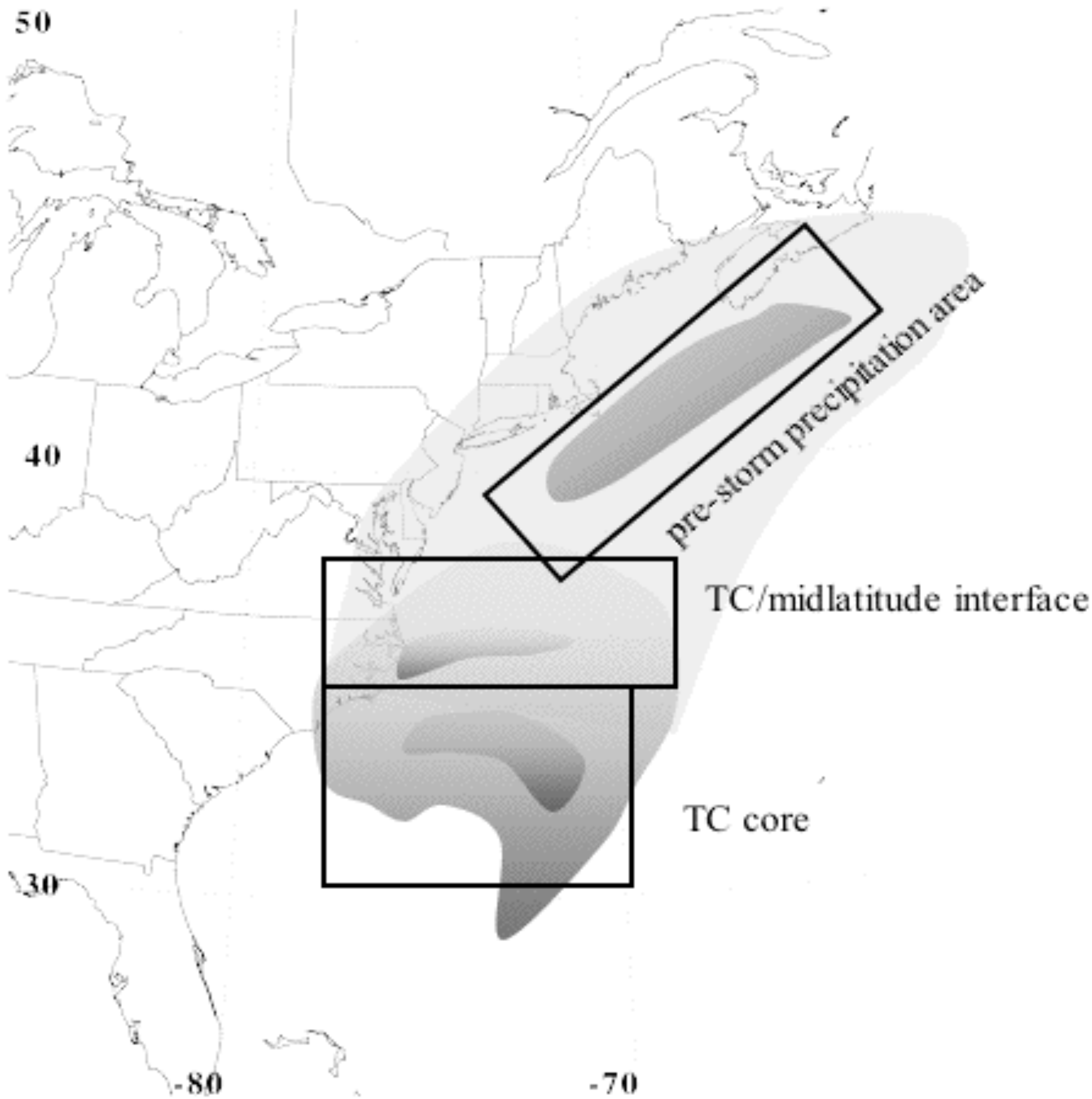


Figure 8-1: Schematic of Tropical Cyclone undergoing extra-tropical transition.

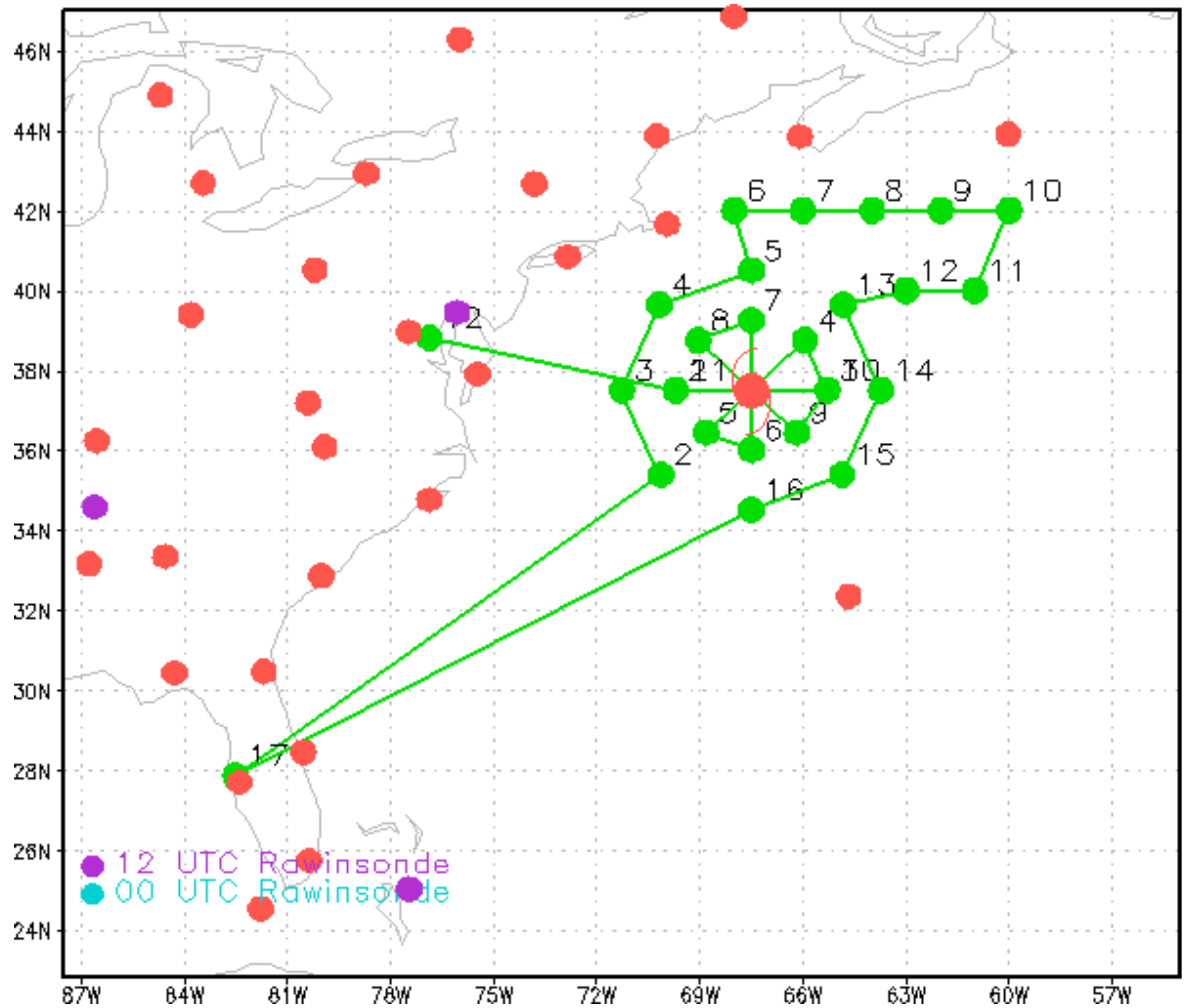


Figure 8-2: Proposed flight tracks for G-IV and P3 aircraft.

9. Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor, and Wallace Hogsett (NHC)

Links to IFEX:
It supports the following NOAA IFEX goals:

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

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

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

Background:
Tropical cyclogenesis can be viewed as a rapid increase of low-level cyclonic vorticity organized on the mesoscale within a region of enhanced convective activity. Numerous hypotheses have been advanced in the literature to explain how this vorticity develops and amplifies. One of the key aspects differentiating these hypotheses centers on whether the lower-tropospheric cyclonic vorticity begins in the mid-levels and develops downward to the surface or begins in the lower troposphere and builds upward to the middle troposphere – the so-called top-down vs. bottom-up mechanisms. Prominent top-down theories include one study which showed observations of multiple midlevel vortices prior to genesis in the West Pacific (Ritchie et al. 1997) that led them to view the genesis process as a stochastic one whereby chance merger and axisymmetrization of these midlevel vortices leads to growth of the circulation to the surface by increasing

the Rossby-Prandtl-Burger penetration depth of potential vorticity anomalies associated with the vortices. Another study supporting the top-down approach showed observations of genesis in the East Pacific (Bister and Emanuel 1997) and hypothesized that downdrafts driven by evaporational cooling advected the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production.

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

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

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

1. <u>Tropical cyclogenesis is primarily a bottom-up process that requires a broad area of convective processes in concert with stratiform precipitation</u>

This hypothesis will be tested by documenting the development of low-level vorticity in the presence of a midlevel vortex center, and vice versa, as well as by documenting the interactions between low- and mid-level vortices in pre-genesis environments. It will also consider the precipitation structures within the developing circulation and how these structures (convective vs. stratiform) evolve over time.

2. <u>The interaction of an incipient vortex with the Saharan Air Layer (SAL) overall is detrimental for tropical cyclogenesis.</u>

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

3. As stated in DMW08 and WMD09, genesis tends to occur near the intersection of a tropical wave critical surface and the precursor parent wave's axis, which is the center of a "pouch".

The objective of marsupial tracking is to track the wave pouch (rather than the diabatic vortices inside the pouch) and estimate its propagation speed and predict the genesis location, which can be used to provide useful guidance for flight planning during IFEX.

4. Convective systems that ingest low-level flow rich in helicity preferentially produce low-level cyclonic vorticity and accelerate near-surface spin-up.

MCSs that exhibit a deep convective line and an adjacent stratiform region are symptomatic of a locally vertically-sheared environment. Depending on the vertical profile of the near-MCS horizontal winds, updraft-shear interactions may result in preferential generation of cyclonic vorticity. To test the hypothesis, the vertical profile of horizontal winds in the immediate vicinity of the leading convective line, with a focus on low-level inflow, will be sampled.

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

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

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

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

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

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

Staggered missions with the P-3 aircraft will begin with the aircraft flying one of two survey patterns at max 12,000 ft (4 km). The primary purpose of these patterns will be to collect F/AST Doppler radar and dropwindsonde data in the area of deep convection in order to map the evolution of the three-dimensional wind and thermodynamic structure of the deep convection and incipient vortex. Two possible patterns can be flown, with the decision of which pattern determined by the degree of organization of the system. For incipient systems that are relatively disorganized, a lawnmower pattern is flown (Fig. 5-1) along the axis of an easterly wave. Leg lengths will be 150-200 nm (250-300 km), with some variability dependent on the size of the system and the time available on station. The pattern will be centered approximately on any discernible circulation or wave axis, if identifiable, or in the absence of such features, on a dominant area of convective activity. Priority will be placed, however, on centering the pattern on the mesoscale circulation pattern (i.e., the pouch), and *not* targeted at transient convective activity.

As a system becomes better organized, a second survey pattern is flown (Fig. 5-2), consisting of a square-spiral centered on a broad low- or mid-level circulation center. If multiple mesoscale convective systems exist embedded within a parent circulation, the pattern will be centered on the parent circulation. Dropwindsondes are released at regular intervals to create a near uniform grid covering the circulation and including any MCSs, if possible. The spacing between the outer spiral and the inner box pattern is nominally set for 60 nm (111 km), but it can be varied to ensure optimal representation of the convective and mesoscale features.

Once a persistent low-level vortex is identified, subsequent missions will include a rotating figure-4 pattern (Fig. 5-3) centered on the vortex. Flight legs will be 60-120 nm (111-225 km) to allow for the collection of data with high temporal and spatial resolution in the vicinity of the vortex center. The length of these flight legs is designed to completely include the low-level vortex and convection associated with it. Depending on

the leg lengths and the time available on station, the pattern may consist of higher azimuthal resolution. The tail radar will operate in F/AST mode during the entirety of these patterns.
If available, the G-IV will fly a synoptic pattern at maximum altitude to observe the troposphere with dropwindsondes in the pre-genesis and incipient tropical disturbance environment. The most likely scenario calls for the G-IV to fly a star pattern to sample and possible interaction of the system with a SAL (e.g. as depicted in Fig. 5-5).

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

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

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

When possible, it will be desirable to fly patterns with the NOAA aircraft that are coordinated with the GH aircraft. For the NOAA P-3, "coordinated" means flying legs where the P-3 and GH are vertically-stacked for at least a portion of the flight leg. Both the inner-core and environmental GH can fly patterns that are similar in geometry to the NOAA P-3 patterns, including lawnmower (Fig. 6), square-spiral (Fig. 7), and figure-4 type patterns (Fig. 8). The across-track displacement during such coordination should be kept as small as practicable, e.g., no greater than 5-10 km. In practice, the NOAA P-3 will likely fly its patterns as indicated in Fig. 1-3. To achieve coordination the inner-core GH would align its legs such that the GH will be stacked with the P-3. It is likely that not all of these aircraft will be flying simultaneously; rather, efforts will be made to have an aircraft either in the inner core or the environment at all times.

Convective Burst Module:
This is a stand-alone module that takes one hour or less to complete. Execution is dependent on system attributes, aircraft fuel and weight restrictions, and proximity to operations base. The objectives are to obtain quantitative description of the kinematic, thermodynamic, and electrical properties of intense convective systems (bursts) and the nearby environment to examine their role in the cyclogenesis process. It can be flown separately within a mission designed to study local areas of convection or at the end of one of the survey patterns. Once a local area of intense convection is identified, the P-3 will transit at altitude (12,000 ft.) to the nearest point just outside of the convective cores and fly a circumnavigation of the convective area (Fig. 5-4). The circumnavigation will consist of a series of straight legs just outside of the main convection. The tail radar should be operated in F/AST sector scan and regularly spaced dropwindsondes (10-20 km apart) will be released during this time. While flying parallel to the leading convective line, dropwinsonde deployment should occur as close to the leading line as is safely possible. Once the circumnavigation is completed, and the P-3 is near the original IP, two straight-line crossings of the convective area should be performed with the P-3 avoiding the strongest cores, as necessary for safety considerations. The P-3 should fly at a constant altitude of 12,000 ft – radar or pressure altitude is fine. If time permits, the P-3 should descend to the lowest safe altitude and perform another circumnavigation (or partial one) of the convective burst. No dropwindsondes will be released during the low-level run.

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

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

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

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Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

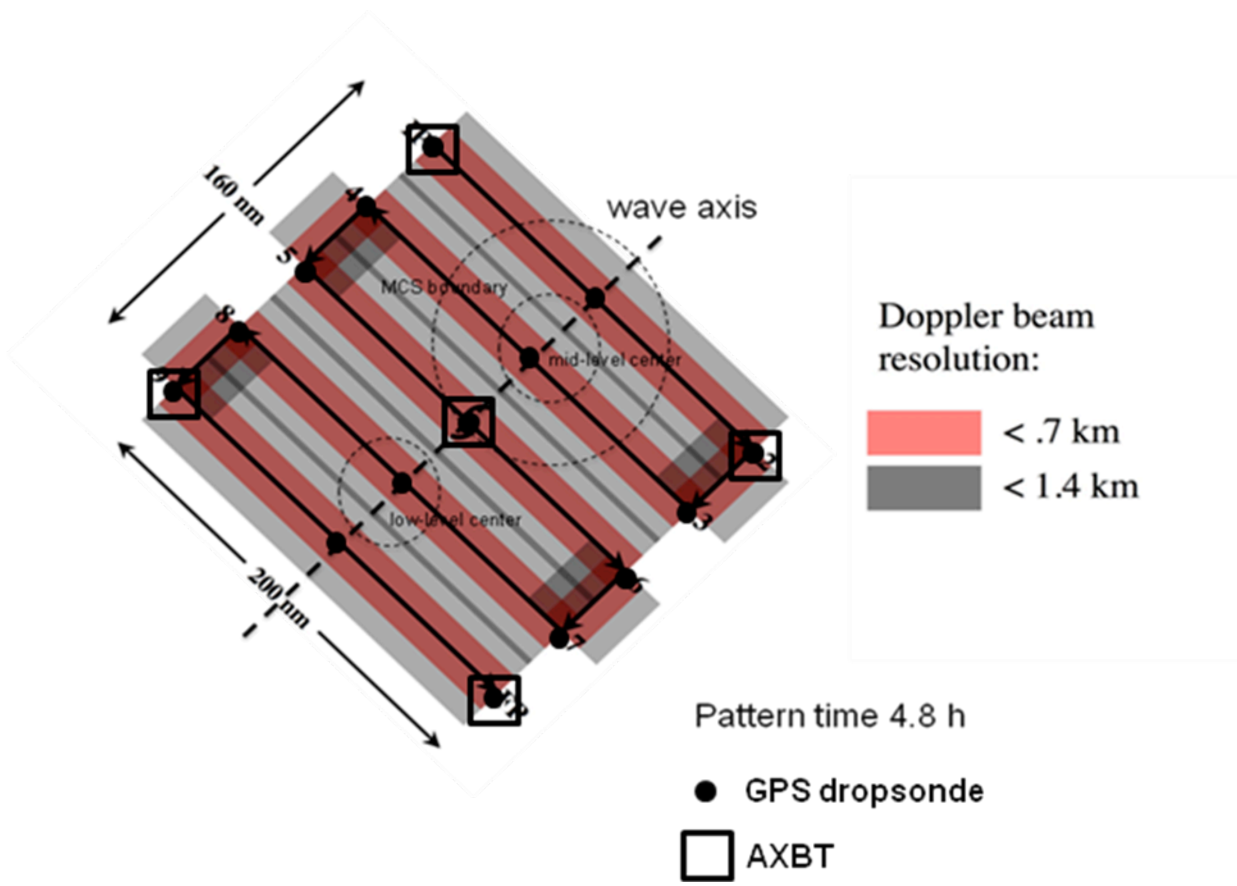


Figure 9-1: P-3 Pre-genesis early organization vortex survey pattern – Lawnmower pattern.

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

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

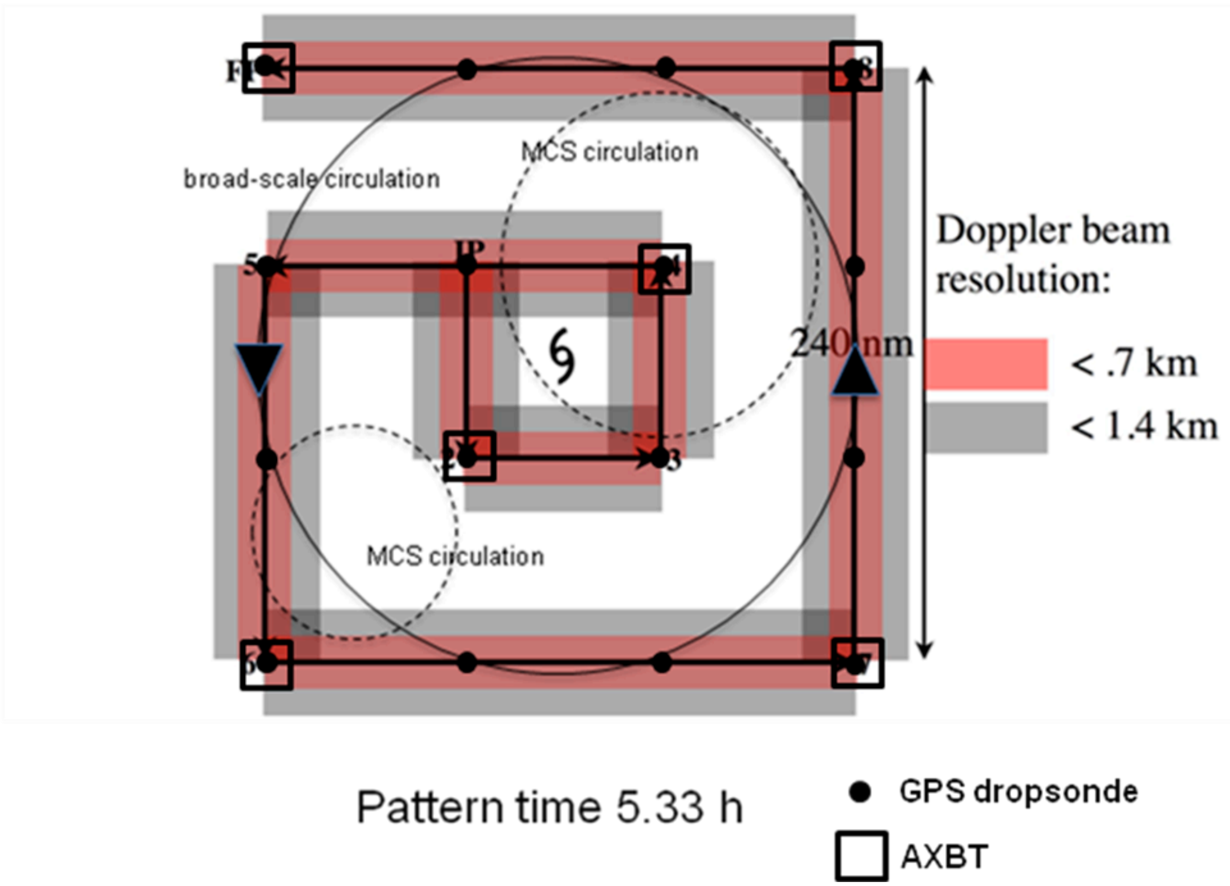


Figure 9-2: P-3 Pre-genesis late organization vortex survey pattern – Square-spiral pattern.

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

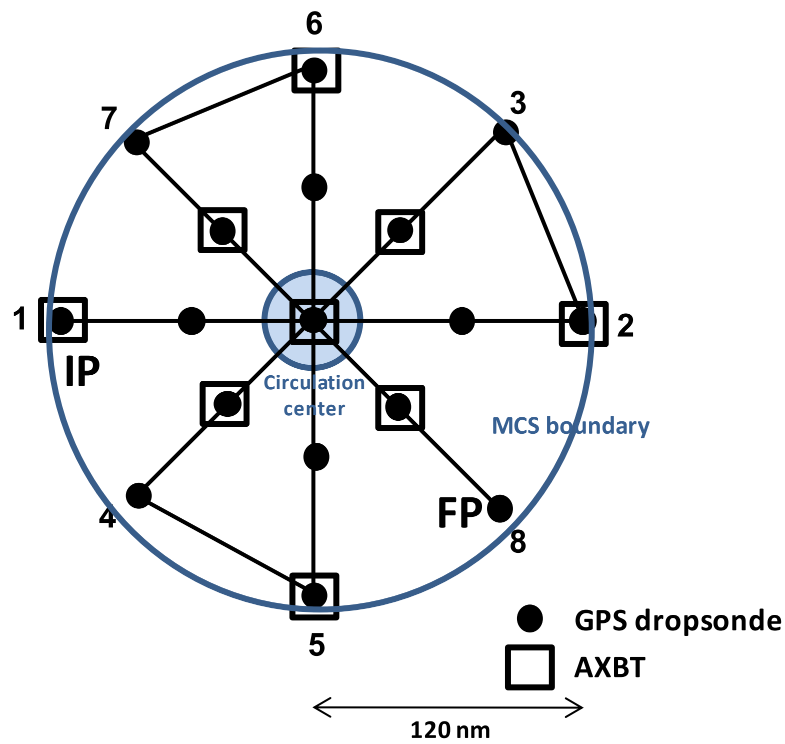
Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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



Pattern time: ~5.0 h

Figure 9-3: P-3 Post-genesis rotating figure-4 pattern.

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

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

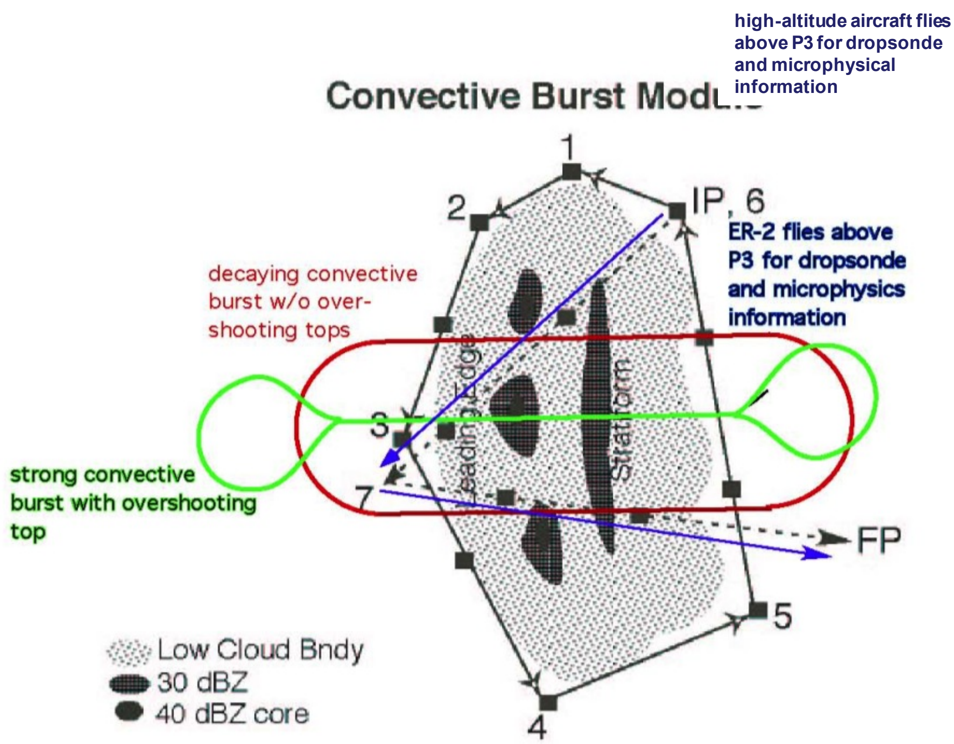


Figure 9-4: P-3 Convective burst module.

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

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers, Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

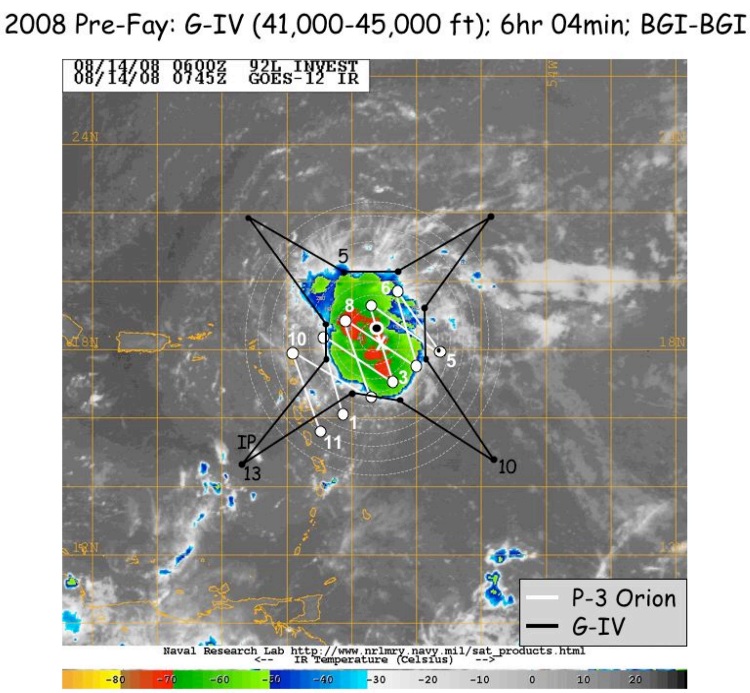


Figure 9-5: G-IV Pouch module.

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

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

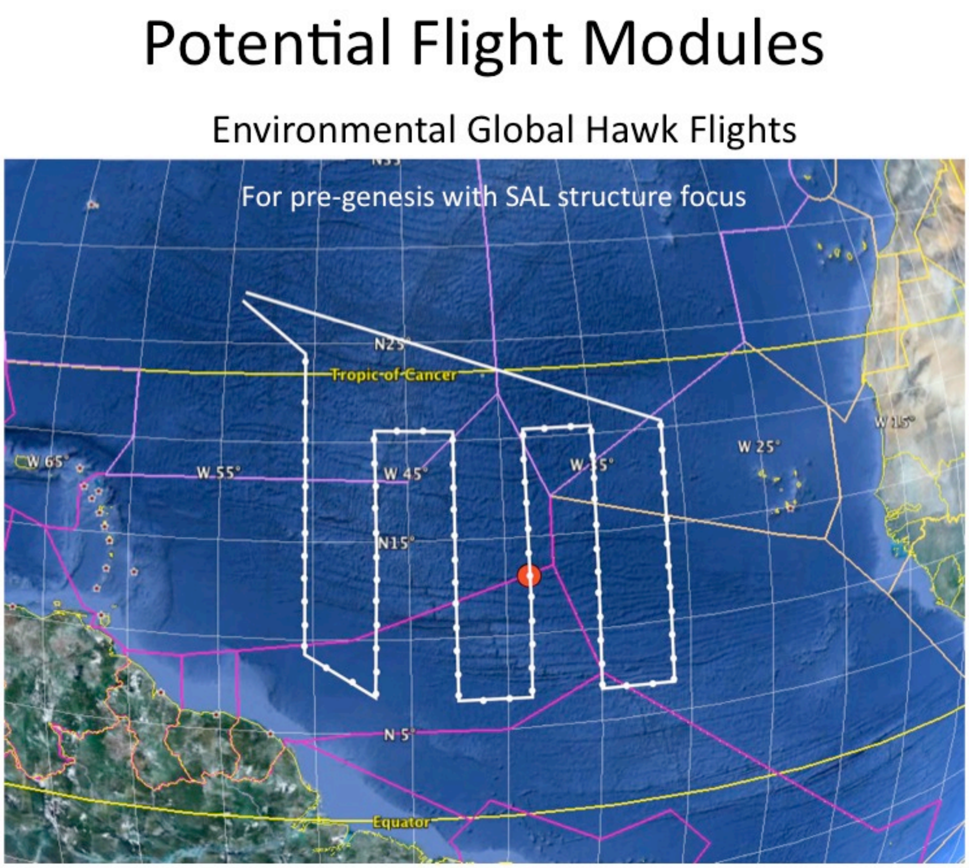


Figure 9-6. Sample lawnmower flight pattern for GH over a developing TC in the central Atlantic.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

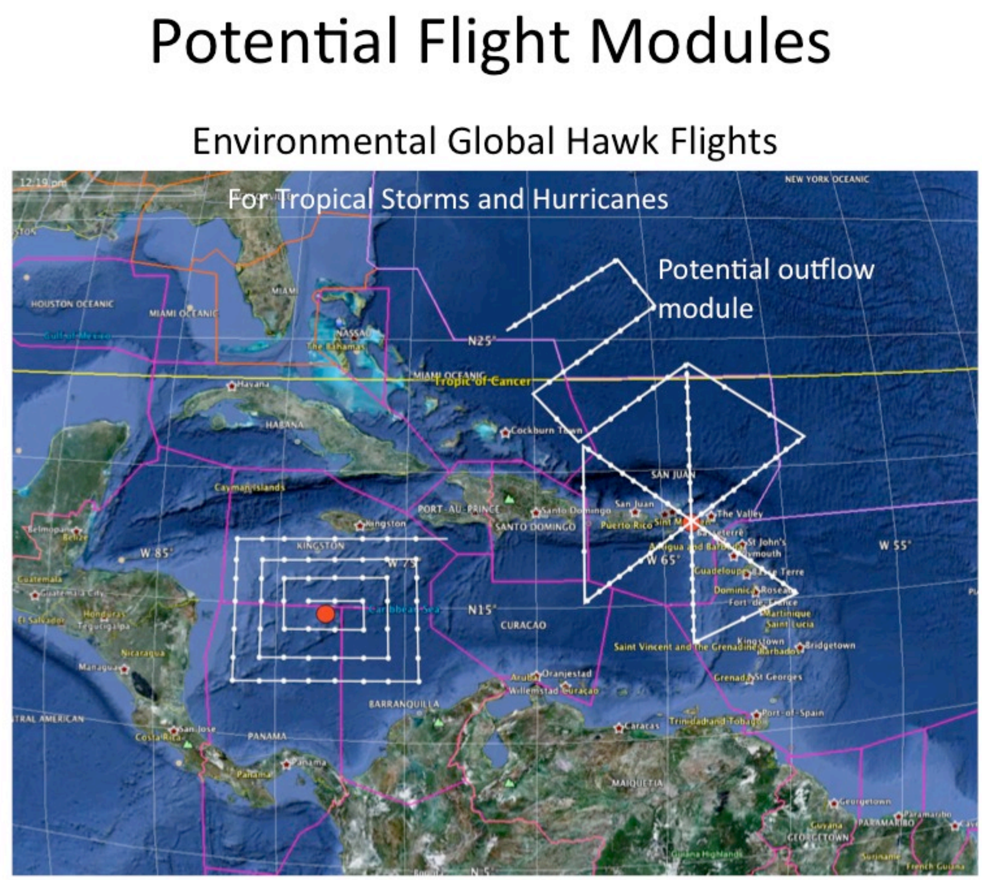


Figure 9-7. Sample square-spiral (in West Caribbean) and outflow module (in West Atlantic) flight patterns for GH’s over two developing TC’s in the Gulf of Mexico.

Tropical Cyclogenesis Experiment

Principal Investigator(s): Robert Rogers,Paul Reasor, and Wallace Hogsett (NHC)

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

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

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

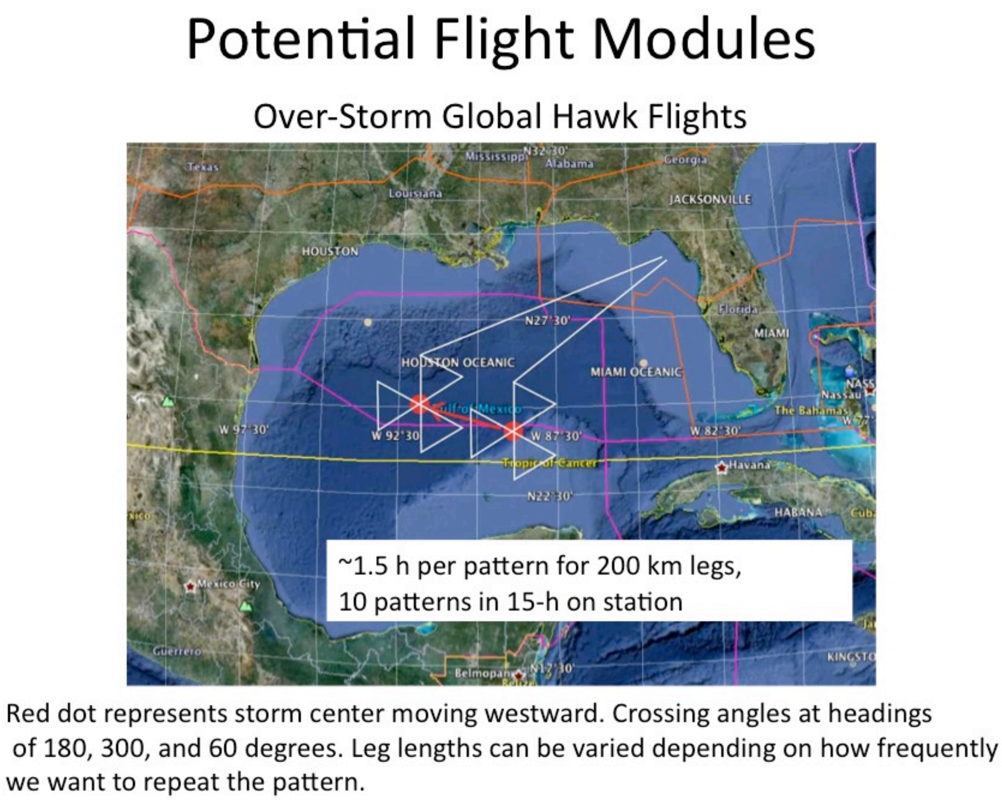


Figure 9-8. Sample figure-4 flight pattern for GH over a developing TC in the Gulf of Mexico.

10. Rapid Intensification Experiment (RAPX)

Principal Investigators: John Kaplan, Robert F. Rogers, and Jason P. Dunion

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

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 2008) 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 30% of the skill in RI forecasts in the Atlantic basin, 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 (24-48 h) while both the RII and 3-D numerical models will be used for the longer time ranges (i.e. beyond 48 h).

Hypotheses:

- By gathering observations that span spatial scales from 10s to 100s of kilometers it is possible to improve our understanding of the atmospheric and oceanic conditions that precede RI, particularly within the less observed inner-core region.

- Characteristics of the tropical cyclone inner core, both on the vortex- and convective-scale, contribute a non-negligible amount to explaining the variance in the prediction of RI.

- The aforementioned multi-scale RAPX data sets can be used both to initialize and evaluate numerical model forecasts made for episodes of RI and that successful completion of these tasks will lead to improved numerical/statistical model predictions of RI.

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. 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 a total of 3 (12) AXBTs/GPS pairs are dropped during the course of each completed figure-4 leg (pattern) as shown in Fig. 10-1. 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. 10-2 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 particularly 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. 10-2 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. 10-1) in the inner-core while the G-IV simultaneously flies the environmental surveillance pattern shown in Fig. 10-2 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. 10-2, 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. Finally, when possible this experiment may also make use of the NASA Global Hawk aircraft.

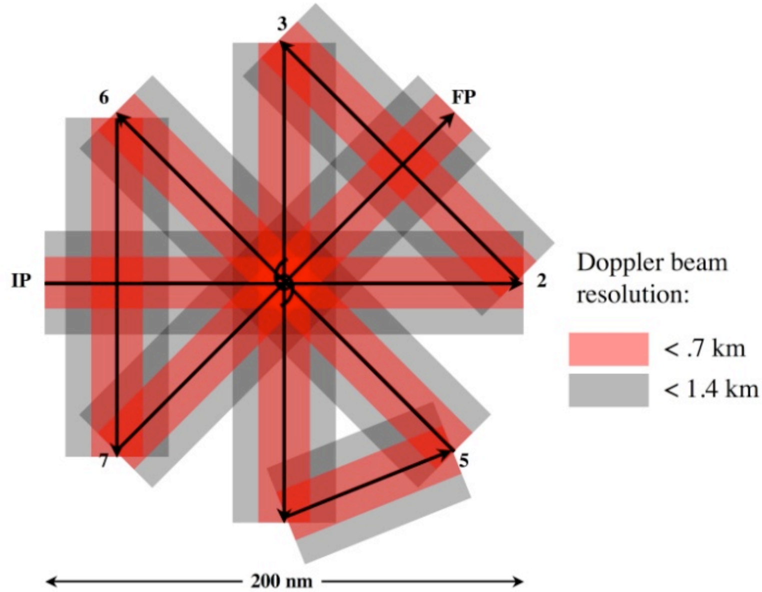


Figure. 10-1. Sample rotated figure-4 flight pattern for RAPX mission. The red shading denotes locations where vertical spacing of Doppler beam < 0.7 km, grey shading where vertical spacing < 1.4 km. GPS dropsondes should be released at all turn points (past the turn after the aircraft has leveled), at midpoints of inbound/outbound legs, and at center point between IP/2 and 5/6. If available, release AXBT's coincident with dropsondes at turn points, midpoints, and center points. Note that the above in-storm P-3 flight pattern requires about 3-4 hours to complete.

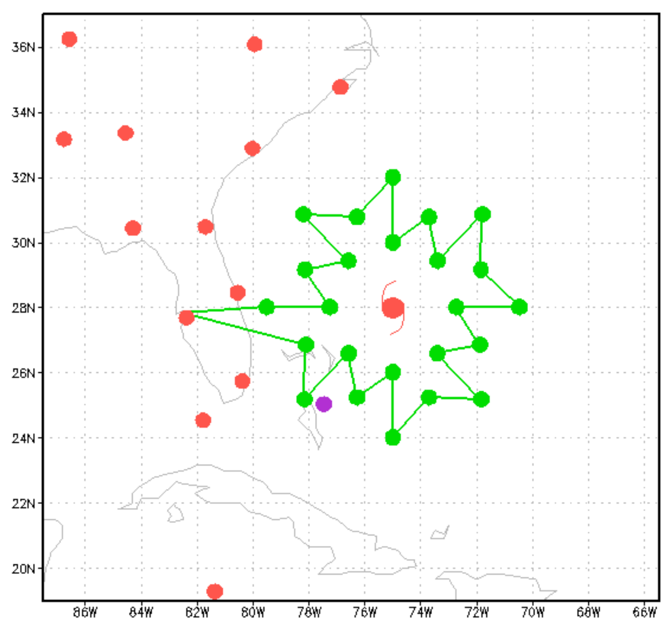


Figure 10-2. A sample G-IV flight pattern for the RAPX mission. The green dots denote the desired dropsonde locations at 220, 330, and 440 km radius from the storm center. Note that the end points of each leg can be rounded slightly as required for aircraft flight considerations. The flight pattern shown in Fig. 2 (excluding ferry time to and from the storm) requires about 6 hours to complete.

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. 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.

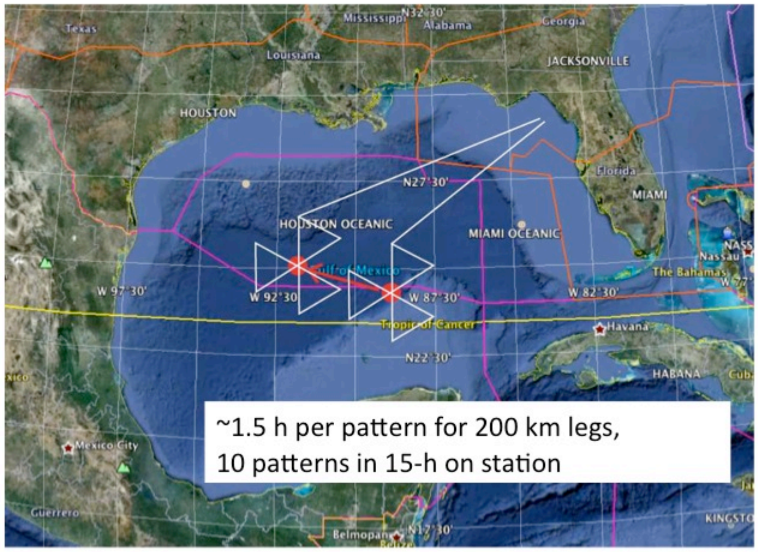
Coordination with Supplemental Aircraft

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

When possible, it will be desirable to fly patterns with the NOAA aircraft that are coordinated with the GH aircraft. For the NOAA P-3, "coordinated" means flying 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. 10-1. The inner-core GH can fly patterns that are similar in geometry to the NOAA P-3 patterns (Fig. 10-3). To achieve coordination the inner-core GH would align its legs such that the GH will be stacked with the P-3.

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 10-3. Sample flight pattern for inner-core GH over a TC in the Gulf of Mexico.

11. Saharan Air Layer Experiment (SALEX): Arc Cloud Module

Principal Investigator: Jason Dunion

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;

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 11-1), 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 cool rings 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 cool ring propagation throughout the local morning hours and signs of arc cloud formation.

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

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

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

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, or TC Rapid Intensity Experiment or as part of operational G-IV Synoptic Surveillance and NHC-EMC-HRD P-3 Tail Doppler Radar (TDR) missions. Total precipitable water (TPW) satellite imagery will be used to identify mid-level dry air (≤45 mm TPW) in the periphery of the AEW or TC. These areas of mid-level dry air will be favorable locations for arc cloud formation, especially when TC diurnal pulses are passing radii where this low to mid-level dry air is located. UW-CIMSS real-time TC diurnal pulsing imagery will be used to track these favored regions where arc clouds might form (i.e. along the leading edge of the cool ring). Also, the 200-850 hPa shear vector may be an additional indicator of arc clouds formation. When TPW imagery indicates the presence of mid-level dry air and the shear vector is indicating a shear direction toward the storm center (in that same quadrant or semicircle), arc cloud formation may be especially favorable. These targeted areas will be regions of preferred arc cloud formation and should be monitored closely using satellite imagery (preferably 1 km visible and 37 GHz microwave) during the mission. Depending on connection rates on the aircraft, supplemental communications via X-Chat with scientists on the ground would be desirable, especially given the unpredictability and rapid evolution of arc cloud features.

<u>Option #1: G-IV aircraft</u>. Once an arc cloud feature has been identified, a GPS dropsonde sequence (preferably running perpendicular to the arc cloud) should be made between the convective area where the arc cloud originated to at least 50 km beyond the leading edge of the arc cloud. Special attention should be paid to the transition zone across the leading edge of the arc cloud and to the environment adjacent to the convective core area where the arc cloud originated (behind the arc cloud). GPS dropsonde spacing should be ~35 km and the transect can be made inbound (sampling in front of, across, and then behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC. In addition to the more common arc cloud that propagates away from the AEW/TC, a second arc cloud has occasionally been observed propagating in toward the AEW/TC. This second arc cloud appears to spawn from the same convective region as the outbound arc cloud and simply moves toward the AEW/TC instead of away from it. If a second inward propagating arc cloud is identified, the GPS dropsonde sequence should be extended to span the environments ahead of (relative to arc cloud motion) both arc clouds. Figures 11-2 and 11-3 provide example G-IV flight patterns across arc cloud candidates. This option can be easily incorporated into pre-existing flight patterns with minimal additional time requirements.

<u>Option #2: WP-3D aircraft</u>: After an arc cloud feature has been identified, a multi-level flight pattern running perpendicular to the arc cloud should be initiated. The Doppler radar should operate in F/AST mode to permit sampling of the three-dimensional winds throughout any precipitating arc clouds. The *initial* pass should extend between the convection where the arc cloud originated to at least 20 km beyond the leading edge of the arc cloud. Flight altitude should be >3000 m to permit the deployment of multiple GPS dropsondes. Special attention should be paid to the transition zone across the leading edge of the arc cloud and to the environment adjacent to the convection where the arc cloud originated (behind the arc cloud). GPS dropsonde spacing should be ~20 km [reduced to ~10 km spacing closer (≤20 km) to the arc cloud] and the transect can be made inbound (sampling in front of, across, and then behind the arc cloud) or outbound

(sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC. For the *second* pass, the aircraft should turn and descend to ~1000 m before proceeding back along the same transect extending from the originating convection to at least 20 km beyond the leading edge of the arc cloud. For the *final* pass, the aircraft should again turn and descend to ~500 m before again proceeding along a similar transect across the arc cloud. Flight altitudes for the second and final passes can be adjusted as needed for aircraft safety, but should sample as low as possible in order to capture any near-surface density current with the flight-level sensors. No dropsondes should be deployed on the second and final low-level passes. After the final low-level pass, the primary flight pattern can be resumed. The total time to complete this option should not exceed 60 min, and in most cases can be completed in less time. Figures 11-2, 11-3, and 11-4 show sample fight patterns for this multi-level option.

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

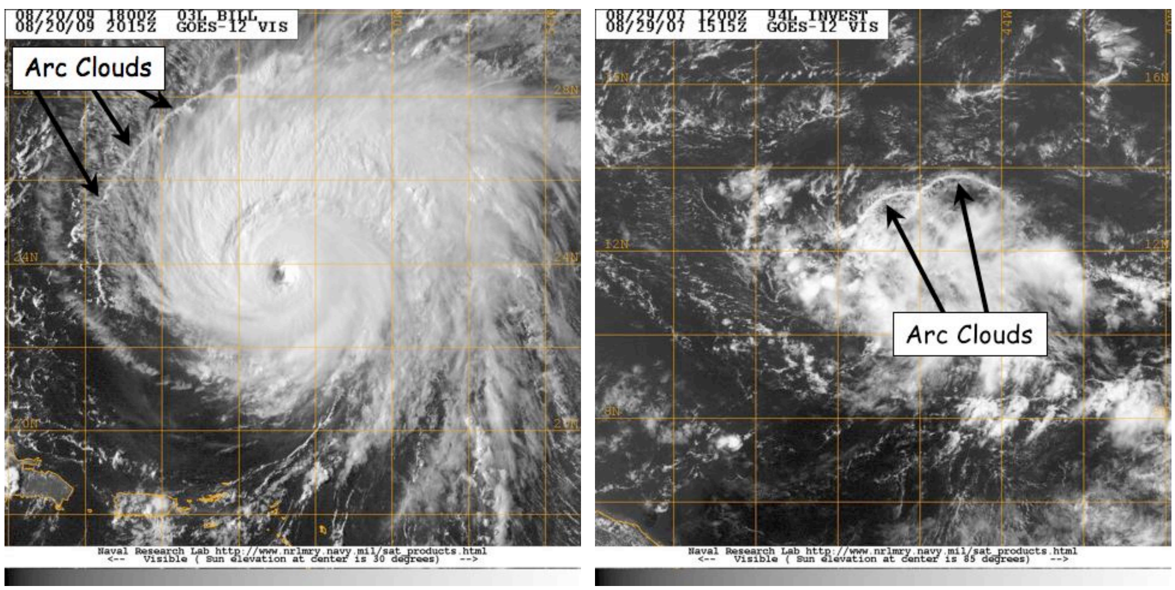


Figure 11-1: GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2009 Hurricane Bill and (right) 2007 Pre-Tropical Depression Felix.

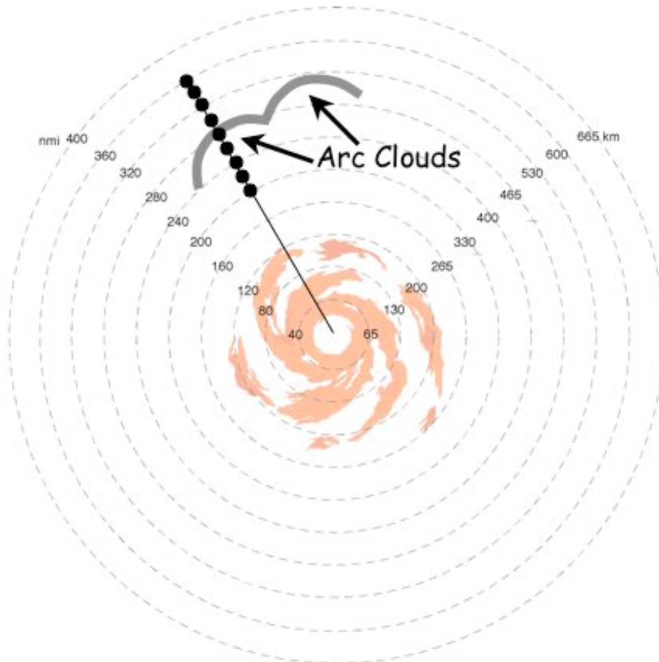


Figure 11-2: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the arc cloud are candidates for this module. When multiple arc clouds are present, the feature closest to the pre-determined flight track is desirable.

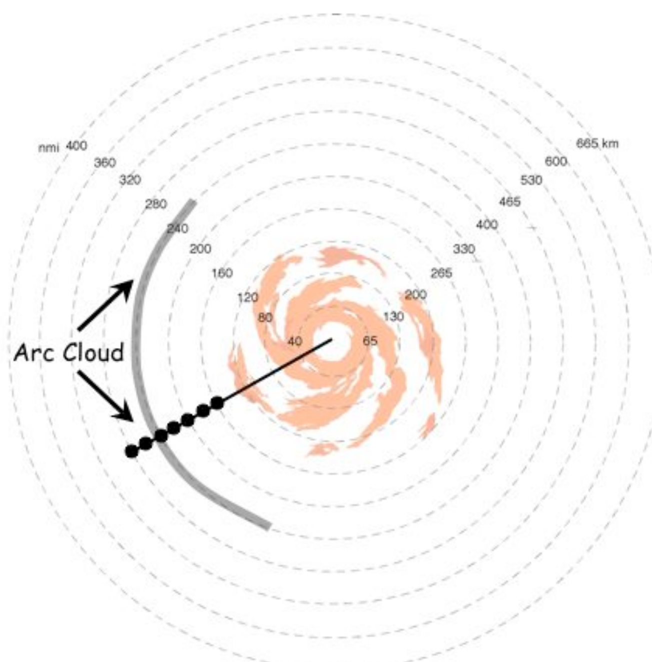


Figure 11-3: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the arc cloud are candidates for this module.

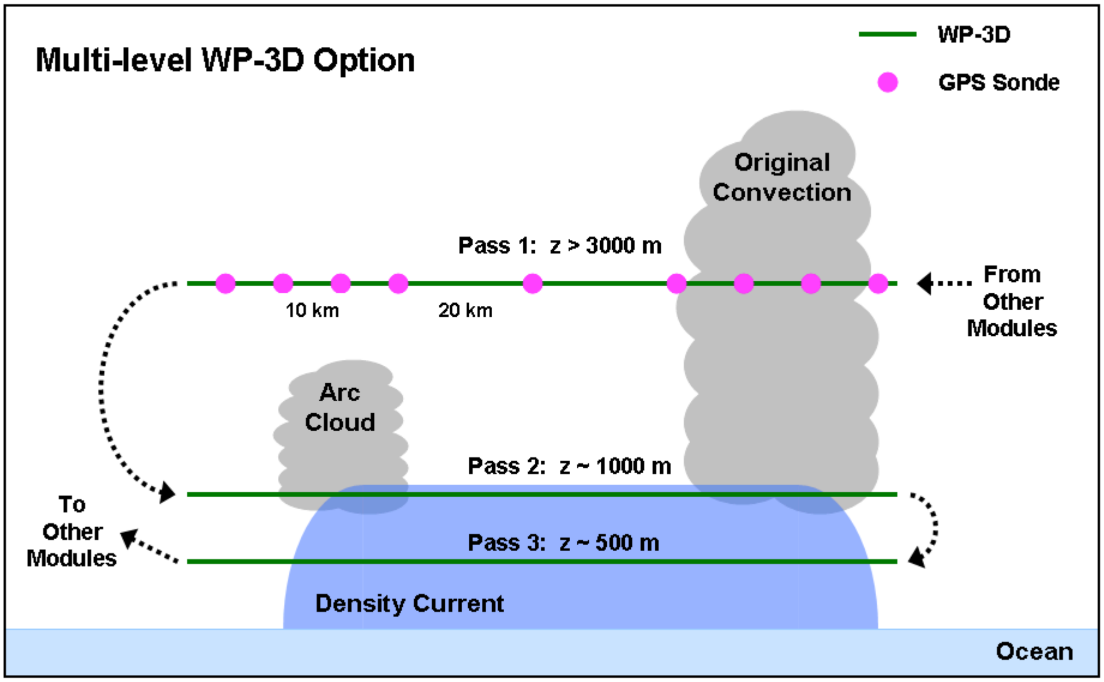


Figure 11-4: The WP-3D flight track for the multi-level option. Azimuth and length of initial midlevel pass with GPS dropsonde sequence will be dictated by the pre-determined flight plan. Lengths of the low-level passes should span much of the distance between the arc cloud and its initiating convection, 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).

12. Tropical Cyclone Landfall and Inland Decay

Principal Investigators: John Kaplan and Peter Dodge

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

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

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

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

Analysis of Doppler radar, GPS dropwindsonde, SFMR, flight-level and SRA or AWRAP data collected during hurricane flights can help achieve the IFEX goals for the 2012 Hurricane Field Program. A major goal is to capture the lifecycle of a TC and while landfall is usually at the end of the lifecycle the same data collection strategies developed for mature hurricanes over the open ocean can also be applied at landfall. Subsets of the data collected can be transmitted to NHC and to EMC, for assimilation into HWRF. The Doppler and GPS dropwindsonde data can be analyzed to derive three-dimensional wind fields to compare with output from the HWRF and data from the SRA can be compared to HWRF wave fields. In addition to shear and heat flux from the ocean, hurricanes at landfall experience other conditions that may affect intensity change. These include change in ocean wave action in shallow waters, change in surface roughness, drier and cooler inflow from the land, and topography. Radar, dropwindsonde, and SFMR data can help define those conditions. Decay over land is also important and data collected during and shortly after landfall should help refine both operational statistical decay models (such as the Kaplan/DeMaria model) and 3-dimensional numerical models like HWRF.

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

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

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

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

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

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

Objectives:

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

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

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

The above landfall datasets, in combination with high-resolution surface wind measurements collected by land based collection teams, can be used to validate statistical and 3-D numerical model landfall surface wind forecasts.

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

The miniature supercells and/or tornadic cells exhibit many basic kinematic, thermodynamic, and dynamic structures as those found in severe thunderstorms across the Great Plains. Traditional environmental parameters (such as CAPE and vertical shear) may be used to distinguish those sectors of the storm most supportive of supercell development and thus narrow the scope of any severe weather watches.

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

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

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

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

All modules support real-time and post-storm surface wind analyses. The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars. The first two modules could be easily incorporated into a tasked operational mission. The other two modules are suited to research missions, where the patterns are not constrained by fix or gale-force wind radii requirements.

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

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

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

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

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

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

Post Landfall Module: This module is designed to collect kinematic and thermodynamic data ~1-2 h prior to and up to 6 h after a hurricane makes landfall. It is essential that ground-based measurements are obtained in conjunction with those that are being made by aircraft, since the primary goal is to determine the kinematic and thermodynamic changes that occur after a hurricane makes landfall throughout the depth of the lower troposphere.

The P-3 will fly a coastal survey pattern followed by a figure-4 pattern over land (Fig. 12-4) with ~ 150-km legs at an altitude of ~15,000 ft (5 km). The P-3 tail radar should be in F/AST mode. These data will aid in rainfall estimation and will help document the changes in vortex and rain band structure over land that are crucial to understanding the environment that supports tornado and mesovortex development.

Over land, available portable wind towers, mesonet stations, profilers and DOWs should be deployed along the path of the landfalling hurricane to identify the changes in storm structure as the hurricane moves inland. The wind towers and mesonet stations will obtain high-resolution surface wind, temperature, pressure, relative humidity, and perhaps rainfall measurements. If available, a profiler could be placed at the center of each line of mesonet stations. The profilers and RASS sounder will provide wind and temperature measurements within the lowest 3 and 1 km, respectively. Rain gauges should be located at each profiler and DOW site to obtain high-resolution rainfall measurements, both for calibrating the radar rainfall algorithms and for documentation of storm rainfall.

The first set of towers and mesonet stations should be placed as close as possible to the coastline (<10 km) to enable accurate documentation of the surface wind field just after landfall. Other towers or mesonet stations should be placed ~65 and 135 km inland respectively; however, these distances will vary depending upon the intensity and speed of motion of the landfalling storm as well as safety considerations. The spacing between the mesonet stations located within each group should be ~30 nm (50 km) perpendicular to the track to maximize the likelihood that one of the mesonet stations will be located near the RMW of the landfalling storm.

If the inland profilers are mobile, it will be possible to follow severe weather producing rain bands if safety and logistical considerations allow. The DOWs should be placed roughly halfway between the two rear lines of mesonet and profiler stations. The DOWs, in combination with the profilers with RASS, will aid in documenting the changes in kinematic and thermodynamic structure of the hurricane after landfall. An accurate analysis of such changes is crucial to learning more about the development of mesovortices and/or tornadoes spawned by landfalling hurricanes. They will also help document the changes in wind speeds within the PBL of a landfalling hurricane. Finally, the radars will aid in the measurement of the rainfall associated with the landfalling hurricane.

Analysis Strategy: Wind measurements for all landfalling cases for which simultaneous measurements were obtained by both NOAA-P3 aircraft and land-based collection teams will be converted to a uniform averaging time (1-min.), height (10-m), and exposure (Z0=0.01 or 0.03 m) using the methodology of Powell et al. (2009). The Kaplan/DeMaria empirical decay model will then be run for each of these cases and the surface wind forecasts from this model will be compared to the standardized surface winds at the appropriate observation location and time. Similar comparisons will also be made using the 3-D (e.g. HWRF or HWRF-X) numerical model surface wind forecasts. However, before such comparisons are made, the 3-D numerical model predicted winds will first need to be converted to open exposure or alternatively the observed surface winds will need to be standardized using the same exposure that was used in the 3-D model prediction at each surface observation location to enable a fair comparison to be made between the model predicted and observed wind.

Offshore Intense Convection Module: This module focuses on the collection of dual-Doppler radar and vertical profiles of the lower atmosphere near intense convective cells (> 35 dBZ on the LF radar) located in an offshore outer rain band (>150 km from the storm center) but embedded within the onshore flow. This module can be easily incorporated during either the real-time module, the coastal survey module, or the onshore wind profile module when a qualified outer rain band is encountered. Figure 12-5 shows an example flight pattern along the Carolina coast. In order to provide adequate estimates of low-level vertical shear and instability, the aircraft should fly this module at an altitude of 3000 m or higher. The Doppler radar should operate in F/AST mode to provide wind estimates on each side of the aircraft track. A minimum of 10 GPS sondes should be deployed. The first flight leg should cross the target band ~20-25 km downwind of the intense convective cells and proceed until the aircraft is 25 km outside the rain band axis, deploying a GPS sonde at the band axis and end point. The aircraft then turns upwind and proceeds along a straight track parallel to the rain band axis, deploying GPS sondes every 20-25 km. This length of this leg can adjusted as needed, but should be a minimum of 75 km. When the aircraft is ~20-25 km upwind of the target cells, the aircraft turns and proceeds along a track orthogonal to the band axis until the aircraft is 25 km inside the rain band. GPS sondes should be deployed at the initial and endpoints of this leg as well as at the band axis. Finally, the aircraft turns downwind and proceeds along a straight path parallel to the rain band axis, deploying GPS sondes every 20-25 km. The end point of this final leg should be ~20-25 km downwind of the initial target cell to ensure adequate dual-Doppler radar coverage of all cells. From here other modules can be resumed. The total time to complete this module should not exceed 60 min, and in most case can be completed in less time.

Significance: As tropical cyclones move inland and weaken, tornadoes also become a significant threat to society and one of the most difficult forecast problems. Since 2004, over 650 tornadoes have been spawned by 26 tropical cyclones impacting the U.S. coastline, resulting in 24 deaths, over 300 injuries, and more than $400 million in damage. Many of these tornadoes are spawned by ***miniature supercells***. Much of the forecast challenge is due to significant differences in structure, organization, and environment from the classic midlatitude supercell: the miniature supercells are shallower, weaker, shorter-lived, and less buoyant, but occur in a very moist, high-wind, high-rotation environment with more vertical wind shear. Furthermore, individual miniature supercells often occur in close proximity to one another along organized outer rain bands, whereas their midlatitude counterparts often occur in relative isolation. As a result, midlatitude conceptual models have shown very limited success when applied to tornado forecasting in tropical cyclones. Numerous studies have documented the onshore environmental conditions and evolution of miniature supercells associated with TC-tornado outbreaks, but little is known about the ***offshore environment and cell evolution*** just prior to tornado outbreaks. The goal of the Offshore Intense Convection module is to document the structure, evolution, and low-level environment of the stronger convective cells (>35 dBZ) located offshore in an outer rain band (>150 km from the TC center) that will soon move onshore and potentially spawn tornadoes. This goal is consistent with the three primary goals of the Intensity Forecasting Experiment (IFEX).

<u>**Note**</u>**:** This module's flight pattern can be reversed depending either on the location of the intense cells relative to the aircraft's initial approach vector or the need for flight safety. This module could also be easily incorporate into any tasked operational or research missions in which an outer rain band (>150 km from the storm center) with embedded intense convective cells (>35 dBZ on the LF radar) is encountered during ferry to or from the storm core. **In other words, this module is <u>not</u> strictly limited to the Landfall and Inland Decay Experiment.**

Analysis Strategy: The P-3 Doppler radar data will be carefully edited and then synthesized into a three-dimensional wind field. Dropsonde and flight-level data will be analyzed and combined with an available rawinsonde and surface (e.g. buoys, CMAN, etc.) observations to establish the thermodynamic environment of the targeted cells. Any available land-based radar will be used to augment the cell evolution documented by the airborne radars. The cell's environments and structures will be compared with those of mid-latitude supercells.

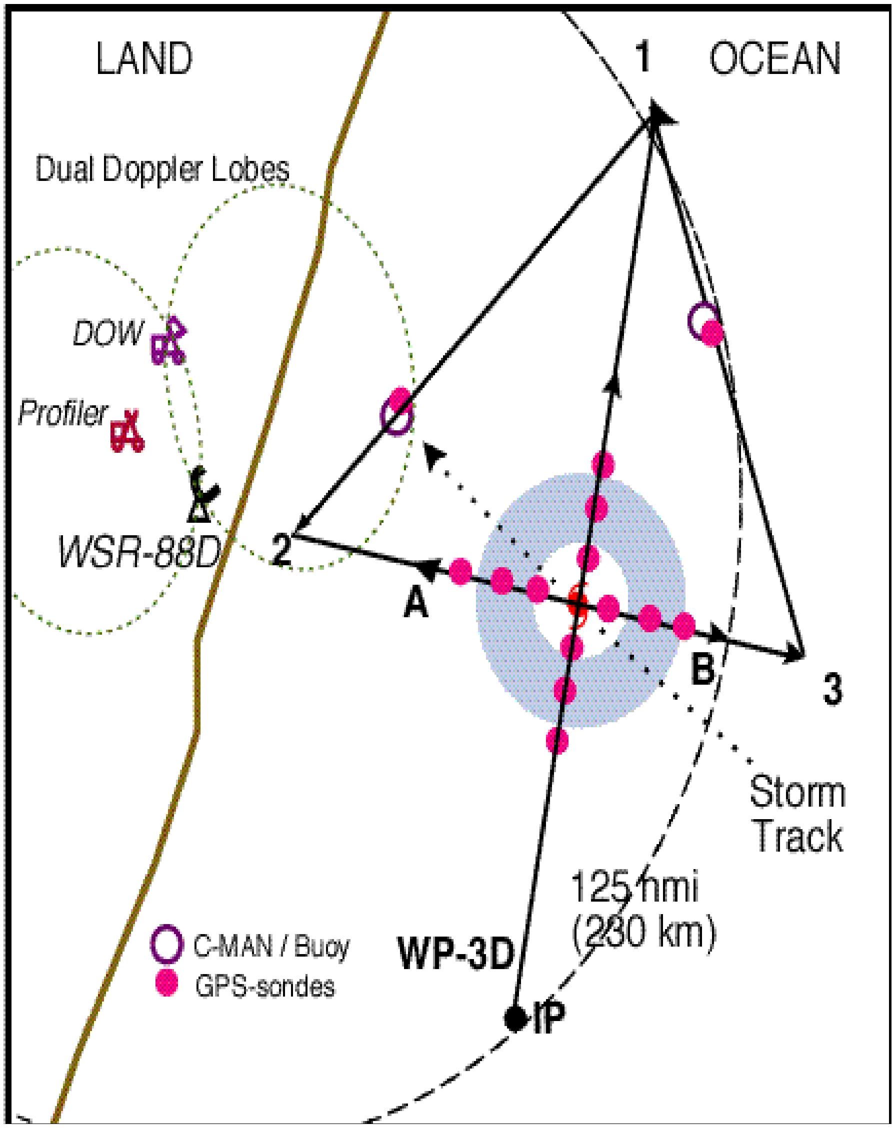


Figure 12-1: Real-time module.

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

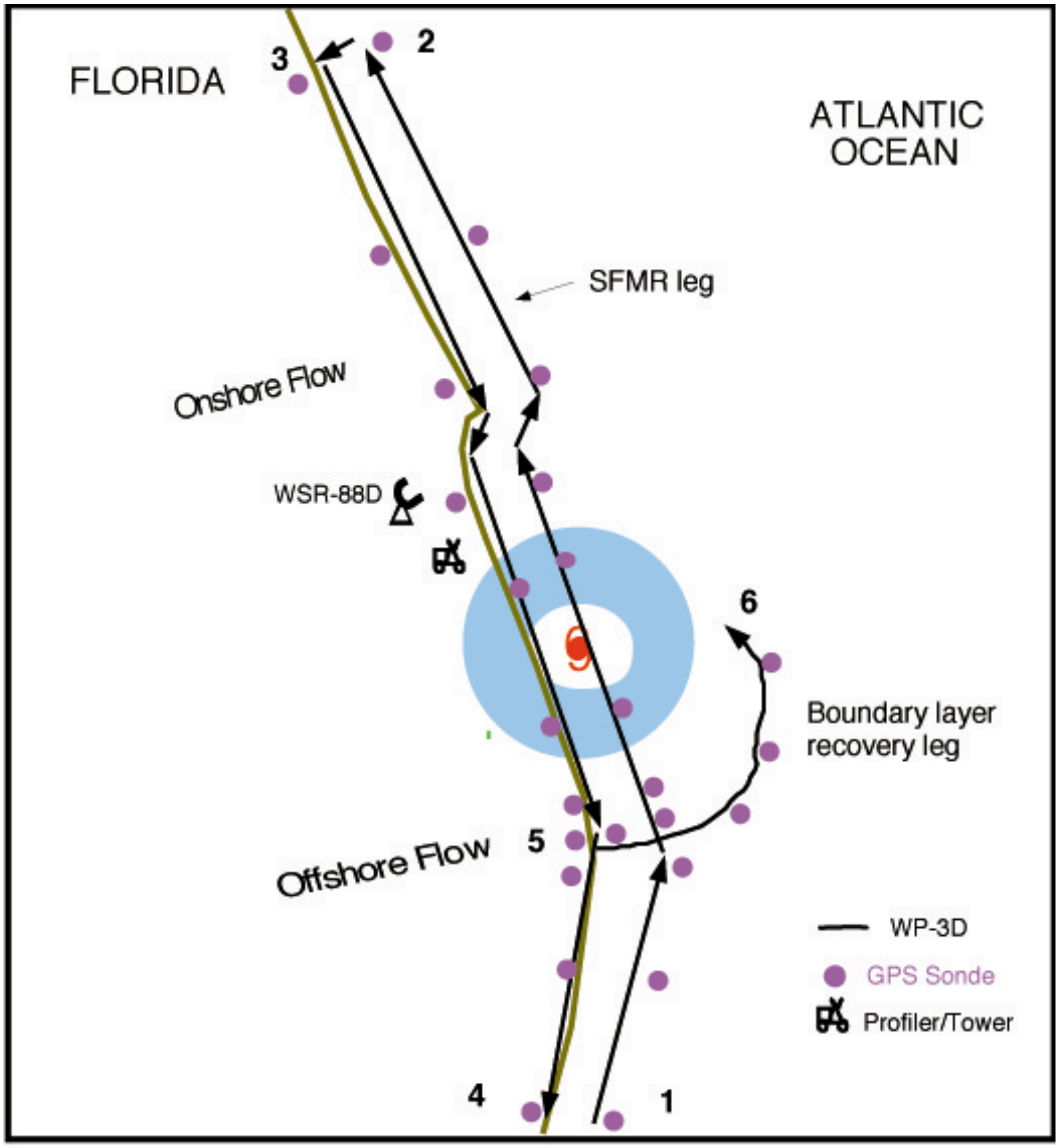


Figure 12-2: Coastal Survey pattern.

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

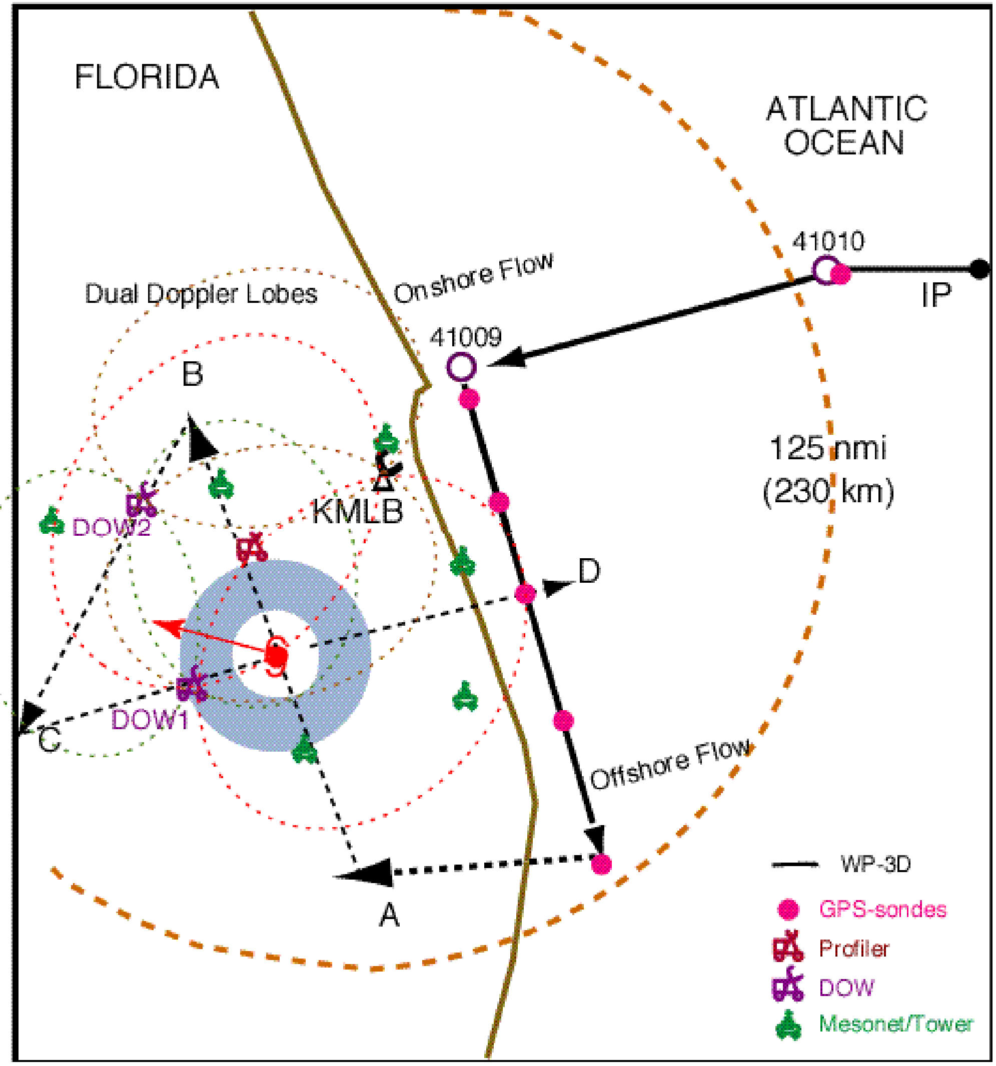


Figure 12-3: Post landfall module flight pattern.

- Coastal survey pattern (solid line) at ~10,000-15,000 ft (3-4 km) with dropwindsondes near buoys of opportunity and within 10-20 km of the shore in both the onshore and offshore flow
- Inland figure-4 pattern (dashed line) centered on the storm with leg lengths of ~80 nm (150 km) at an altitude of ~15,000 ft (5 km).
- P-3 should fly legs along the WSR-88D radials.
- Set airborne Doppler radar to F/AST on all legs.
- Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

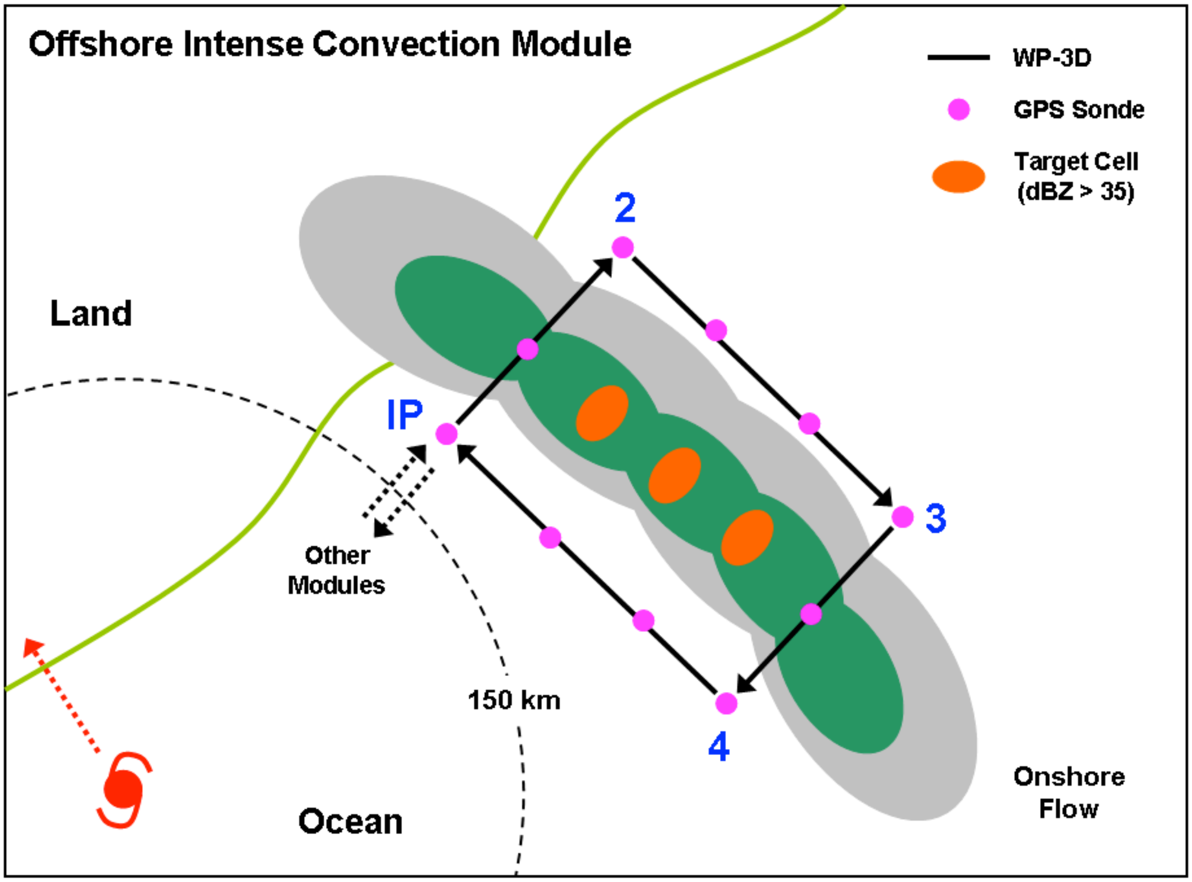


Figure 12-4: Offshore Intense Convection pattern.

The **IP** should be a minimum of 150 km from the storm center. The first leg (**IP-2**) starts 25 km inside the rain band axis. Legs **IP-2** and **3-4** should be ~20-25 km downwind and upwind of the target cells to ensure adequate Doppler coverage. Legs **2-3** and **4-IP** should be 25 km inside and outside the rain band axis. The length of legs **2-3** and **4-IP** can be adjusted but should be 75 km at minimum. Deploy dropwindsondes at the start or end points of each leg, at the band axis crossing points, and at ~20-25 km intervals along each leg parallel to the band. Aircraft altitude should be at 10,000 ft (3000 m) or higher. Set airborne Doppler to scan in F/AST mode on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly over land).

13. Tropical Cyclone Eye Mixing Module

Principal Investigator: Sim Aberson

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

Significance: Eyewall mesovortices have been hypothesized to mix high entropy air from the eye into the eyewall, thus increasing the amount of energy available to the hurricane. Signatures of such mesovortices have been seen in cloud formations within the eyes of very strong TCs, and from above during aircraft penetrations. However, the kinematic and thermodynamic structures of these features have never been directly observed. Observations within the eye below the inversion can allow for the study of these mesovortices and improve knowledge of small-scale features and intensity changes in very strong TCs.

Objective: The objective is to directly observe the kinematic and thermodynamic structures of eyewall mesovortices for the first time. This would allow research into the impact these features have on subsequent intensity changes.

Requirements: A TC with a clearly defined visible eye, eyewall, and inversion and an eye diameter of at least 25 nm is needed. This should only be done during daytime missions. The inversion level is defined as the interface between cloudy air below and clear air above inside the eye.

Hypothesis: Eyewall mesovortices play an important role in tropical cyclone intensity change.

Description: Although this is not a standalone experiment, it could be included within any missions during aircraft passage through the eye. The P-3 will penetrate the eyewall at the altitude proposed for the rest of the flight. Once inside the eye, the P-3 will descend from that altitude to a safe altitude below the inversion while performing a figure-4 pattern. The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 nm from the edge of the eyewall. Upon completion of the descent, the P-3 will circumnavigate the eye about 2 nm from the edge of the eyewall in the shape of a pentagon or hexagon. Time permitting; another figure-4 will be performed during ascent to the original flight level. Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

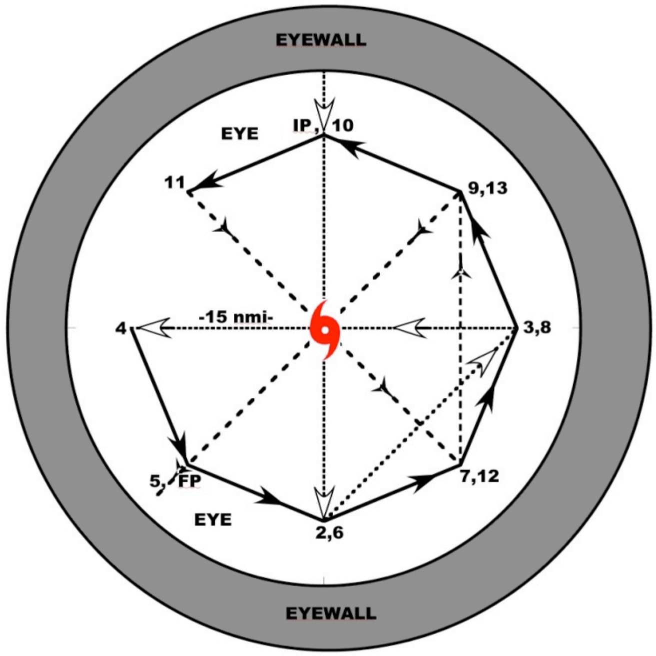


Figure 13-1. The P-3 approaches from the north, penetrates the eyewall into the eye, and descends below the inversion while performing a figure-4 (dotted line) in the eye. The P-3 circumnavigates the eye in an octagon or pentagon (solid line), and then ascends while conducting another figure-4 (time permitting) rotated 45 degrees from the original (dashed line).

14. Eyewall Sampling and Intensity Change Module

Principal Investigator: John Gamache and Gary Barnes (U of Hawaii)

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

Hurricane intensity, defined by either minimum sea-level pressure or maximum sustained wind speed, is determined by processes in the core (radial distance < 100 km). These processes include, but are not limited to, enhanced sea to air fluxes near and under the eyewall, eye-eyewall mixing, convective outbreaks in the eyewall, increased mass and moisture inflow to the eyewall, contraction of the eyewall, and the interaction of the upper-level flow with the eyewall. To more fully understand these processes the research community needs detailed monitoring of the core of several hurricanes. The observations can also serve some real-time needs of NHC.

This module is designed to address the following questions:

(a) How variable is the inflow equivalent potential temperature around the TC?

(b) Is mass and moisture flux to the eyewall correlated with TC intensity? If we sample the same TC twice during the flight or twice or more during its lifetime we can correlate inflow traits with intensity change. With the collection of several circumnavigations around several different TCs we could build a relationship between inflow traits and TC intensity. This would take a number of years to collect but could show a range of behaviors from a tropical storm to a high category TC.

(c) Where are the main updrafts with respect to the maximum mass and moisture horizontal flux into the eyewall?

(d) Is the eyewall driven by convective updrafts or is it better described as a mesoscale ring of ascent?

(e) How variable is the radial and tangential flow outside and in the eyewall as a function of azimuth?

(f) How do inflow rate, azimuthal extent and depth vary with TC speed and direction?

(g) How do the inflow rate, azimuthal extent and depth vary with respect to the large-scale vertical shear of the horizontal wind?

Dropwindsondes, when combined with the TC track, will allow the calculation of storm-relative variables. Each dropwindsonde will provide estimates of inflow rate and depth, and energy content. These profiles can then be assembled to construct an azimuth-height surface that extends from a few hundred meters below aircraft altitude to the sea surface around the eyewall. The azimuth-height surface allows the estimation of fluxes of mass, moisture, and energy flux to the eyewall for the entire inflow. If the module is repeated at other radii (e.g., 100 km or just inside the eyewall), net vertical transports through a given altitude, or net fluxes through the sea surface can be determined using divergence to infer processes between the two surfaces. The surface fluxes may be solved as a residual or estimated using the data collected at 10 m by the dropwindsonde. Mixing across the top surface remains an issue, but if the aircraft is equipped with turbulence sensors, this exchange can be determined.

The plan views of the eyewall region from the lower fuselage radar are used to estimate net LHR. As the aircraft moves around the eyewall it will get views of each quadrant. These quadrants are assembled for a complete view of the eyewall region that limits beam filling or attenuation issues. A Z-R relationship is then applied to this map of reflectivity to estimate LHR. LHR can be compared to other standard measures of TC intensity such as MSLP and maximum sustained wind speeds estimated from the aircraft. LHR has the advantage that it does not rely on a single pass or reading, instead it is the integration of the net LHR from the entire eyewall region. The lower fuselage radar also reveals if the eyewall consists of one or more cumulonimbus clouds, is more mesoscale, or is asymmetric. The tail radar provides estimates of echo top, and echo slope. These also serve as measures of TC intensity – higher, less sloped systems are expected for higher category TCs. As the aircraft circumnavigates the eyewall F/AST can be applied. F/AST provides approximately 2-km horizontal resolution wherever there are scatterers. Continuity applied to these windfields results in an estimate of the vertical velocity field. The dropwindsondes provide data that can be used as an initial condition for the lowest 500 m where sea clutter may contaminate the Doppler wind estimates.

The pattern is a circumnavigation around the eyewall with the P-3 flying counterclockwise to exploit strong tailwinds (Fig. 14-1). The aircraft would maintain a ~10 km separation from the eyewall that places the aircraft in an excellent position to obtain tail radar data for both reflectivity and Doppler wind measurements. In addition to providing the necessary azimuthal dropwindsonde observation, another advantage of a circumnavigation of the eyewall is 360-degree Doppler-radar coverage of the eyewall, while a single linear pass through the eyewall often does not cover the full circumference of a large eyewall. Altitude may be 8500 feet to 11,500 feet (750 to 650 hPa). Circumnavigation around the eyewall can be done relatively quickly, on the order of one-half hour, for an eyewall radius of about 35 km, and a tailwind of minimal hurricane force. About 12 dropwindsondes would be deployed during circumnavigation that provides estimates of the depth, rate and thermodynamics of the inflow. AXBTs should also be deployed at points 1, 5, 8, and 11. The circumnavigation can be done as part of the standard figure-4 pattern used routinely during reconnaissance missions and often at the start and finish of research missions.

There are several possible variations. More dropwindsondes could be released in the eyewall in rapid succession. It would also be possible to do multiple rings. For hurricanes with a large eyewall a circumnavigation along the inner edge of the eyewall would be possible to ascertain more about the interaction of the eye and eyewall. More distant circumnavigations allow for an assessment of where the inflow is gaining or losing energy as the inflow approaches the eyewall.

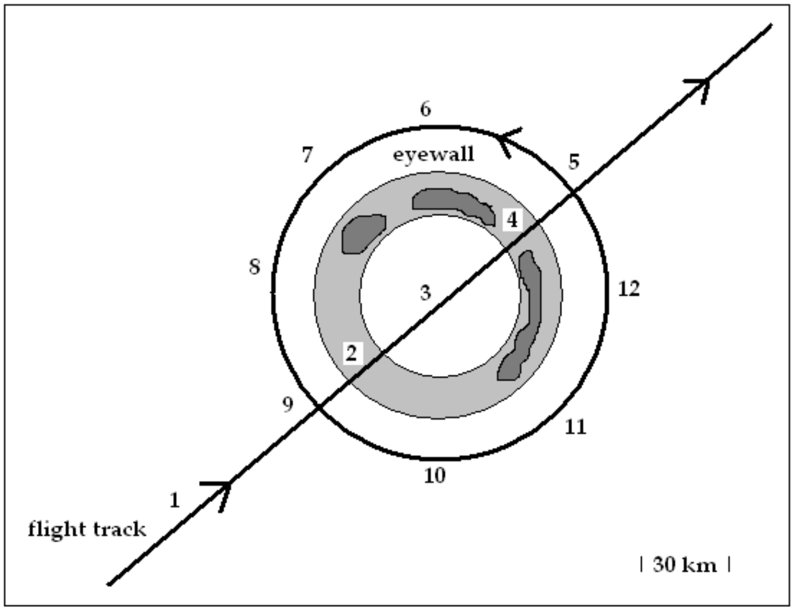


Figure 14-1: Flight track (bold line), eyewall (gray region), and GPS dropwindsondes (numbered)

Note 1. Unless specifically requested by the LPS, tail Doppler radar should be operated in F/AST with a fore/aft angle of 20 degrees relative to fuselage.
Note 2. IP (1) can be at any desired heading relative to storm center, preferably one that maximizes the continuity of the module with the rest of the flight plan. IP should be about 30 km out from the eyewall.
Note 3. To maximize dropwindsonde coverage, aircraft should operate at highest altitudes that still minimize the likelihood of icing or graupel damage.
Note 4. Radius from storm center should be enough to accommodate about 10 km standoff from the eyewall, to maximize the observation of boundary layer inflow and upper-level outflow.
Note 5. Both dropsonde and Doppler capability are required for this flight module
Note 6. PRF should be single at 2400 for hurricanes, and 2800 for major hurricanes
Note 7. Sondes should be dropped at points 1-12, and should be backed up
Note 8. AXBTs should be dropped at 1, 5, 8, and 11

15. Air-Sea Surface Fluxes Module

Principal Investigator: Michael Bell and Michael Montgomery (Naval Postgraduate School)

HRD Point of Contact: Rob Rogers

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

Air–sea exchanges of heat and momentum are important elements in understanding and skillfully predicting hurricane intensity, but the magnitude of the corresponding wind-speed dependent bulk exchange coefficients is uncertain at hurricane force wind speeds. Since direct turbulent flux measurements in these conditions are extremely difficult, the momentum and enthalpy fluxes can be alternatively deduced via angular momentum and total energy budgets (Fig. 15-1). This module was successfully executed during the CBLAST field campaign with good results from the methodology reported by Bell (2010). Further research with data from additional hurricanes would add to the confidence in the derived exchange coefficients. This module could be performed by either of two existing flight patterns. The first would be to repeat the original CBLAST flight pattern with high frequency dropwindsonde deployments through the eyewall region (Fig. 15-2). This would allow for an axisymmetric budget calculation derived from azimuthally averaging the dense dropsonde data and tail Doppler radar derived winds. A second option (Fig. 51-3) could be executed using the Ocean Winds experiment flight pattern. This consists of a series of pie-shaped wedges originating in the eye and extending outward to just beyond the eyewall and high wind inner core nominally 50 km (37 nm), and which rotate downwind with time. These pie slices will be concentrated in the high wind right and front quadrants of the storm and be flown with the two WP-3D aircraft flying 'in trail', maintaining same lateral and vertical spacing. This would enable the budget calculation to be performed without the axisymmetric assumption, and include an estimate of the wind and energy tendency terms from the lagged aircraft measurements. The Ocean Winds pattern would require extra drops on the outer edge of the pie wedge in order to complete the budget around the entire circuit.

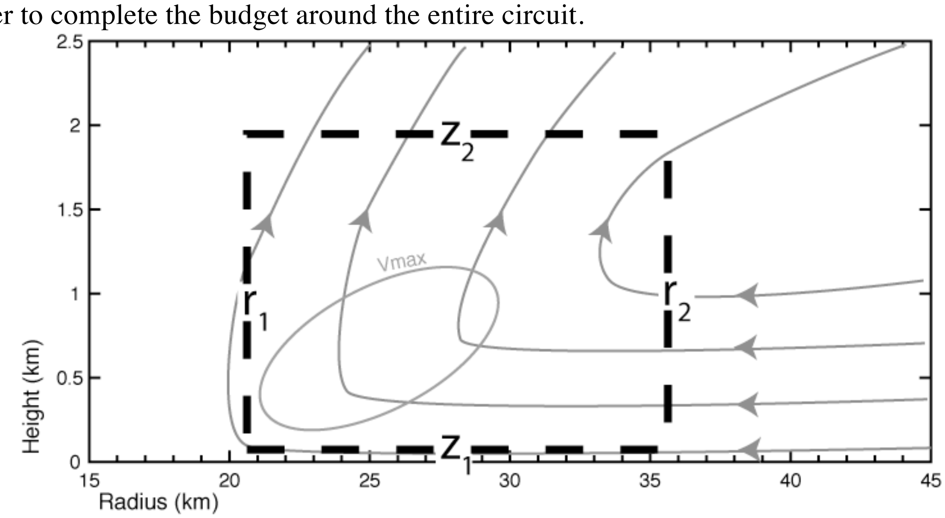


Figure 15-1. Schematic illustrating hypothetical control volume (black dashed line) used for the budget methodology. A simplified secondary circulation (gray streamlines) and region of maximum wind (v_{max}) are shown to indicate the control volume encompasses the eyewall region.

Mature Storms Experiment

CBLAST MODULE

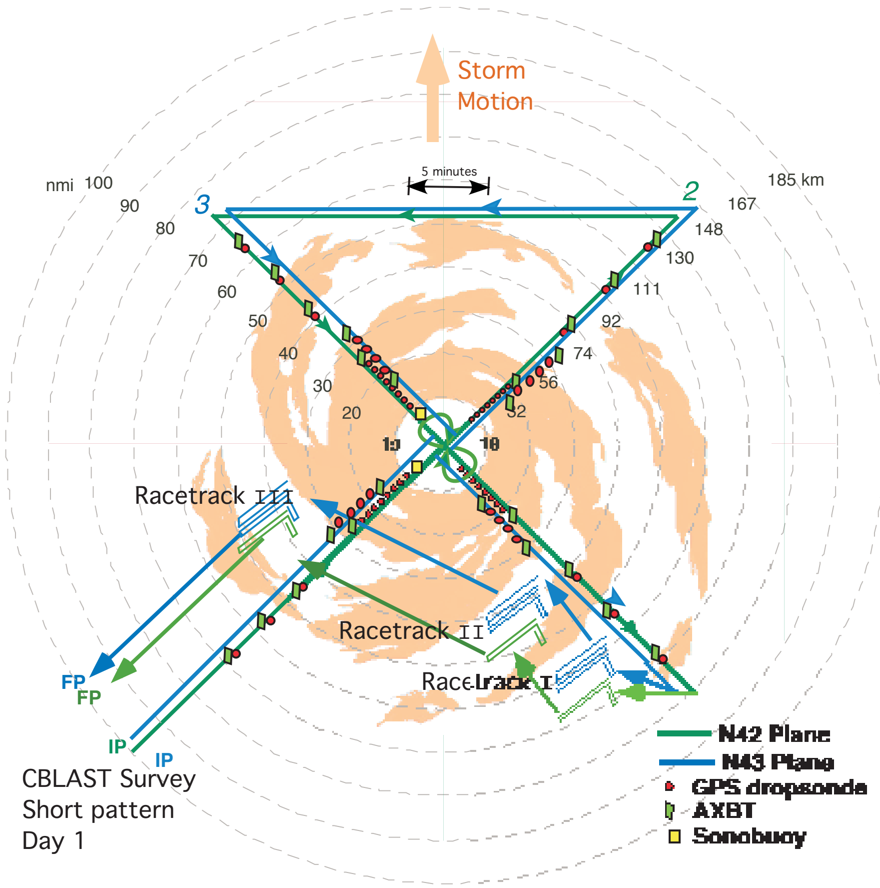


Figure 15-2. CBLAST eyewall sonde module.

• Note 1.	The pattern should be aligned 45° from storm heading. Preferred **IP** is in left-rear quadrant, but can be in any quadrant.
• Note 2.	The two WP-3Ds fly ‘in trail’ with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
• Note 3.	Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 120 nm, and the **IP** for the lower WP-3D at a radius of 108 nm.
• Note 4.	The lower WP-3D will commence a sequence of four near-eyewall drops on inbound legs at approximately $2R_{MAX}$ or twice the eyewall thickness radially-outward. High-level aircraft should commence series of 8 eyewall drops 30 s after end of low plane drops, ending at inner edge of eyewall. Orbit in the center until all drops have cleared. Reverse the sequence on the outbound legs.
• Note 5.	Operate NOAA 43 Tail Doppler in continuous mode on all coordinated legs.

Mature Storms Experiment
OCEAN WINDS EXPERIMENT/MODULE

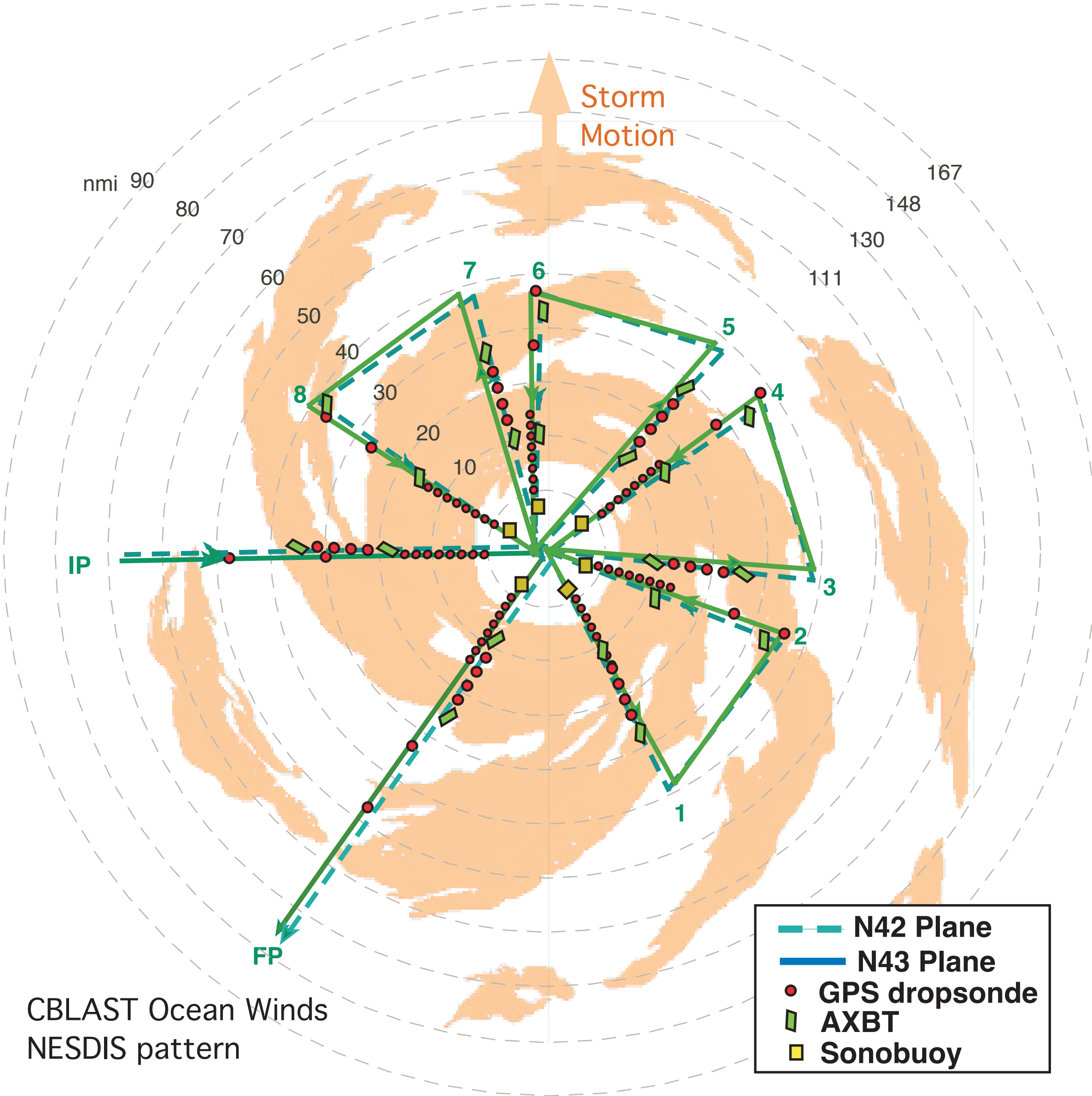


Figure 15-3. Ocean Winds Pattern

• Note 1.	Preferred **IP** is in west quadrant, but can be in any quadrant.
• Note 2.	The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
• Note 3.	Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 108 nm, and the **IP** for the lower WP-3D at a radius of 97 nm.
• Note 4.	The high WP-3D will commence a sequence of six eyewall drops on inbound legs at approximately 1.5RMAX or near the outer edge of the eyewall, ending at inner edge of eyewall. Reverse the sequence on the outbound legs.
• Note 5.	NOAA 43 TA radar should be operated in continuous mode (**not** F/AST) while flying coordinated legs with NOAA 42.

16. Boundary Layer Inflow Module

Principal Investigators: Eric Uhlhorn and Jun Zhang (HRD)

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

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 2011). 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. 16-1). 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. 16-1. 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?

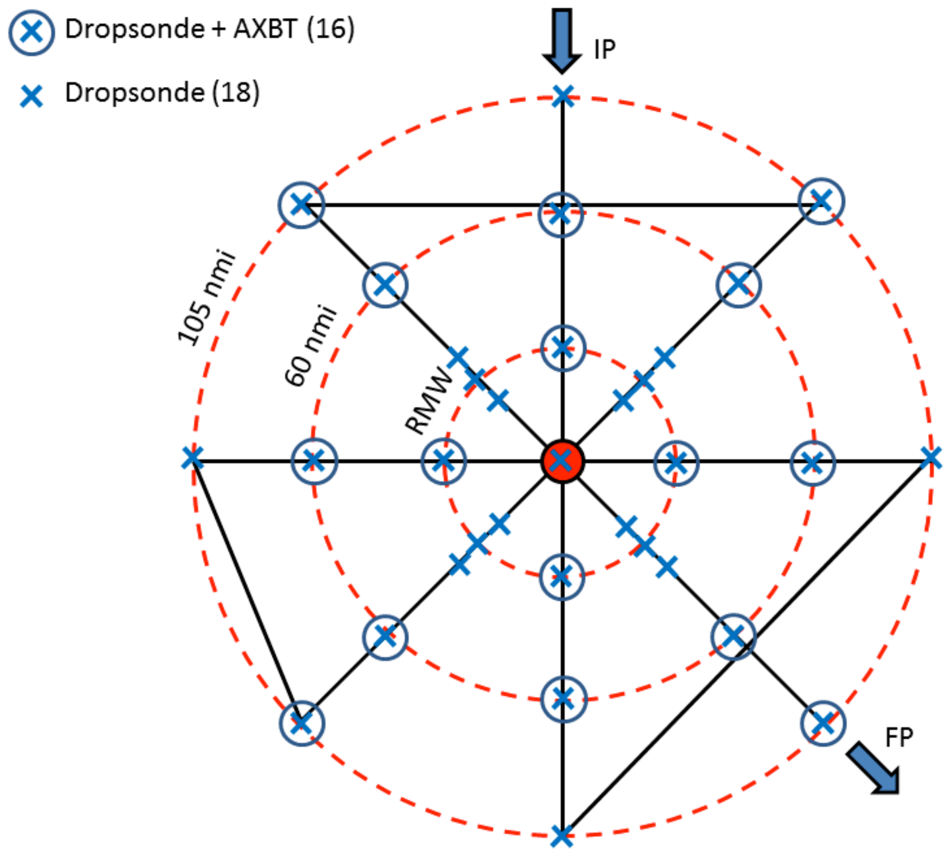


Figure 16-1: Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/Figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. 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.

17. Hurricane Boundary Layer Entrainment Flux Module

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

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

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

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

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

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

Objectives

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

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

Turbulence Calibration Module (2-3 hours)

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

1). Dynamic Yaw--2 sets:

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

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

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

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

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

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

Stepped-descent module (40 minutes):

The module is flown between the eyewall and an outer rainband by NOAA-43, which is equipped with the turbulence sensors. It does not require any penetration of convective cells, the eyewall or convective rainbands. Preference is for a region that is either rain-free or stratiform rain only. For the simplest experiment 5 legs would be flown, each about 40 km or 5 minutes in duration (Fig. 17-1 and 17-2). 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 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 data at the end of outbound radar leg to diagnose the boundary layer height. Then we turn back into the storm to do the stair-step. The aircraft would descend to 600 m above the inflow top (about 2400 m) and fly toward the eyewall along an approximate radial. This leg will cover 40 km or require about 5 minutes. The aircraft will then turn and descend ~500 m and fly out-bound for 5 minutes. Two more legs will be completed, each another 500 m below the previous pass. The last pass will be 700 to 800 m above the sea. If the aircrew deems it safe a final pass could be flown 400 to 500 m above the sea. All legs will finish with a turn upwind to keep the legs nearly vertically aligned and in the same portion of the TC. Time to complete the module is about 40 min including descents and turns.

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

Box Module (20-25 minutes):
If we wish to estimate divergence and there are too few scatterers to obtain this estimate from the Doppler radar we would like to execute a box pattern (Fig. 17-3) 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).

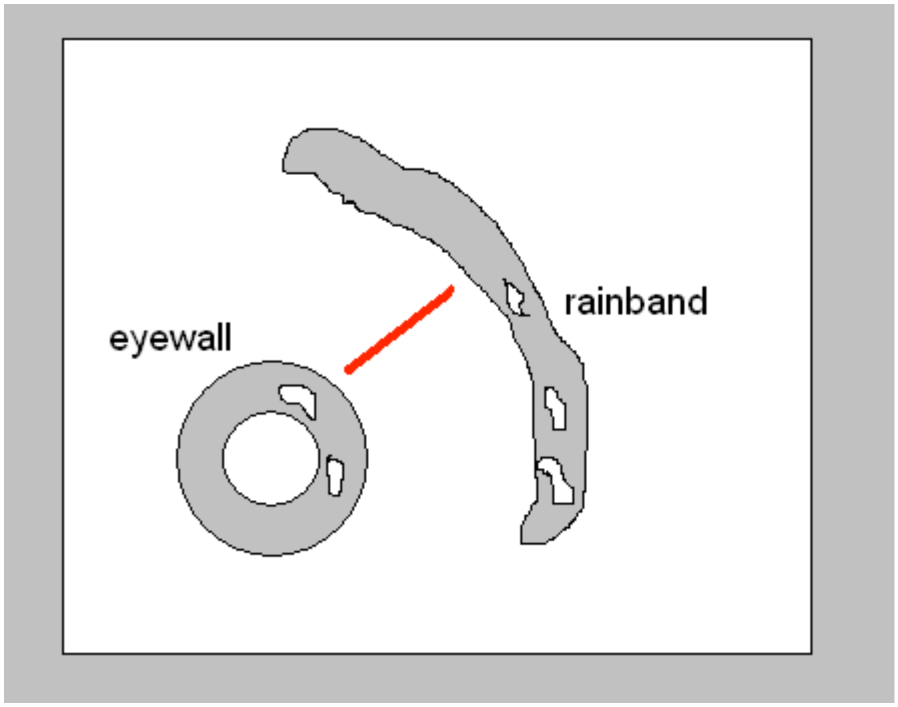


Figure. 17-1. Plan view of the preferred location for the stepped-descent module. Red line shows aircraft track.

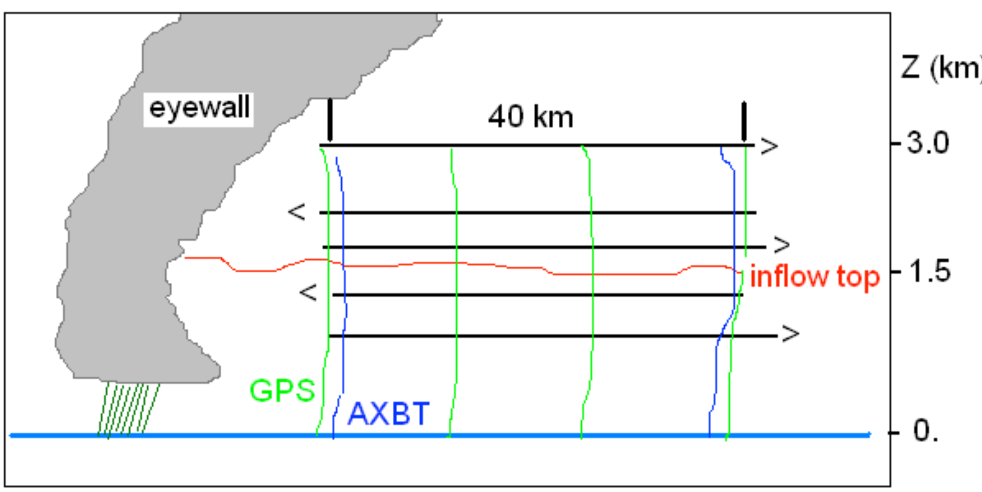


Figure17-2. Vertical cross-section of the stepped-descent module.

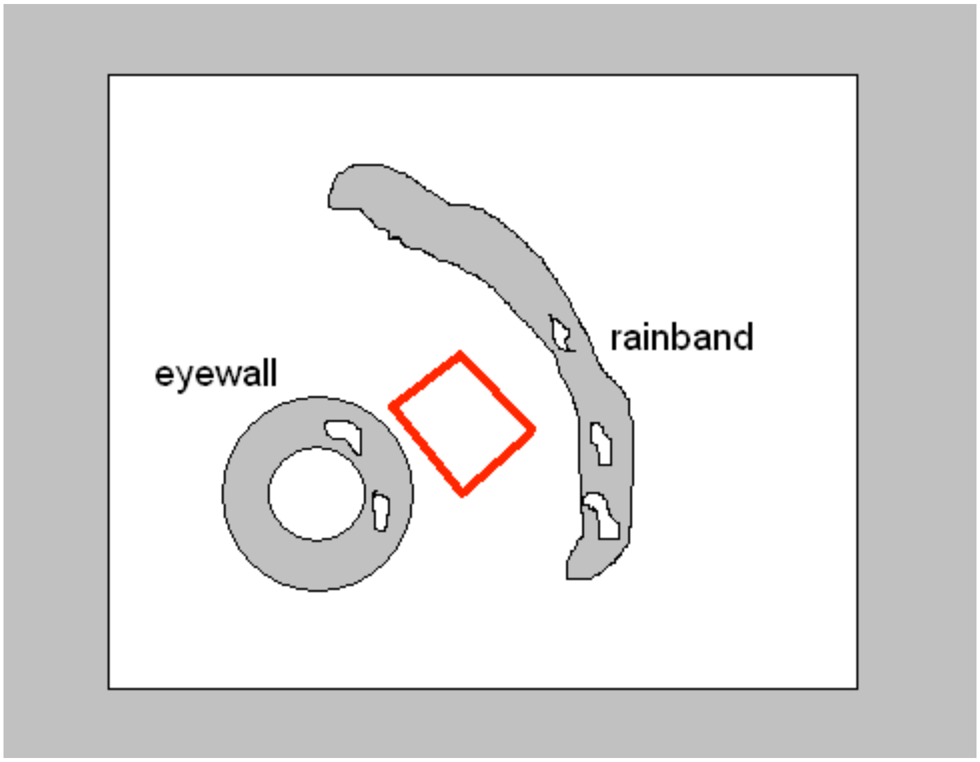


Figure17-3. Box module used to calculate divergence if no scatterers exist in the volume.

18. Aerosol/Cloud Droplet Measurement Module

Principal Investigator: Bob Black

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

The concentration, mass content, and size distributions of the precipitating particles in hurricanes remains a critical component necessary for improving the ability of the numerical hurricane models to properly characterize the storm environment. The precipitation is also the result of the vertical heat flux realized in the storm, another critical parameter in the numerical models. Measurement of these particles has not been done in a systematic manner since the 1980's and early 1990's (Black and Hallett, 1986, 1999), (Black et al, 1994), and those measurements were accomplished using probes that were incapable of recording all of the particles present. Worse, the early measurements included no measurements of the microphysical critical cloud droplets, particles with a diameter < ~50 μm.

The recent acquisition of the DMT CCP, CAS and PIP probes has finally removed these limitations, but these probes have never been exposed to the full brunt of the precipitation in the hurricane, especially above the melting level. Therefore, their capabilities remain potential, rather than confirmed. The CCP includes a 25μm resolution (0.025 - 1.6 mm) imaging probe and a 3 - 47μm cloud droplet probe (CDP). The CAS has a different sampling geometry from the CDP, producing cloud droplet spectra in the range 0.61 - 50μm, plus having the ability to distinguish aerosol particles that are either solid or liquid. The PIP has performed well in recent seasons, and measures precipitating particles in the size range 0.1 - 6.4 mm. Neither of the imaging probes are Greyscale, but this limitation is significant only for the smaller (< 0.5 mm diameter) ice particles.

To address this deficiency in our knowledge, I propose that the WP-3D aircraft resume standard "Rotating Figure-4" flight patterns without avoiding the convection for normal HFIP operations. These passes should be done at several altitudes, including above the melting level, AOC willing. Should the DMT probes perform adequately in the rain (there is potential for inadequate de-icing power at cold temperatures with them since they use 28 VDC de-icers), we should do an intensive study of the convection. To this end, a series of radial flights (Fig. 17-1) through the heaviest precipitation should be done. These passes should be accomplished at several altitudes from 2 km - 4 km MSL (1-km vertical separation) to document the evolution of the rainfall spectra with altitude, and to extend to higher rain rate values the conditions into which the DMT probes have been exposed. Each pass will require 10 - 15 minutes to execute, and while it would be best for these to be consecutive, multiple altitude penetrations made at any time are appreciated. In the current database, the highest rain rates the DMT probes have been exposed to is only 38 dBZ, and this must be extended to higher rates. Should AOC relent and allow the highly sought after passes at and above the melting level, I'd like to extend them to 6.0 km, such as we did prior to 1993, because good hurricane precipitation measurements above the melting level have not been obtained since then.

Aerosol/Cloud droplet measurement module
The sub-cloud aerosol determines the cloud base droplet concentration, which in turn controls the rate of precipitation formation. Recent work (Rosenfield et al, 2007) has shown that pollution aerosol might have a significant suppression effect on the hurricane intensity through the introduction of large quantities of aerosols in the form of cloud condensation nuclei (CCN). The mechanism Rosenfield et al propose for weakening a hurricane works by suppressing the warm rain process in the outer rain bands and eyewall.

In 2010, only one aerosol pass was obtained because N43 was on a night schedule for most of the season. Analysis of these data has commenced, but no details are available.

In order to properly assess the likelihood of this scenario, it is necessary to determine the natural range and number concentrations of the sub-cloud aerosol in hurricanes that are far from land, unaffected by pollutants. These pristine oceanic aerosols are thought to be primarily sea-salt aerosol created by spray and ammonia salts with organic origins. The measurement of the sub-cloud and low-level cloud base aerosol and droplet spectra in the hurricane has not been heretofore accomplished. However, since the purchase of new droplet spectra probes, as well as a new cloud liquid water meter in 2009, this measurement has finally become possible. In addition, might be possible to once again obtain a new Droplet Measurement Technologies (DMT) dual-chamber CCN counter and a new fast-response hygrometer in time for hurricane season. These devices offer the ability to measure the concentration of the cloud - active parts of the aerosol. This information, along with accurate, fast-response hygrometer data will enable us to determine the fraction of the aerosol that is CCN.

While these new devices cannot determine the aerosol composition, they can determine the number concentration and activity spectra of these aerosols, and the new cloud droplet probe can measure the activated cloud base droplet spectra. This latter measurement is crucial to determining if the mechanism proposed by Rosenfield et al has any chance of operating. In order to do this, it will be necessary to fly the properly equipped WP-3D aircraft in the sub-cloud zone in several areas in various wind conditions, from benign trade wind to weak tropical storm strength through hurricane strength.

In the non-storm environment, it would be sufficient to fly in the sub-cloud layer at 1200' or a bit lower (if they'll do it, depending on circumstances) for 10 minutes, climbing 500', flying for another 10 minutes, then flying just above the trade-wind cumulus cloud base, to penetrate (non-precipitating) trade-wind Cu to obtain the low cloud droplet concentrations. In the Saharan Air layer (SAL) area, passes should also take place in the dry layer to determine the cloud-active proportion of the SAL aerosol. In a hurricane, such passes (Fig. A-1) should take place in non-precipitating cloud both inside and outside the rain bands. The final pass through the low cloud base should take place in the nearest rain band. Outside the eyewall, passes like these should end with a pass just above the nearest cloud base altitude. Should there be a will, a radial penetration of the eyewall at 1.5 km radar altitude would be desired to obtain the low level cloud number concentrations and water contents.

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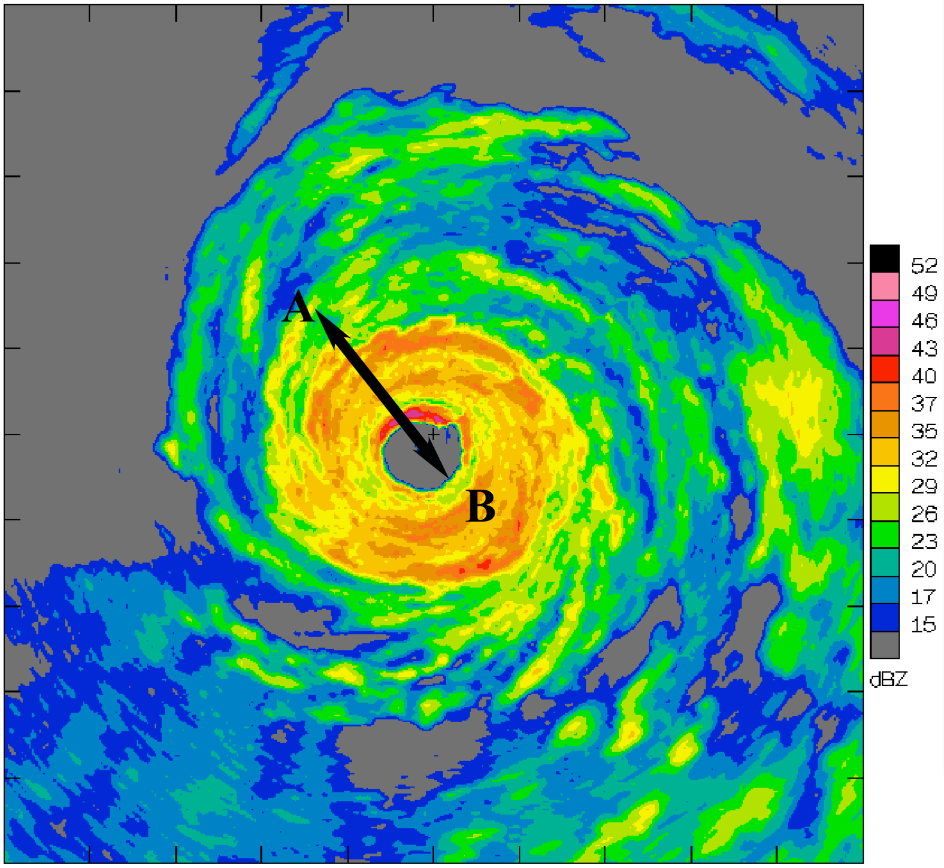


Figure 18-1: Radial microphysical passes should be obtained along a line such as A-B. These can be done at any altitude from 2 - 6 km, so long as the strongest reflectivity is sampled.

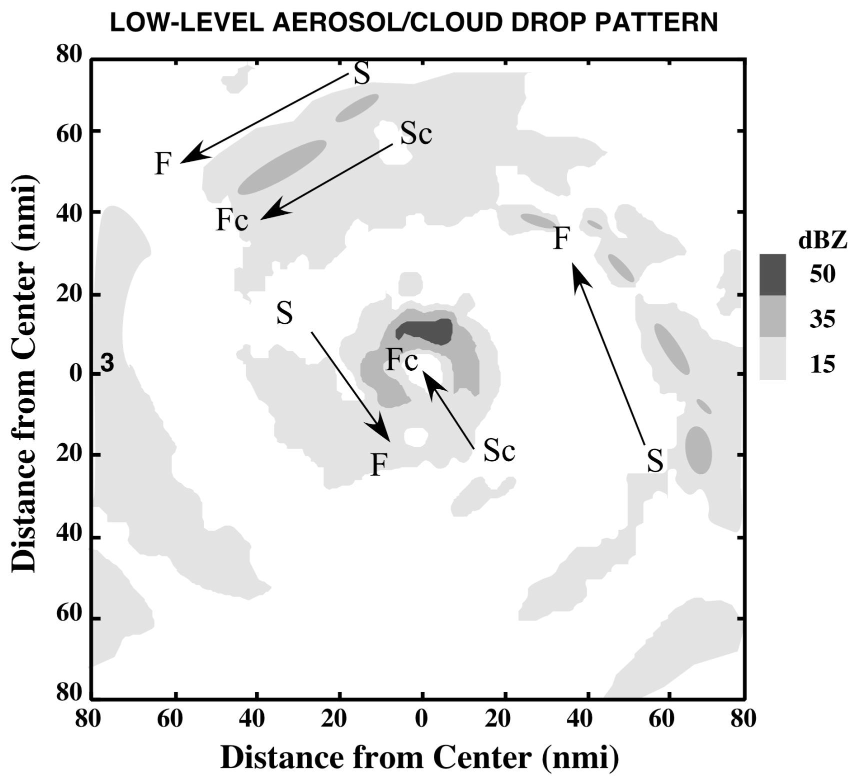
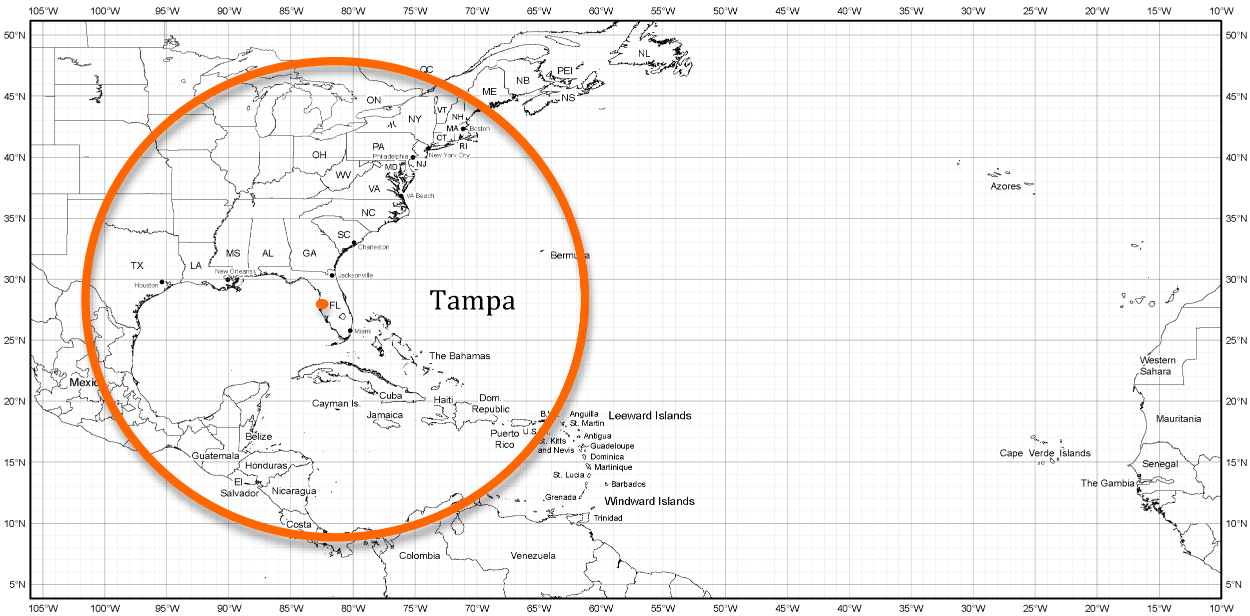


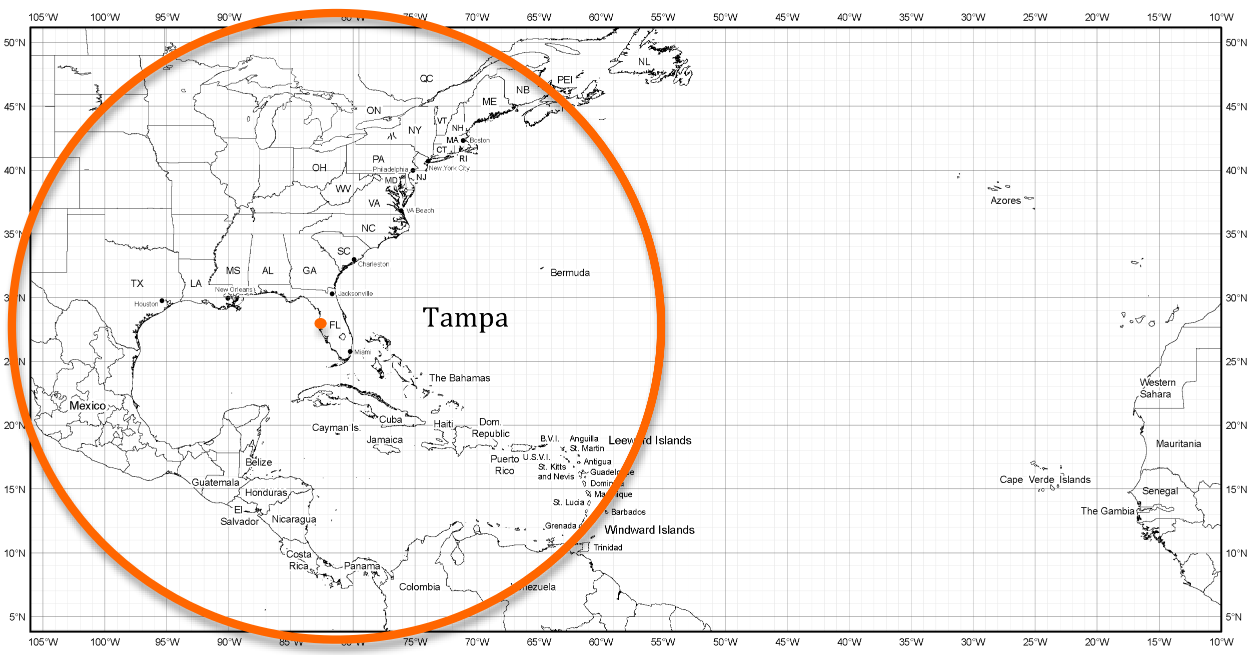
Fig. A 1. Aerosol/cloud droplet measurement flight pattern.

- Note 1. The pattern may be flown along any compass heading.
- Note 2. Fly S - F at 1,200 ft (0.4 km) in rain-free areas. Path is mor-or-less straight for 5 min, then increase elevation by 500 ft & continue until cloud base elevaton is reached.
- Note 3. After performing one or more passes, make one pass through cloud base nearest to end point (e.g Sc - Fc)
- Note 4. Pattern should be repeated as often as possible at various radii and horizontal wind velocities.

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.