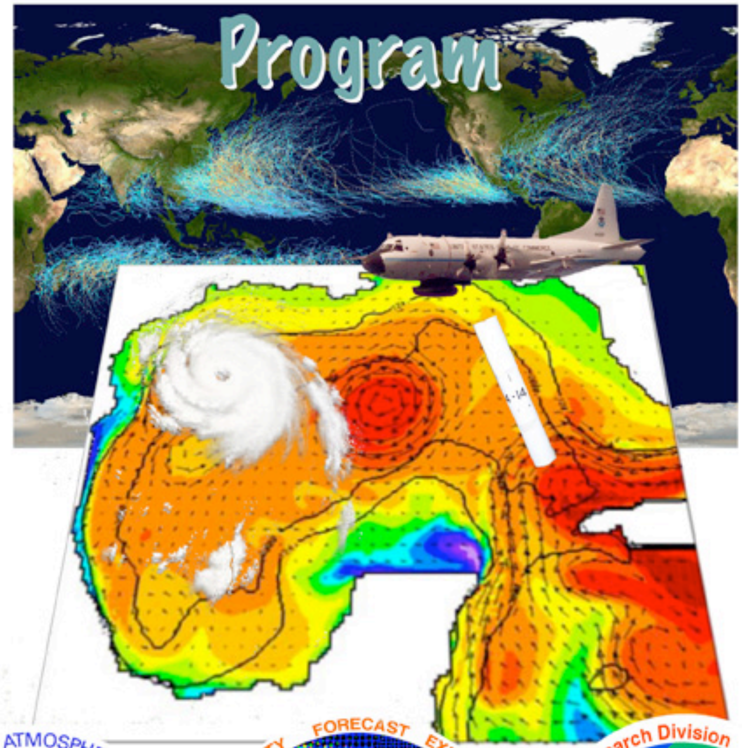
2009
Hurricane Field Program



NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

INTENSITY FORECAST EXPERIMENT
IFEX
EMC - TPC -HRD

Hurricane Research Division
AOML / NOAA

2009 Hurricane Field Program Plan

Hurricane Research Division
National Oceanographic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
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Cover: A NOAA P-3 overflies the Gulf of Mexico, deploying AXBTs that help to define the ocean heat content as portrayed in the computer simulation of a loop eddy. Meanwhile, a hurricane feeds off the warm temperatures and threatens the western Gulf coast. Behind is a depiction of the last thirty years of tropical cyclone tracks, demonstrating how they transport heat and moisture from the tropics to the mid-latitudes.

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INTRODUCTION

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

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 and rainfall. The lack of improvement in intensity and rainfall forecasting 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 next-generation TC model, HWRF, is now operational. It runs at high resolution (~9 km), using improved physical parameterizations. Such a configuration holds the hope 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, NOAA has proposed an experiment designed to improve operational forecasts of TC intensity, called the Intensity Forecasting EXperiment (IFEX). 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 and rainfall by providing data to improve the operational numerical modeling system (i.e., HWRF) and by improving understanding of the physics of intensity change and rainfall. 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 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;

A unique, and critical, aspect of IFEX is the focus on providing measurements of TCs at all stages of their life cycle, from pre-genesis to intensification and subsequent landfall, decay over water, or extratropical transition. The focus of hurricane research flights during the past 25 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.

The field program aircraft missions presented in this document are separated into two distinct sections: 1) NHC and EMC operational missions, and 2) IFEX research experiments. 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.

The mission that will get the largest allotment of hours allocated to HRD and NCEP is an operational mission (1), designed to improve the forecast of hurricane structure and intensity by sampling the evolution of tropical-cyclone structure and intensity using airborne Doppler radar, SFMR, and dropwindsondes, from tropical depression to major hurricane. Other experiments include 2) probing the evolution of structure and intensity of TCs that make landfall, in particular studying the weakening and dissipation of storms as they move inland, 3) using the Aerosonde unmanned aircraft system (UAS) to sample the TC environment, including the low-level regions of the TC boundary layer, 4) studying tropical cyclogenesis, 5) studying the ocean microwave emissivity at angles of as much as 60 degrees from zenith, to permit a scanning SFMR that will provide surface wind speeds over a wide swath below the aircraft or a satellite, 6) understanding how propagating arc clouds affect the evolution of African Easterly Waves (AEWs) or TCs, 7) investigating the impact of the Saharan Air Layer (SAL) on TC intensity change, 8) measuring sea-salt aerosol and cloud-base Cloud Condensation Nuclei (CCN) number concentrations in TCs, 9) looking at eyewall droplet and ice-particles size distribution and habits and water content with new cloud-physics probes to improve microphysical parameterizations of numerical simulations of TCs, 10) probing the interaction of the ocean and atmosphere in TCs, and 11) an operational mission designed to improve model forecasts of TC track by sampling the surrounding tropical-cyclone environment. These experiments and operational missions will be conducted with the two NOAA P-3s and Gulfstream IV-SP aircraft. A summary of each, along with which IFEX goals it specifically addresses, is included below. A detailed description of each experiment or operational mission follows, including descriptions of the scientific and details of the associated flight patterns.

(1) Three-Dimensional Doppler Winds: 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. The overall experiment is comprised of two parts: one designed to obtain regular 12- or 24-h resolution airborne Doppler-radar observations of hurricanes, with optional dropwindsondes, and one, the National Environmental Satellite, Data, and Information Service (NESDIS) Ocean Winds and Rain Experiment, designed to improve understanding of microwave surface scatterometery in high-wind conditions over the ocean by collecting surface scatterometery data and Doppler data in the boundary layer of hurricanes.

(2) Hurricane Synoptic Surveillance: This is a multi-option, single or multi-aircraft operational mission that uses dropwindsondes launched from the NOAA G-IV, and the AFRES C-130 to improve landfall predictions of TCs by releasing dropwindsondes in the environment of the TC center. These data will be used by NCEP to prepare objective analyses and official forecasts through their assimilation into operational numerical prediction models. Because the atmosphere is known to be chaotic, very small perturbations to initial conditions in some locations can amplify with time. However, in other locations, perturbations may result in only small differences in subsequent forecasts. Therefore, targeting locations in which the initial conditions have errors that grow most rapidly may lead to the largest possible forecast improvements. Locating these regions that impact the particular forecast is necessary. When such regions are sampled at regularly spaced intervals the impact is most positive. The optimal targeting and sampling strategies is an ongoing area of research. This addresses IFEX Goal 1.

(3) 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 goals 1, 2, and 3 are directly addressed.

(4) 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. It addresses IFEX Goals 1, 2, and 3.

(5) 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. It addresses IFEX Goals 1 and 3.

(6) SFMR Evaluation Experiments: This is a single aircraft series of experiments designed to improve surface wind measurements in various conditions encountered during flights. Specific goals are to obtain in situ surface wind data in shallow bathymetry, intense rainfall, and large off-nadir incidence angles, exclusive of one another. IFEX goal 2 is addressed by this experiment.

(7) Tropical Cyclone/AEW Arc Cloud Experiment: This is a single-aircraft experiment, designed to collect observations across arc cloud features in the periphery of an AEW or TC using aircraft flight-level and dropwindsonde data to improve understanding of how these features may limit short-term intensification. Observations could be made using either the P-3 aircraft conducting another experiment, or the G-IV during a synoptic surveillance mission.

(8) 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. It addresses IFEX Goals 1 and 3.

(9) Tropical Cyclone-Midlatitude Interaction Experiment: This is a multi-option, multi-aircraft mission 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. This experiment will only be conducted at the end of a TC life cycle if that particular TC has been sampled previously.

(10) Rapid Intensity Change Experiment: This is a multi-option, multi-aircraft experiment designed to obtain detailed observations at multiple scales during a TC rapid-intensification event, defined as an increase greater than 30 kts in 24 hours. This experiment addresses IFEX goals 1 and 3.

In addition to the experiments presented above that comprise IFEX, several other are occurring simultaneously and will be partnering with IFEX:

1. NESDIS will be conducting the Ocean Winds Experiment, using N43RF for part of the season. The goal is to further understanding of the ocean surface wind vector retrievals in high wind speed conditions and in the presence of rain for all wind speeds from microwave remote-sensing measurements.

2. EMC ran HWRF in operational mode for the first time in 2007. In addition a parallel run of HWRF will be run that assimilates the airborne Doppler observations. These will be run simultaneously with the operational run to evaluate the assimilation of airborne Doppler observations.

OPERATIONS

1. Locations

Starting on 01 June, N43RF and Gulfstream IV-SP (N49RF) aircraft will be available for possible missions. Operations for both aircraft will primarily base out of Tampa, Florida, with provision for deployments to Barbados, St. Croix, and Bermuda for storms in the Atlantic basin (including the Atlantic Ocean and the Caribbean Sea) 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. It is anticipated that N42RF will be available by 01 September.

2. Field Program Duration

The hurricane field research program will be conducted from 01 June through 30 September 2009.

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 30 September 2009. Also, the G-IV aircraft should be available, on a non-interference basis with tasked operational missions from 01 June to 30 September 2009.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of the 2009 Hurricane Field Program Plan is the responsibility of the field program director, who in turn, reports directly to the HRD director. The field program director will be assisted by the field program ground team manager. In the event of deployment, the field program ground team manager shall be prepared 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 2009 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

The Miami Ground Operations Center (MGOC) will operate from offices at AOML on Virginia Key (4301 Rickenbacker Causeway, Miami, FL) or from NHC (11691 S.W. 17th Street, Miami, FL). MGOC, operating from AOML or NHC, will serve as the communications center for information and will provide interface with AOC, NHC, and CARCAH (Chief, Aerial Reconnaissance Coordinator, All Hurricanes). In the event of a deployment of aircraft and personnel for operations outside Miami, the field program ground team manager will provide up-to-date crew and storm status and schedules through the field program director or the named lead project scientist. Personnel who have completed a flight will provide information to MGOC, 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. Examples of co-investigators are NASA-sponsored NAMMA investigators and associated university or other Governmental partners.

All requests for NOAA data gathered during the 2009 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 through CARCAH 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).

OPERATIONAL MISSIONS

1. Three-Dimensional Doppler Winds

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 four main goals: 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.

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 2009, 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 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.

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. The NESDIS/Office of 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. It is part of an ongoing field program whose goal is to further understanding of microwave scatterometer and radiometer retrievals of the ocean surface wind vector in high wind speed conditions and in the presence of rain for all wind speeds. This knowledge will be used to help improve and interpret operational wind retrievals from current and future satellite-based scatterometers. The hurricane environment provides the adverse atmospheric and ocean surface conditions required. The AWRAP and the SFMR (USFMR), both designed and built by UMASS, are the critical sensors. AWRAP consists of two scatterometers operating at Ku-band and C-band, which measure the reflectivity profile in precipitation in addition to the surface backscatter. The capabilities of AWRAP are essential in unraveling the effects of precipitation on scatterometer wind retrievals. A raw data mode acquisition system was tested for AWRAP during the Winter Storms Experiment this year, and it will be fully implemented during this hurricane season. 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.

A secondary objective of NESDIS is to explore how much of this remotely sensed data collected on the P-3 can be processed and sent off the plane in near real time. NESDIS has been working with Remote Sensing

Solutions, Inc. in developing an effective data processing, distribution and display system to accomplish this within the constraints of a satellite phone data connection. AOC and HRD have been integral partners in accomplishing this task. Remotely sensed surface data is not only extremely useful for flight planning but also to the hurricane analysts at the Tropical Prediction Center as has been demonstrated with the use of the SFMR on the P-3s and C130s. The P-3s are equipped with a dedicated Globalstar satellite phone and a computer system to process and distribute to the ground the flight-level serial data stream and the lower fuselage radar data in near real time. A second Globalstar satellite data connection will be used to test dissemination of products derived from the X-band tail radar, a near real-time processing system for AWRAP and USFMR, and the serial data stream from the AVAPS station. The transmission of full resolution tail radar data packets may also be tested if a higher bandwidth satellite phone system becomes available.

Due to similar operating frequencies, the AWRAP and P-3 lower fuselage radar can interfere. Therefore, NESDIS may request the LF radar be operated in sector mode, where aft scans are not obtained. For coordination purposes, the LF radar should be operated in full-scan mode for the entirety of the first Figure-4 pattern. After completing this pattern, sector scanning can be enabled if so requested.

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 date 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 as possible) is important, for both initialization and verification of HWRF. This has been verified in communication with EMC. In 2009, 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 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, 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 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 Doppler 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. 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 illustrate 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.

Tropical Cyclone Eye Mixing Module: 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. Observations within the eye below the inversion can allow for the study of the dynamic and thermodynamic structures of these mesovortices and improve knowledge of small-scale features and intensity changes in very strong TCs.

Although this is not a standalone experiment, it could be included within any of the following missions: SALEX, or TC Landfall and Inland Decay Experiment. A Category 4 or 5 TC with a clearly defined eye and eyewall and an eye diameter of at least 25 nm is needed (Fig. 1-7). 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 (about 2500 ft) 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.

Eyewall Sampling and Intensity Change Module: 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.

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 are then 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 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. TDDW-8). 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. 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. 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.

Three-Dimensional Doppler Winds

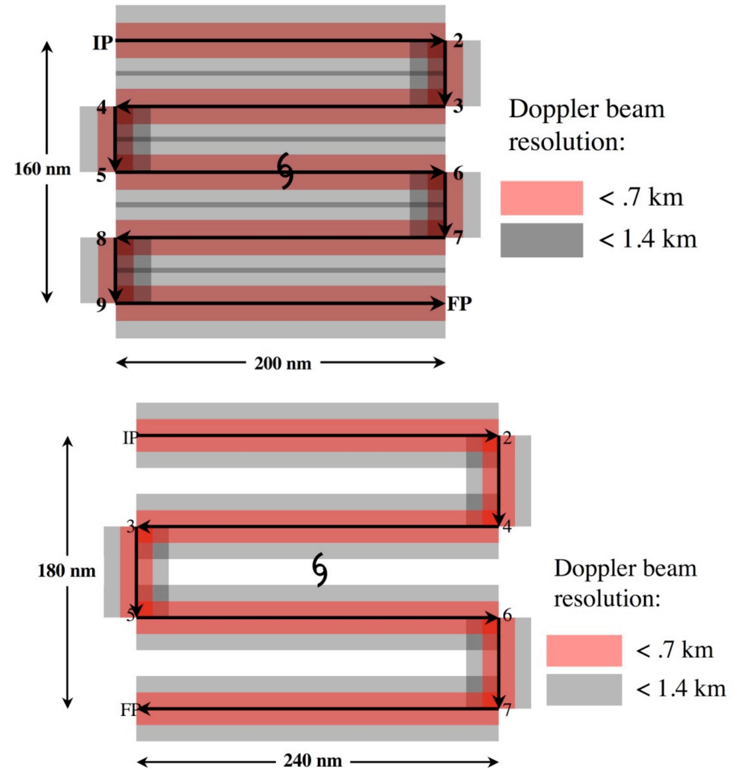


Figure 1-1: Display of Doppler coverage for A (upper panel) and B (lower panel) lawnmower patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 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 requested it is an operational request.
Note 2.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. 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 in F/AST, but it should be confirmed, nevertheless that the scanning is continuous, rather than sector scanning.
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.

Three-Dimensional Doppler Winds

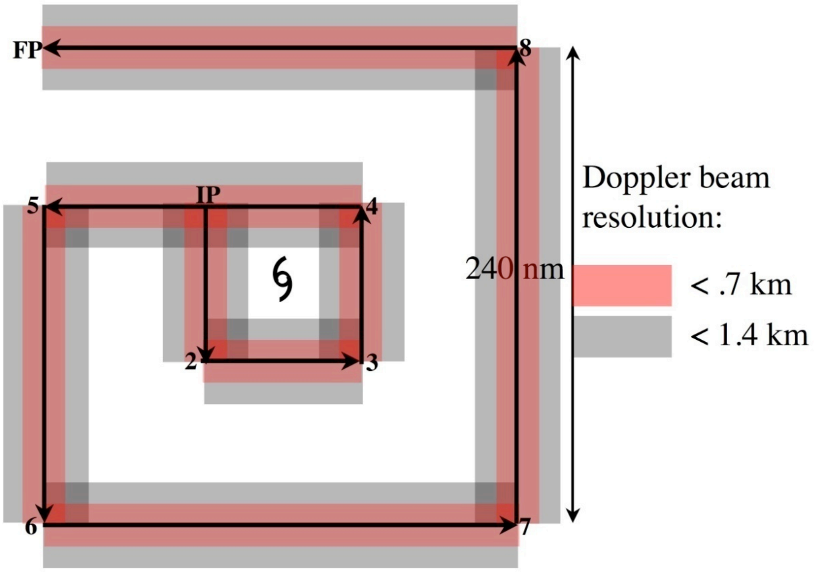


Figure 1-2: Doppler radar coverage for box-spiral pattern A. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately 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.
Note 2.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. 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 in F/AST, but it should be confirmed, nevertheless that the scanning is continuous, rather than sector scanning.
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.

Three-Dimensional Doppler Winds

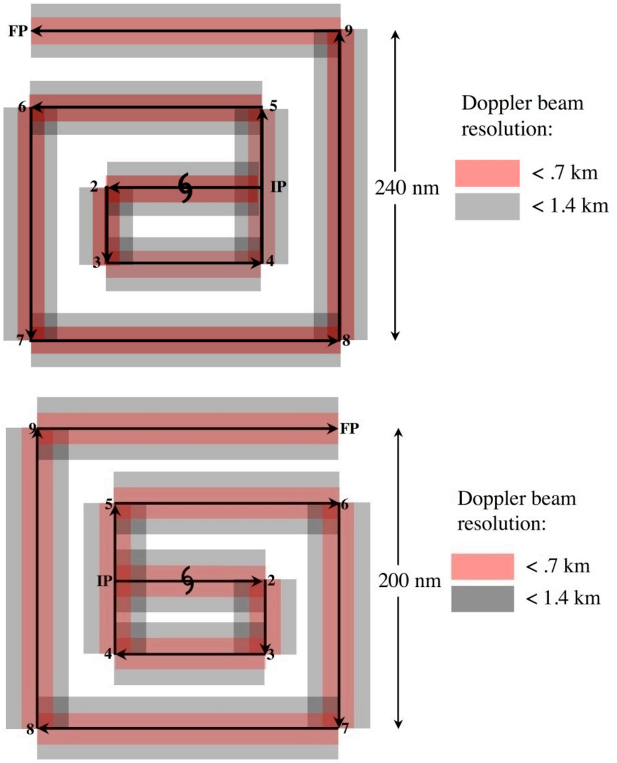


Figure 1-3: Doppler radar coverage for box-spiral pattern with 200- (top) and 240- (bottom) nm legs. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately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

Note 1.	This is to be 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 2400-3200. The default will be 2400 PRF. 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.
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.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
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.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

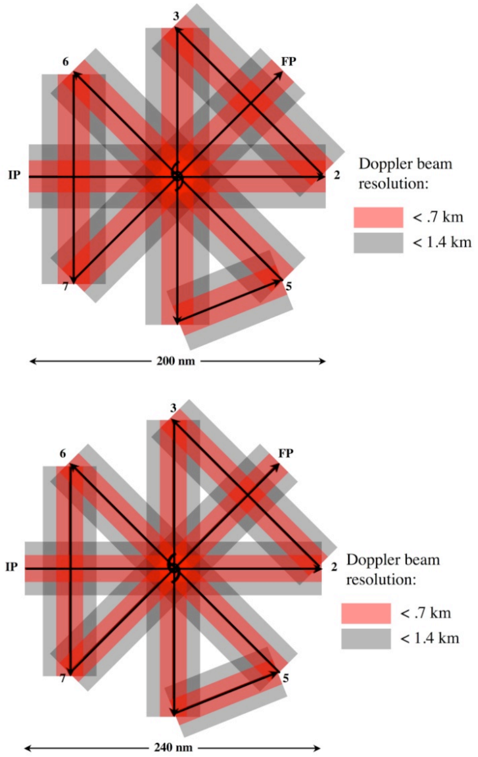


Figure 1-4: Doppler radar coverage for radial extents of 100 (top) and 120 (bottom) nm of the rotating figure-4 patterns. Pink region shows areas where vertical beam resolution is better than 0.7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent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

Three-Dimensional Doppler Winds

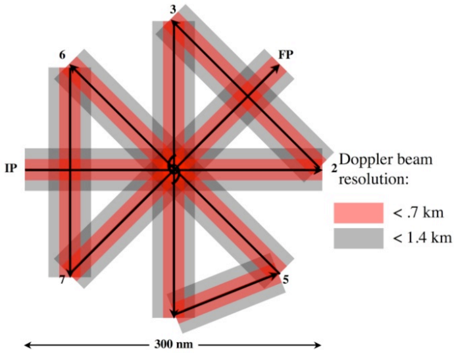


Figure 1-4 (continued): Doppler radar coverage for 150-nm legs for a rotating figure-4. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

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. 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.
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.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
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.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

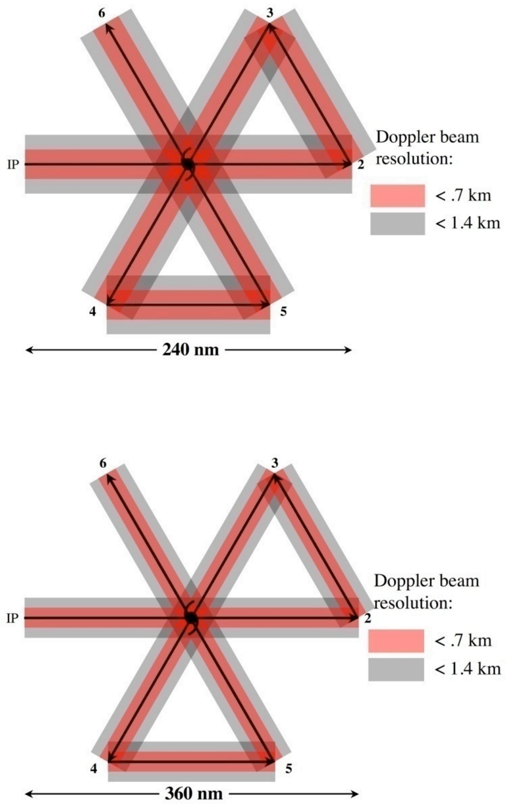


Figure 1-5: Doppler radar coverage for 120- (top) and 180- (bottom) nm legs for the Butterfly pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 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. 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.
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.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
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.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

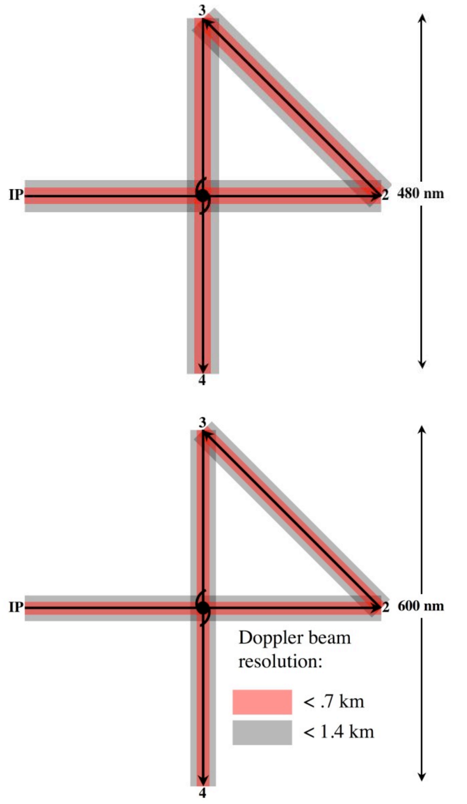


Figure 1-6: Doppler radar coverage for 300-nm legs for a single figure-4 pattern. Pink region shows areas where vertical beam resolution is better than 0.75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from 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. This pattern should be flown 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. 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.
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. Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6. Maximum radius may be decreased or increased within operational constraints
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.
Note 9. Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

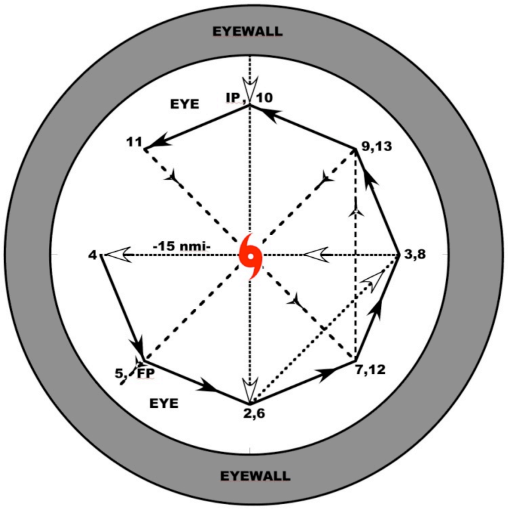


Figure 1-7: The P-3 approaches from the north, penetrates the eyewall into the eye, and descends below the inversion to 2500 ft while performing a figure-4 (dotted line) in the eye. The P-3 circumnavigates the eye in an octagon or pentagon (solid line), and then ascends while conducting another figure-4 (time permitting) rotated 45 degrees from the original (dashed line).

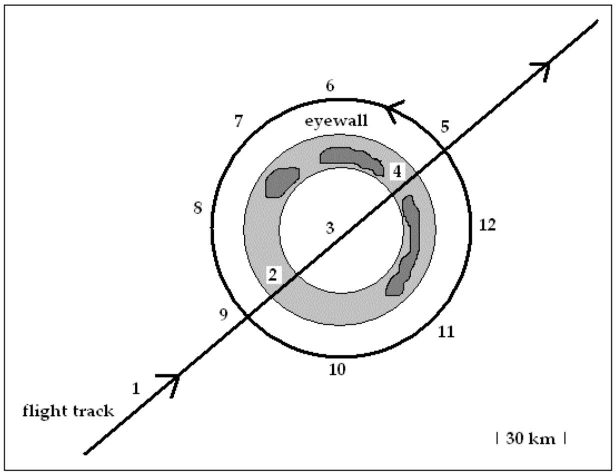


Fig. 1-8: Flight track (bold line), eyewall (gray region), and GPS dropwindsondes (numbered).

2. Hurricane Synoptic Surveillance

Program Significance: Accurate numerical TC forecasts require the representation of meteorological fields on a variety of scales, and the assimilation of the data into realistic models. Omega dropwindsonde (ODW) observations from P-3 aircraft obtained between 1982 and 1996 during the Hurricane Synoptic Flow Experiment produced significant improvement in the guidance for official track forecasts. Since 1997, more than 150 operational Synoptic Surveillance missions have been flown with the NOAA G-IV jet in the environments of TCs threatening the United States coastline; some of these have been supplemented with dropwindsonde observations from one or two P-3 or USAF C-130 aircraft. An improved dropwindsonde based on GPS has been developed by the National Center for Atmospheric Research and has replaced the ODW. With further operational use of the G-IV aircraft, and as other mobile observing platforms become available, optimal sampling and utilization techniques must be devised to provide the greatest possible improvement in initial condition specification.

Objectives: The goal of synoptic surveillance is to improve landfall predictions of TCs by releasing dropwindsondes in the TC environment. These data will be used by NCEP to prepare objective analyses and official forecasts through their assimilation into operational numerical prediction models. Because the atmosphere is known to be chaotic, very small perturbations to initial conditions in some locations can amplify with time. However, in other locations, perturbations may result in only small differences in subsequent forecasts. Therefore, targeting locations in which the initial conditions have errors that grow most rapidly may lead to the largest possible forecast improvements. Locating these regions that impact the particular forecast is necessary. When such regions are sampled at regularly spaced intervals the impact is most positive. The optimal targeting and sampling strategies is an ongoing area of research.

A number of methods to find targets are being investigated. Potential vorticity diagnosis can help to find the cause of forecast failure. Singular vectors of the linearized equations of motion can estimate the growth of small perturbations in the model. Related strategies involve the sensitivity vector, and quasi-inverse linear method. A fully nonlinear technique uses the operational NCEP Ensemble Forecasting System in which initially random perturbations are repeatedly evolved and rescaled over a relatively short cycling time. The ensemble spread is related to local Lyapunov vectors and, therefore, define the fastest growing modes of the system. Changes to initial conditions due to synoptic surveillance grow (decay) in regions of large (small) perturbation in the operational NCEP Ensemble Forecasting System. Therefore, these modes provide a good estimate of the locations in which supplemental observations are likely to have the most impact. However, though this method can find locations of probable error growth in the model globally, it does not distinguish those locations, which impact the particular forecast from those that do not. A more generalized method that can use any dynamical ensemble forecast system is the Ensemble Transform Kalman Filter. This method transforms an ensemble of forecasts appropriate for one observational network into one appropriate for other observational networks. Ensemble forecasts corresponding to adaptations of the standard observational network are computed, and the expected prediction error variance at the observation time is computed for each potential network. The prediction error variance is calculated using the distances between the forecast tracks from all ensemble members and the ensemble mean. These methods are currently undergoing testing with Observing System Experiments (OSEs) to discern an optimal targeting technique.

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

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

Mission Description: To assess targeting strategies a relatively uniform distribution of dropwindsondes will be released over a minimal period by various aircraft (the NOAA G-IV and AFRES C-130s) operating *simultaneously.* Specific flight tracks will vary depending on such factors as the location of the storm, relative both to potential bases of operation and to particular environmental meteorological features of interest. A sample mission is shown in Fig. 2-1. The two C-130 aircraft and the G-IV will begin their missions at the same time. Subject to safety and operational constraints, each aircraft will climb as rapidly as possible, then proceed, step-climbing, along the routes assigned during preflight. *It is particularly important that both aircraft climb to and maintain the highest possible altitude as early into the mission as aircraft performance and circumstances allow, and attain additional altitude whenever possible during the mission.*

Of paramount importance is the transmission of the dropwindsonde data to NCEP for timely incorporation into operational analyses, models, forecasts, and warnings. Operational constraints dictate an 0600 or 1800 UTC departure time, so that most of the dropwindsonde data will be included in the 1200 or 0000 UTC analysis cycle. Further, limiting the total block time to 9 h allows adequate preparation time for aircraft and crews to repeat the mission at 24-h intervals. These considerations will ensure a fixed, daily real-time data collection sequence that is synchronized with NCEP analysis and forecasting schedules.

Saharan Air Layer Module: This module will be executed by HRD, using HRD resources and will be carried out within the constraints of the pre-determined operational flight track. Additional intermediate dropwindsondes (HRD-supplied) may be requested along the flight track to target specific areas of interest. Dropwindsondes will be launched from the G-IV (flying at ~200 hPa or ~41,000 ft) or the P-3 (flying at ~500 hPa or ~20,000 ft) along the operational Synoptic Surveillance flight pattern. These additional release locations 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. The main goals are to:

- Better understand how the SAL dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change.
- Include the moisture information from the dropwindsondes in operational parallel runs of the GFS. The impact of this data on the GFS initial or forecast humidity fields and its forecasts of TC track and intensity will be assessed.

Several SAL/TC interaction scenarios are candidates:

Figure 2-2 shows a single TC located along the southern edge of the SAL. Depending on the proximity of these two features, the SAL dry air may be wrapping into the TC low-level circulation (western quadrants). Dropwindsonde sequences will be focused along this dry air inflow region (west of the TC), across regions of high moisture gradients at the SAL leading edge (northwest of the TC), and across the southern boundary of the SAL (north and northeast of the TC). The SAL mid-level jet will also be sampled in the region of the latter transect.

Figure 2-3 shows a single TC is embedded within the SAL and intensifies upon emerging. These systems are often candidates for rapid intensification. Dropwindsonde transects perpendicular to the northern boundary of the SAL and near to possible points of the TC emergence from the SAL are desirable. Additional transects will be focused along the SAL southern boundary (south of the TC). The SAL mid-level jet will also be sampled, particularly along those transects on the eastern sides of the TC.

Figure 2-4 shows a single TC embedded within the SAL throughout most or all of its lifecycle. These systems struggle to intensify and are often characterized by their low-level circulation racing out ahead (west) of their mid-level convection. Depending on the proximity of the TC to the SAL, the SAL dry air may be wrapping into its low-level circulation (western semicircle). Dropwindsonde sequences will be focused along this dry air inflow region (west of the TC), across regions of high moisture gradients at the SAL northern boundary (north of the TC), and across regions of high moisture gradients at the SAL southern boundary (east of the TC). The SAL mid-level jet will also be sampled, particularly in the region of the latter transect.

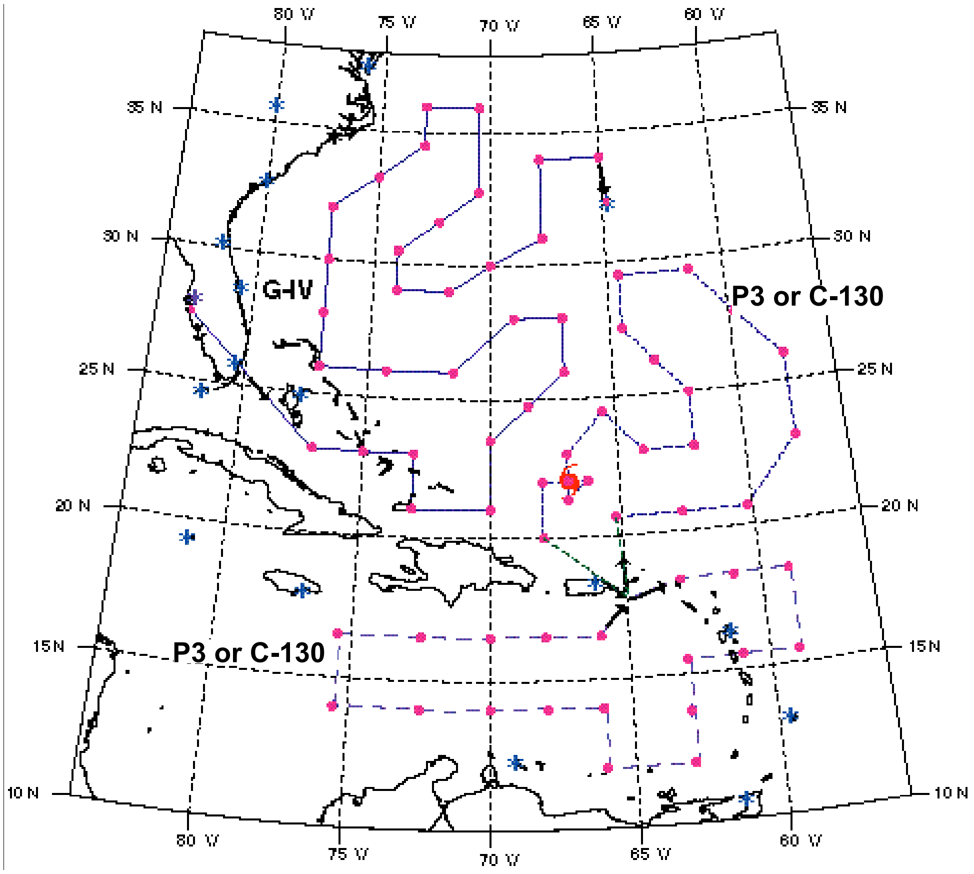


Figure 2-1: Sample environmental patterns.

• Note 1:	During the ferry to the **IP**, the C-130 aircraft will climb as quickly as possible.
• Note 2.:	During the ferry to the **IP**, The G-IV should climb to the 41,000 ft (200 hPa) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

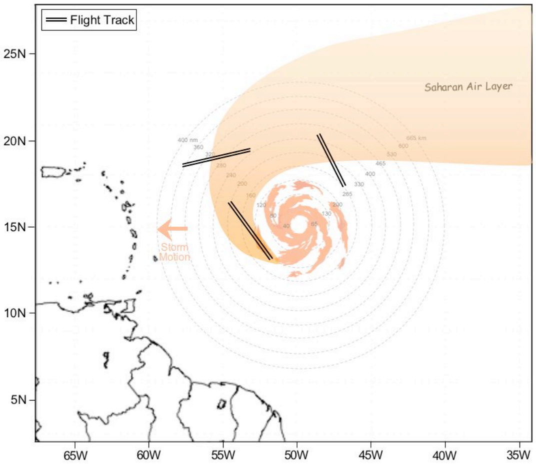


Figure 2-2: Sample flight track for a TC positioned along the SAL southern boundary.

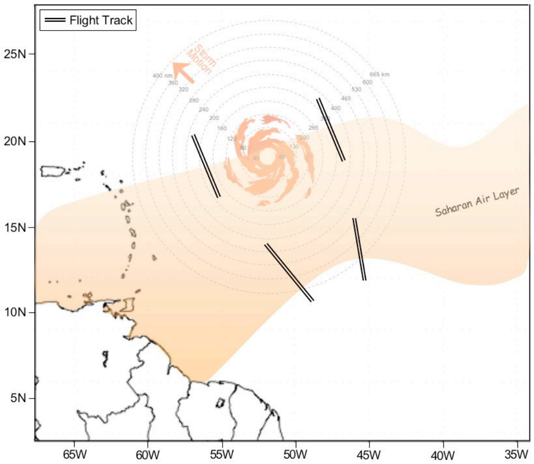


Figure 2-3: Sample flight track for a TC emerging from the SAL.

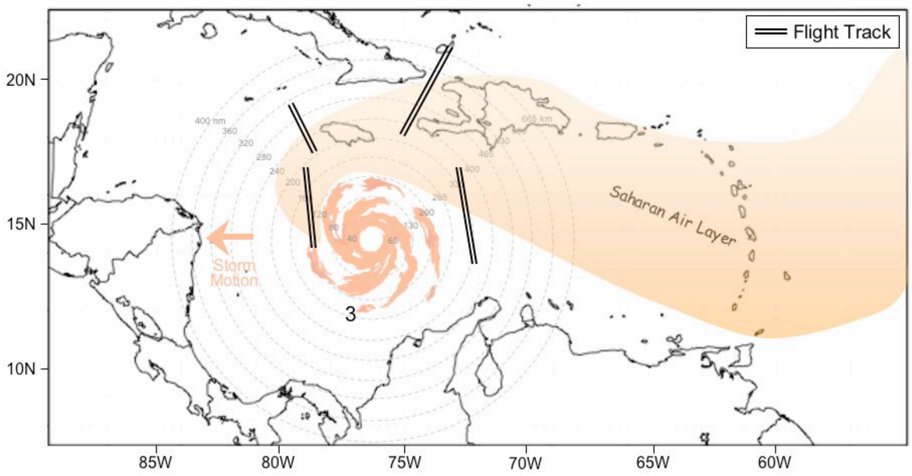


Figure 2-4: Sample flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1: During the ferry to the **IP**, the P-3 aircraft will climb to the ~500 hPa level (~20,000 ft). The 400-hPa level (~25,000 ft) should be reached as soon as possible and maintained throughout the remainder of the pattern, unless icing or electrical conditions require a lower altitude.
- Note 2: During the ferry to the **IP**, The G-IV should climb to the ~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 3: In order to capture the SAL structure, particular attention should be paid to regions of high moisture gradients across its boundaries.

3. TC-Ocean Interaction Experiment

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 2009 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.

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 overriding 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, NOAA is partnering with the Department of Interior's Minerals Management Service (MMS) and the University of Miami to obtain measurements in this rarelyobserved region. MMS has recently installed a field of moorings in the central Gulf of Mexico, which will provide a long record of LC structural variability, including during TC events. In coordination with these observations, upper-ocean temperature and salinity fields in the vicinity of the LC will be sampled using expendable ocean profilers (see Fig. 3-1).

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 near the mooring array in the LC (Fig. 3-1) . 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.

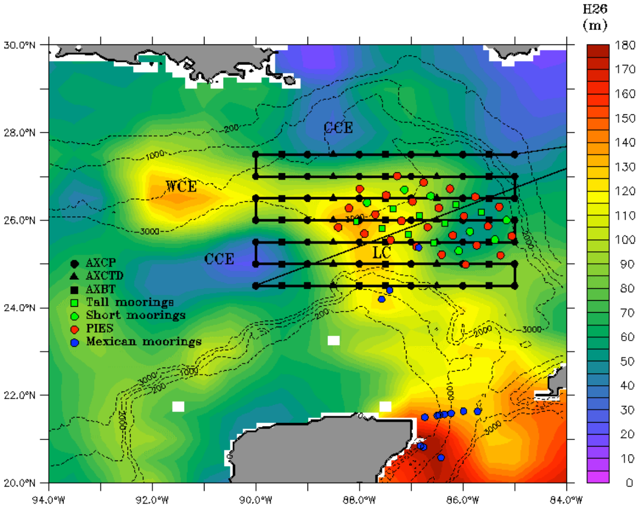


Figure 3-1: Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at KMCF.

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 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 3-2 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.

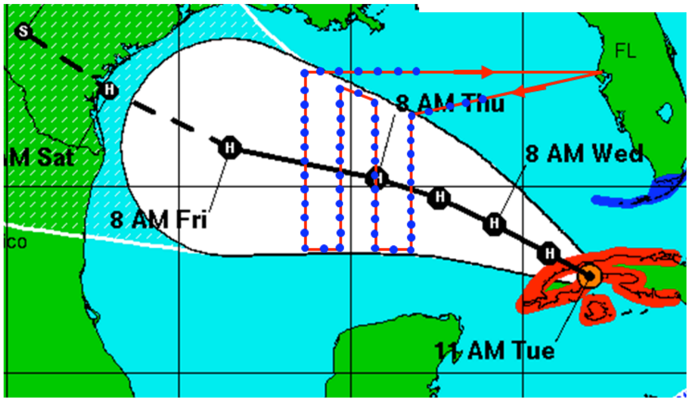


Figure 3-2: Track-dependent AXBT ocean suvey. As for the Loop Current survey, a total of 60-80 probes would be deployed on a grid (blue dots).

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 200m, boundary layer evolution and covariance fluxes of most of these quantities, wind speed and scalar surface wave spectra. E-M 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. Twenty dropwindsondes are externally funded.

This work will be coordinated with NASA P-3 deployments of air-expendable CTD probes, thereby increasing the coverage of the ocean response. If the deployments occur in the Gulf of Mexico, Loop Current area, this work will be coordinated with P-3 deployments of AXBTs 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. Most of these will be cancelled.

Initial BTO (Buoy Tasking Order) - Three days, 72 h before launch, an initial BTO for float and glider deployments will be sent to the 53rd and CARCAH. The array deployment location will be chosen to be 24-36 h ahead of the storm or at a radius of less than 25kts, whichever results in the earlier takeoff time.

Updated BTOs – An updated BTO will be sent two days before launch and will be included in the CARCAH OUTLOOK message. Another will be sent one day before launch and included in the CARCAH POD message. Each of these BTOs should reach CARCAH by 9am EDT.

Flight day BTOs – Two hours before takeoff, an updated BTO will be sent directly to the 53rd, with an info copy to CARCAH. This will be used for the mission briefing.

Final BTO- Final changes can be sent via SATCOM from the CARCAH office after the flight is airborne, but before the first deployment location is reached. Only changes in the release positions can be made, not in the order of releases.

Flights

Day 1- WC-130J Float and drifter array deployment- Figure 3-3 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 3-4 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. 3-5). 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.

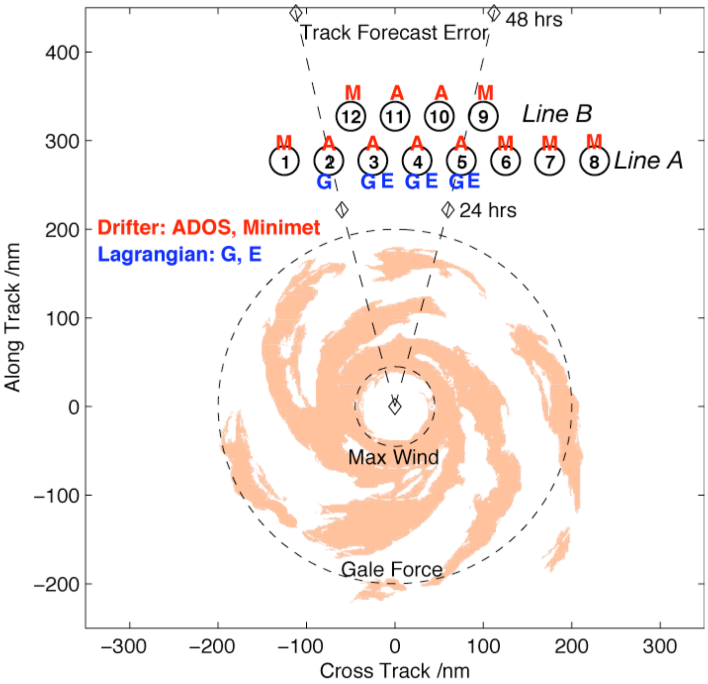


Figure 3-3: Float and drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of a mix of ADOS thermistor chain (A) and minimet (M)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

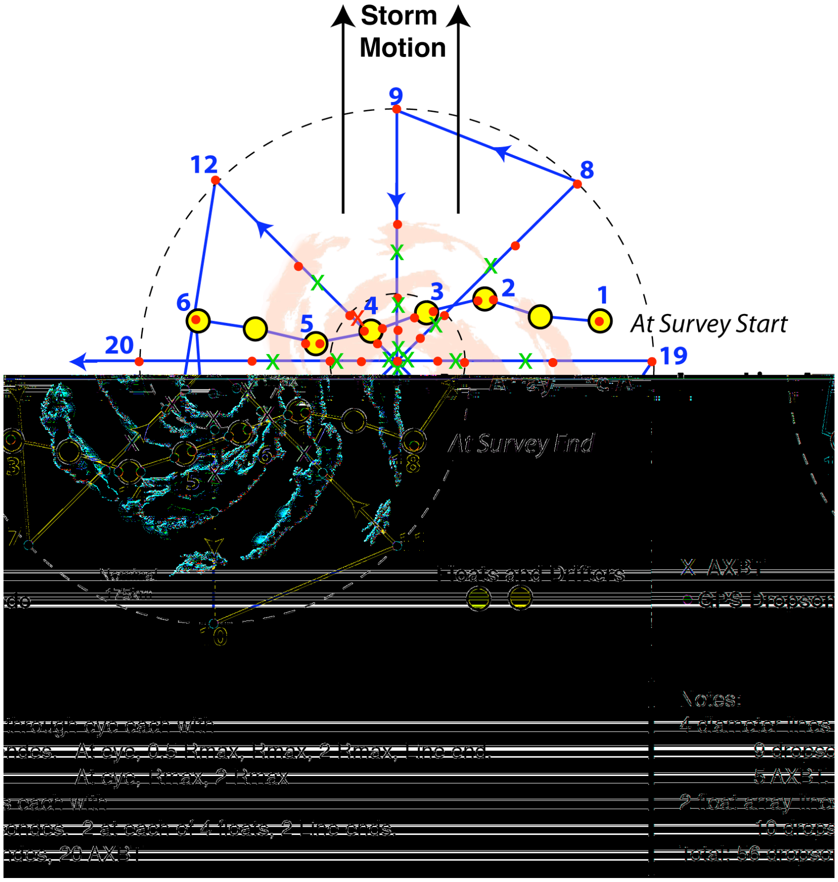


Figure 3-4: P-3 pattern over float and drifter array. The array has been distorted since its deployment on the previous day and moves relative to the storm during the survey. The pattern includes two legs along the array (waypoints 1-6 and 13-18) and an 8 radial line survey. Dropwindsondes are deployed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

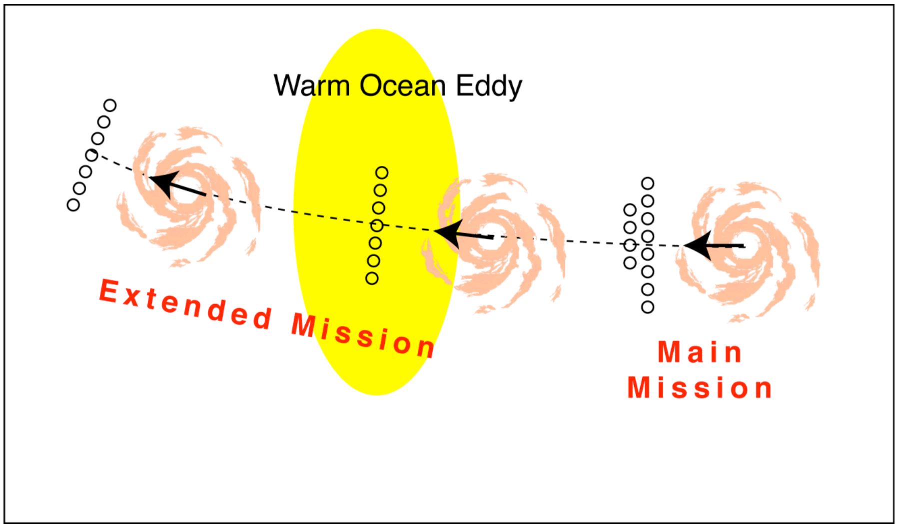


Figure 3-5: Extended Mission. Two additional drifter arrays will be deployed along the storm track.

4. Tropical Cyclone Landfall and Inland Decay

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 be 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 2009 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 windfields 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 (2006).

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 windfields at selected levels transmitted from the aircraft to NHC and NMC. These windfields 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 (Fig C-5 in the Appendix). 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 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 flight-level wind data and make surface wind estimates to improve real-time and post-storm surface wind analyses in hurricanes.
- Collect airborne Doppler radar to combine with WSR-88D radar data in post-storm three-dimensional wind analyses.
- Document thermodynamic and kinematic changes in the storm during and after landfall.
- Measure the characteristics of the middle troposphere and the hurricane boundary layer with dropwindsondes.

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.

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 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. 4-1, 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. 4-1, 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 three 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. 3-1.) The aircraft flies at or below 5,000 ft (1.5 km) (ideally at 2,500 ft [750 m]), 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. 4-1). 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.

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 4-2 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. 4-2). 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. 4-2). 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.

Onshore Wind Profile Evaluation Module: In this module, the aircraft will collect vertical profiles of wind speed in various near shore environments to test the hypothesis that near the coast surface wind speeds may be lower than the operational flight-level wind reduction would suggest. Data collected will help evaluate various effects. For example, roughness lengths may change, especially in higher wind speeds. The boundary layer changes at the coast; dropwindsonde data will help indicate whether there are similar changes from open ocean to coastal waters.

To evaluate the adjustment of wind speeds from normal reconnaissance altitude to the surface in near-shore conditions, the aircraft should fly this module at 700 hPa (10000 ft, ~3000 m). The aircraft follows the flow to the coast (Fig. 4-3), deploying GPS dropwindsondes every 5-10 nm. Then the aircraft turns and flies into the center of the storm, back off shore, and then upwind to a point to start a new onshore profile, where each sequence of dropwindsondes is closer to the RMW. The last sequence could be along the inside edge of the eyewall. To maintain good SFMR, tail Doppler radar, SRA and AWRAP data collection, the onshore flow segments should be flown in short straight segments with quick turns rather than smooth curves.

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. 4-4) 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.

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 3-5 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).

Note: 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 not strictly limited to the Landfall and Inland Decay Experiment.**

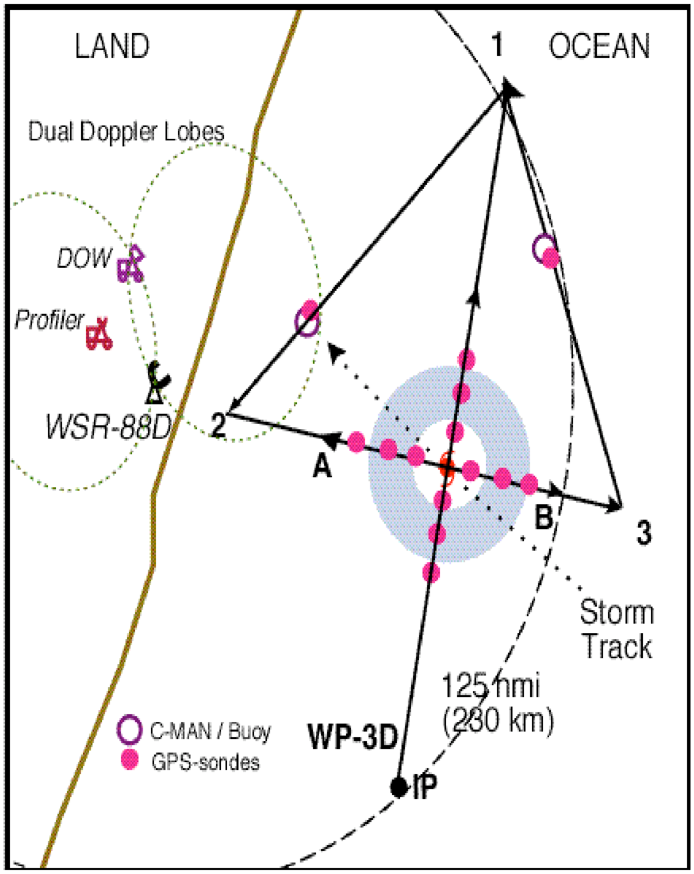


Figure 4-1: Real-time module.

- 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.

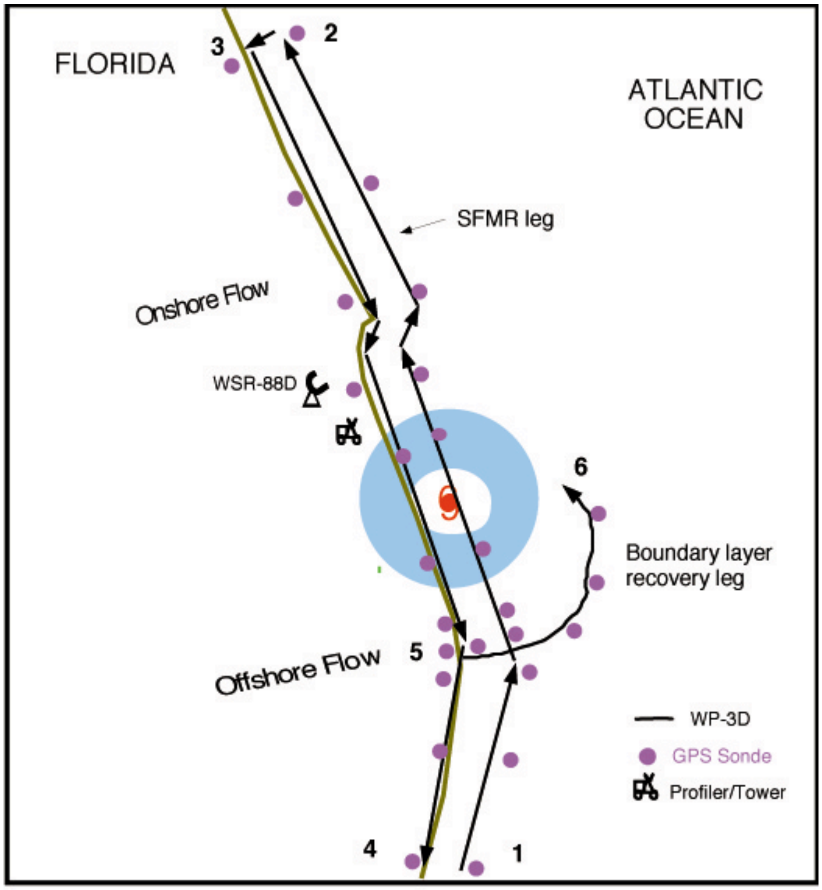


Figure 4-2: Coastal Survey pattern.

- 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).

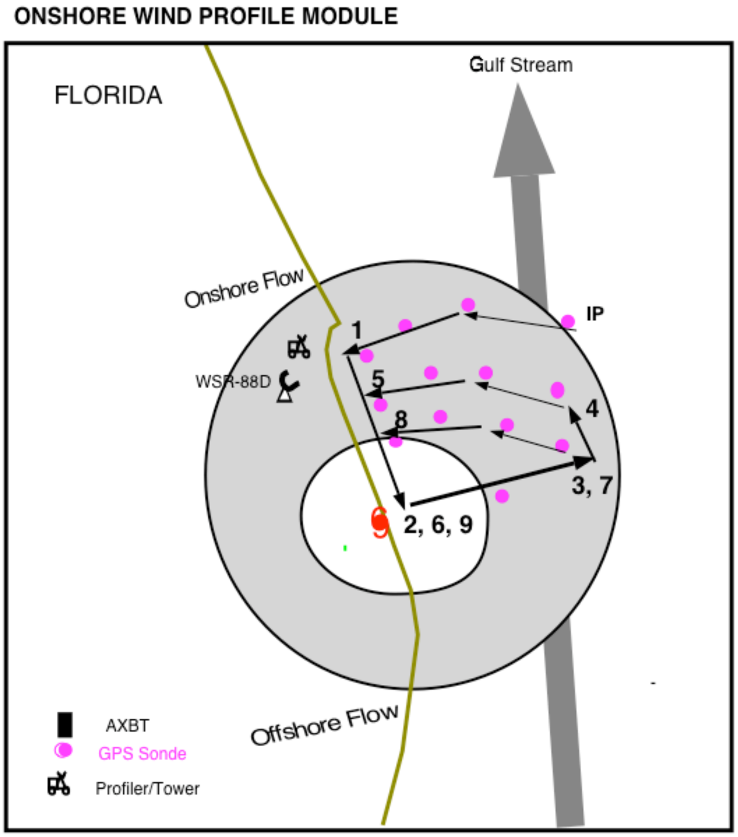


Figure 4-3: Coastal Wind speed Profile Evaluation Module.

- TAS calibration is required. The legs are at 700 hPa (10000 ft, 3000 m) altitude.
- Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20° tilt on all legs.
- Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

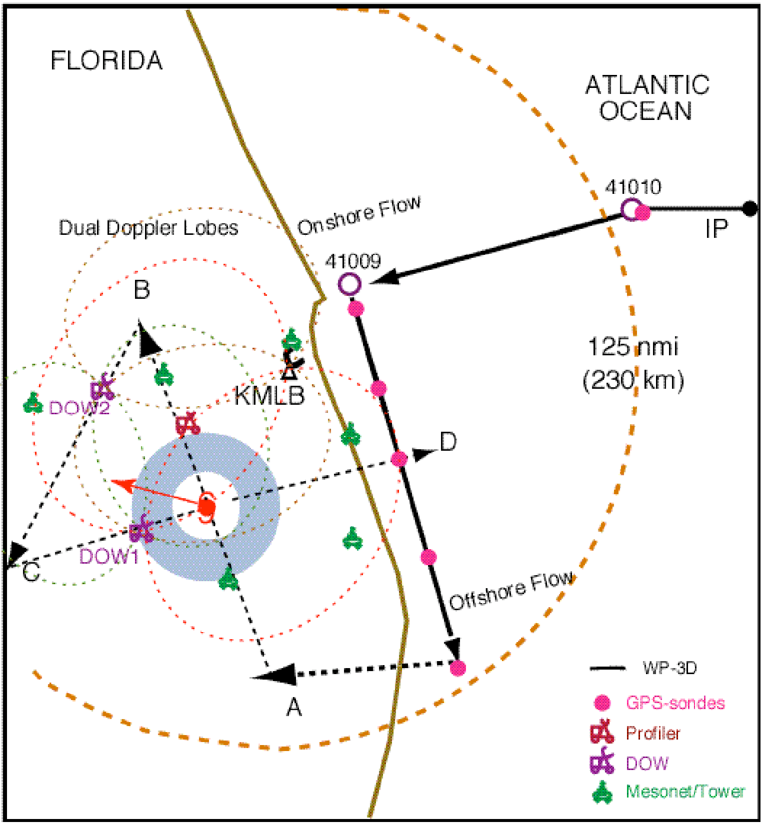


Figure 4-4: Post landfall module flight pattern.

- 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.

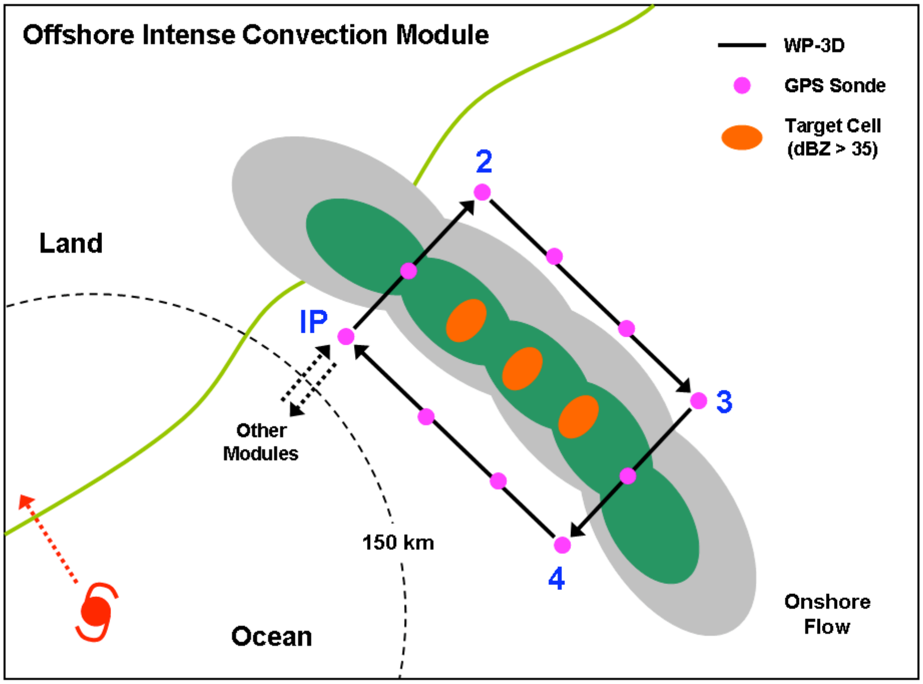


Figure 4-5: Offshore Intense Convection pattern.

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).

5. Tropical Cyclogenesis Experiment

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 balance assumptions and error covariance matrices 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; Montgomery 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. Another set of 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, and Lopez 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 (2008) and Wang, Montgomery and Dunkerton (2009) 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:

- 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;

- The wave critical layer is a region of closed circulation, where air is repeatedly moistened by convection and protected from dry air intrusion;

- The parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave.

Objectives

With the above background in mind, the objectives are defined as follows:

1. Test prevailing hypotheses relating to top-down vs. bottom-up development
   This objective will be addressed by documenting the development of low-level vorticity in the presence of a midlevel vortex center, and vice versa. It will also be addressed by documenting the interactions between low- and mid-level vortices in pre-genesis environments.

2. Document aspects of mesoscale and synoptic-scale environment of incipient disturbances to identify characteristics necessary in genesis
   Key tasks in addressing this objective involve assessing the importance of pre-existing vorticity and broad areas of high humidity and determining the importance of their spatial and temporal distribution in tropical cyclogenesis. Another important question to address is the role, if any, that a midlevel vortex plays in governing the distribution and magnitude of deep convection, and to determine the importance of downdraft suppression in limiting boundary layer stabilization. A final task is to examine hypotheses relating humidity and static stability profiles to downdraft morphology and the vortex response to convective heating.

3. Test marsupial paradigm hypotheses
   The objective of marsupial tracking is to track the wave pouch (rather than the diabatic vortices inside the pouch), estimate its propagation speed and predict the genesis location, which can be used to provide useful guidance for flight planning during the NOAA hurricane field campaign as part of

NOAA/IFEX and the upcoming field experiments NSF-PREDICT and NASA-GRIP in summer of 2010.

Links to IFEX

It supports the following NOAA IFEX goals:

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

Experiment Description

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

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

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

This may be executed with the P-3 alone, but optimally it will involve the participation of the NOAA G-IV aircraft as well. Flights will occur into incipient tropical disturbances over the western Caribbean Sea, Gulf of Mexico, and tropical Atlantic Ocean. For these missions the P-3 will be based primarily in Barbados, though operations can also occur from St. Croix and Tampa. The systems flown here will primarily be incipient systems.

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. Therefore, the staggered P-3 missions are designed to commence on station at midnight (12 AM) local and again on station at noon (12 PM) local. 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 NASA TRMM 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 QuikSCAT 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 sawtooth 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, if identifiable, or on a dominant area of convective activity. After the circulation center or convective area is passed, the sawtooth pattern is mirrored and the aircraft completes a return trip, creating a series of diamond shapes to complete the pattern. This return trip will provide some greater temporal continuity to the observations.

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. For the P-3 using the NOAA antenna, the tail radar will operate in continuous mode during the Microphysics Module.

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 SALEX pattern as the system is interacting with a SAL (e.g. as depicted in Fig. 7-1).

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 diamond 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). 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.

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. 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 radar altitude of 12,000 ft. 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.

R. Rogers 6/16/09 8:35 PM

Comment: I took this out since I'm practically certain AOC won't go for this now. Plus I lowered the altitude to 12,000 ft. in the convection.

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.

Tropical Cyclogenesis Experiment

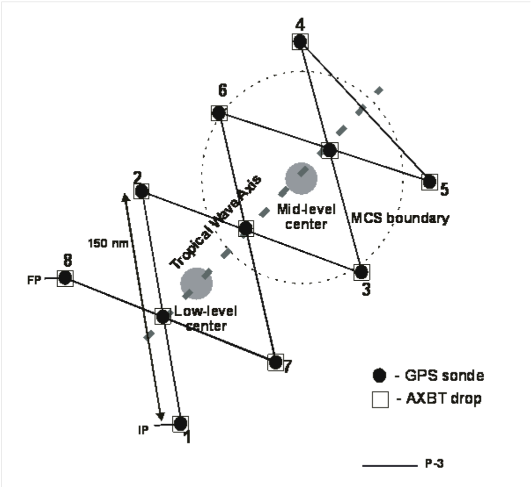


Figure 5-1: P-3 Pre-genesis early organization vortex survey pattern – Diamond pattern.

- Note 1: TAS calibration is required.
- Note 2. The pattern is flown with respect to the wave axis, typically inclined at 30-40° from N, or relative to circulation or vorticity centers.
- Note 3. 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).
- Note 4. Fly 1-2-3-4-5-6-7-8 at 12,000 ft (4 km) altitude, deploying dropwindsondes at all locations denoted by black circles.
- Note 5. Set airborne Doppler radar to scan F/AST on all legs.

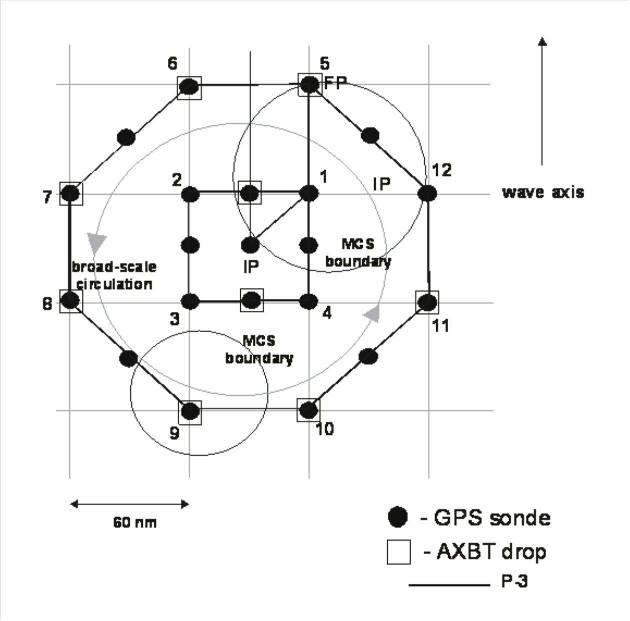


Figure 5-2: P-3 Pre-genesis late organization vortex survey pattern – Square-spiral pattern.

- Note 1. TAS calibration is required.
- Note 2. The pattern is flown with respect to the wave axis, typically inclined at 30-40° from N, or relative to circulation or vorticity centers.
- Note 3. Release dropwindsondes at all numbered points. Releases at intermediate points can be omitted if dropwindsonde supply is insufficient.
- Note 4. 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.
- Note 5. Fly 1-2-3-4-5-6-7-8-9-10-11-12 at 12,000 ft (4.0 km) altitude.
- Note 6. Set airborne Doppler radar to scan F/AST on all legs.

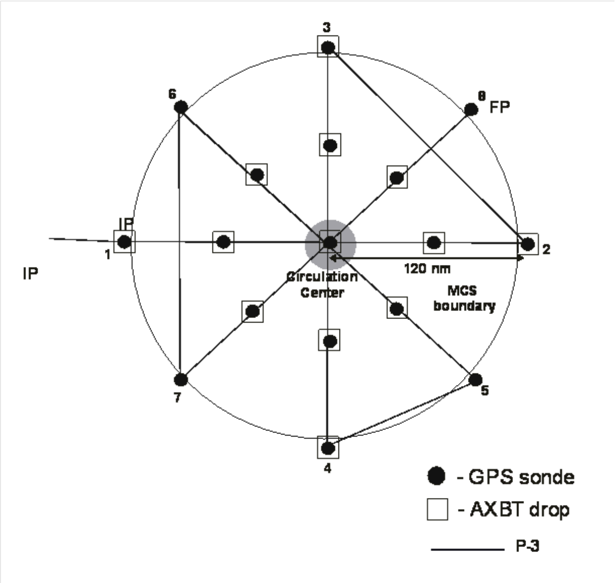


Figure 5-3: P-3 Post-genesis rotating figure-4 pattern.

- Note 1: TAS calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. Fly 1-2-3-4-5-6-7-8 at 12,000 ft altitude, 60-120 nm (111-225 km) leg length.
- Note 4 Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

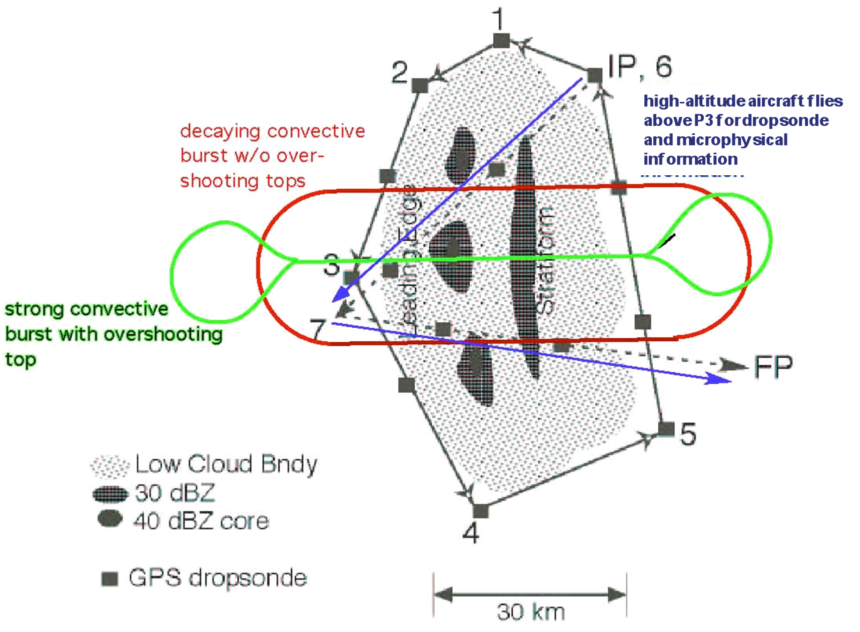
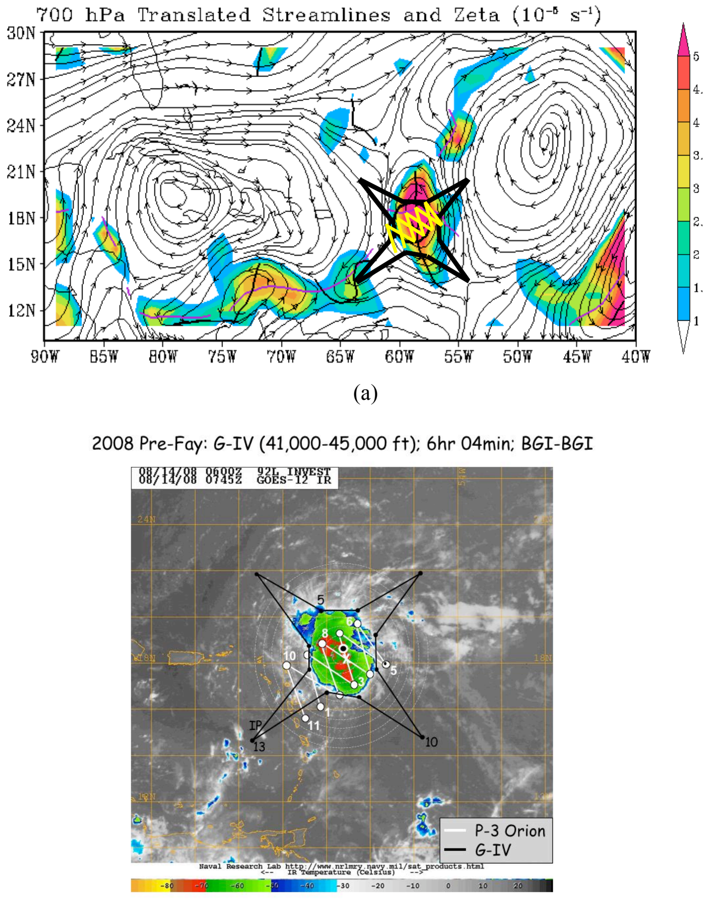


Figure 5-4: Convective burst module.

- Note 1: True airspeed calibration is required.
- Note 2. Circumnavigation (IP to point 6) by single P-3 at 14 kft.
- Note 3. Convective crossing (6-7-FP) at 12 kft.
- Note 4. Repeat circumnavigation (time permitting) at low altitude (200 ft in day, 1000 ft at night).
- Note 5. No GPS sondes for low-altitude option.
- Note 6. High-altitude aircraft (ER-2 or Global Hawk) flies either racetrack or bowtie pattern during P-3 circumnavigation, flies vertically aligned with P-3 during convective crossing.
- Note 7: Set airborne Doppler radar to scan F/AST on all legs.



(a)

(b)

Figure 5-5: Pouch module.

- Note 1: True airspeed calibration is required.
- Note 2. P-3 flown at 12 kft.
- Note 3. G-IV flown as close to cold cloud shield on inner radii as is deemed safe.
- Note 4. Set airborne Doppler radar to scan F/AST on all legs.
- Note 5: Release GPS drops from P-3s at all turn points and midpoints (when not overlapping with previous drop). Release G-IV drops at all turn points and midpoints of radial legs.

6. SFMR Evaluation Experiments

Goal: To improve Stepped Frequency Microwave Radiometer (SFMR) surface wind speed accuracy.

Though not a “self-contained” research experiment, the SFMR Evaluation Experiment consists of a set of modules organized around the common theme of improving SFMR surface wind measurement accuracy. The SFMR wind data has been extensively evaluated under general conditions likely to be encountered during TC flights, however there are a few specific situations in which the SFMR has been found to produce spurious results. Each module described herein can be executed as part of a larger experiment, for example, the Shallow Bathymetry Module could be flown during a Landfall experiment.

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

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

6a. On-shore/Off-shore flow module: This module is similar to the Coastal Survey module, except that it concentrates on the region with hurricane-force wind speeds and is designed to collect data to evaluate the performance of the SFMR in varying ocean conditions near landfall shallow bathymetry could cause changes to the breaking wave field that would cause changes in microwave emissions, besides those changes that correlate directly to wind speed. Fig. 6-1 shows that the aircraft would fly a leg toward the coast, preferably at or below 5000 ft above Mean Sea Level (MSL), to gather high-resolution SRA data to define the wave field. A sequence of combined AXBT and GPS dropwindsondes will map out the thermodynamic and boundary layer wind speeds. This leg is followed by a run along the coast to the maximum offshore flow, where the plane turns and flies offshore, deploying a further sequence of AXBTs and dropwindsondes. From here the module could be repeated or the aircraft could execute another module.

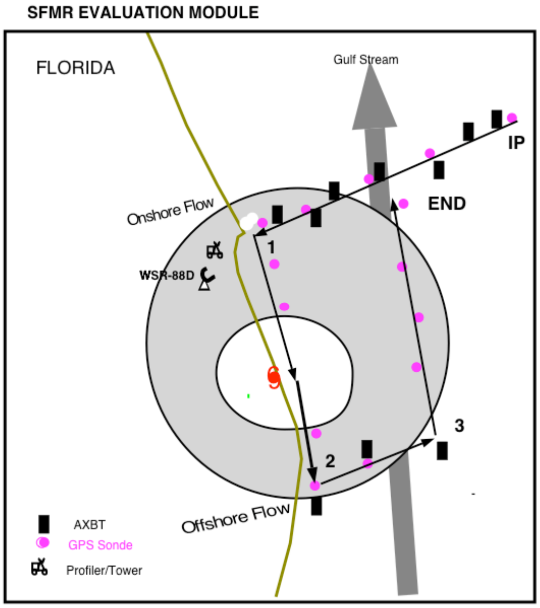


Figure 6-1: On-shore/Off-shore flow module.

6b. Shallow Bathymetry Module. In the annual report from the first year of this project and in subsequent technical reports, higher than expected SFMR wind speed retrievals have been reported in regions where the water depth is less than 50 m. Several mechanisms may be the cause of these anomalies, but the largest is believed to be enhanced wave breaking of both swell and local sea wave components due to shoaling, i.e. when the water depth approaches the dominant ocean swell and local sea wavelength (200-300 m and 50 – 80 m, respectively). As ocean waves enter shallower water their height increases as their speed and length decrease. At the point where the ocean wavelength and depth become approximately equal, the wave becomes unstable and begins to plunge forward and break. The normal wave breaking criteria of wave slope (ratio of wave height to wave length) exceeding 1/7 changes in shallow water and alters frequency of wave breaking and hence the foam and whitecap coverage that the SFMR senses. Since this foam is not directly generated by the local wind, but by a shoaling bottom, and the ocean surface emission is dependent on the amount of foam, the SFMR retrieval process may over estimate the wind speed in these conditions. Therefore, the gradient in the water depth, the direction of the waves, the complexity of the wave field and other parameters may all affect this process. To begin to understand and characterize these effects, SFMR observations and in situ ocean surface wind observations in different water depths, ocean states and wind conditions are required.

To develop recommended modules that will obtain ocean surface wind observations collocated with the SFMR observations in water depths ranging from 50 m to 10 m, and in conditions of onshore and offshore wind to delineate the effect of long-period ocean swell. Potential wind observations from ocean wind scatterometery may not suffer from the same effects, and thus ocean surface backscatter observations collected by the AWRAP system should also be obtained. If analysis of the AWRAP data shows no dependence on bathymetry, the AWRAP ocean wind estimates could be used in future flights to determine the bathymetry effects on the SFMR wind retrievals. Utilizing AWRAP for this purpose has the advantage of requiring fewer resources since dropwindsondes would not be needed and AWRAP would provide continuous wind observations rather than point observations that are obtained with the dropwindsondes. In addition, dual aircraft modules are proposed to obtain collocated surface wave spectra, including swell and local sea components, from the new Operational SRA (OSRA) which will be mounted on N43RF, a different P-3 from N42RF, where AWRAP is be mounted. Both aircraft will have operational OC SFMR systems.

The objective of the bathymetry modules is to obtain collocated SFMR and dropwindsonde estimates of the 10 m wind speed measurements at different water depths (less than 50 m). In addition to the SFMR, AWRAP and OSRA observations are desired. Modules for single and dual aircraft need to be executed for different wind and bathymetry conditions. Ideally the module(s) should be executed at water depths of 10 m, 20 m, 30 m, 40 m and 50 m under gale, storm and hurricane-force wind speeds. Each module is designed to obtain in situ measurements of the 10 m wind speed that are collocated within approximately 200 hundred meters of the center point in the SFMR footprint. Because the wind and bathymetry might be changing spatially and because the SFMR observations are time sequenced and its beamwidths are finite, each module involves orthogonal cross patterns over the dropwindsonde splash point. This will allow the effects of bathymetry on the SFMR to be separated from spatial gradients in the wind field and bathymetry.

In the case where the wind is onshore or offshore and the bathymetry does not change by more than a couple of meters per kilometer, an additional simplified module would simply fly the available aircraft, or the two P-3 aircraft in tandem, downwind for a flight segment beginning at the 60-m isobath and continuing to the 10-m isobath while deploying a sequence of 8 dropwindsondes (from a single aircraft) or 12 dropwindsondes from the two aircraft in tandem. Care would need to be taken to fly parallel to the surface wind so that the aircraft would fly over the dropwindsonde splash point. This would be executed at the onshore and offshore wind speed regimes indicated above.

Figures 6-2 through 6-4 present proposed flight track patterns for a single aircraft mission. The AOC SFMR and dropwindsondes are required. AWRAP is desired but not required. Ocean wave measurements from the

WSRA and/or from buoys are also desired but not required. Wind measurements from buoys are desirable but not required. Wind center penetrations are optional.

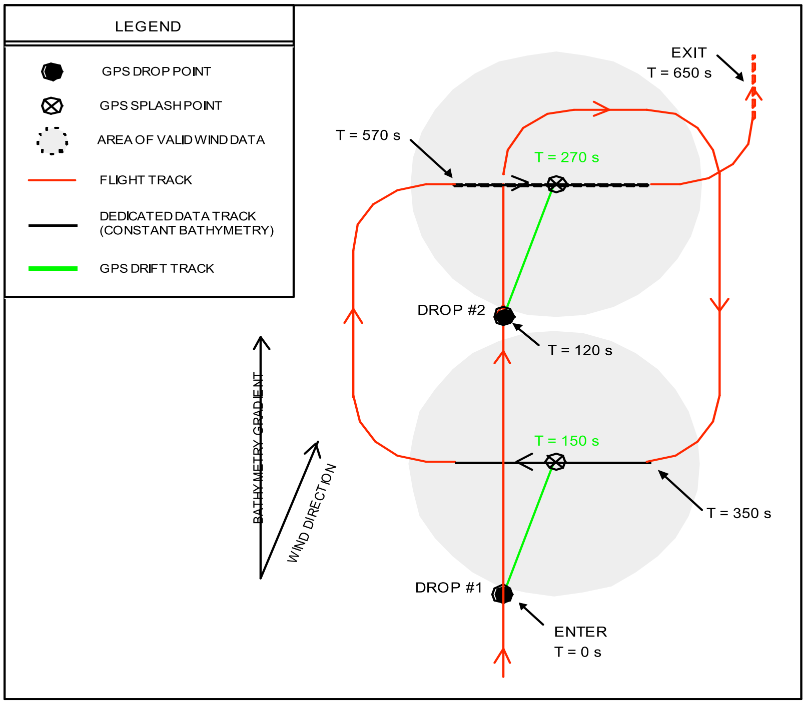


Figure 6-2: Shallow Bathymetry Module.

- Gray area encloses hurricane core with wind speeds > hurricane force.
- TAS calibration is required. The legs are at 1500-3000 ft (500-1000 m) altitude.
- Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20 degree tilt on all legs.
- Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

Notes:

1. P-3 enters pattern heading in the direction of increasing or decreasing bathymetry gradient. If the gradient is not known, this pattern is still recommended as the orthogonal cross pattern will allow the determination of whether the bathymetry was changing and in which direction.
2. At time t = 0 s, dropwindsonde 1 is launched. Aircraft maintains a level flight.
3. Dropwindsonde 2 is launched 2 min later (t = 120 s).
4. Aircraft maintains level flight until the splash location of dropwindsonde 1 is determined.
5. The P-3 executes a series of three 90-degree turns to align for a pass over the splash location of dropwindsonde 1. Each turn should be sharp (30-degree bank) to minimize turning time and non-level flight. Between turns the aircraft should maintain level flight to maximize the amount of valid observations collected with the SFMR (and AWRAP).
6. An 8-km level flight leg centered on the dropwindsonde 1 splash location is executed. The heading of this leg should be orthogonal to the original flight track.

7. Once the splash location of dropwindsonde 2 is known, the P-3 should execute two 90-degree turns (30-degree bank angle) to align for the pass over the second splash location. Between turns the aircraft should maintain level flight.
8. An 8-km level flight leg centered on the dropwindsonde 2 splash location is executed. The heading of this leg should be orthogonal to the original flight track.
9. The P-3 can exit this module.

This module can be embedded as a sub-module or part of a flight track dedicated to analyzing bathymetry effects on the SFMR. For the latter, the aircraft should be heading in the direction of increasing or decreasing water depth.

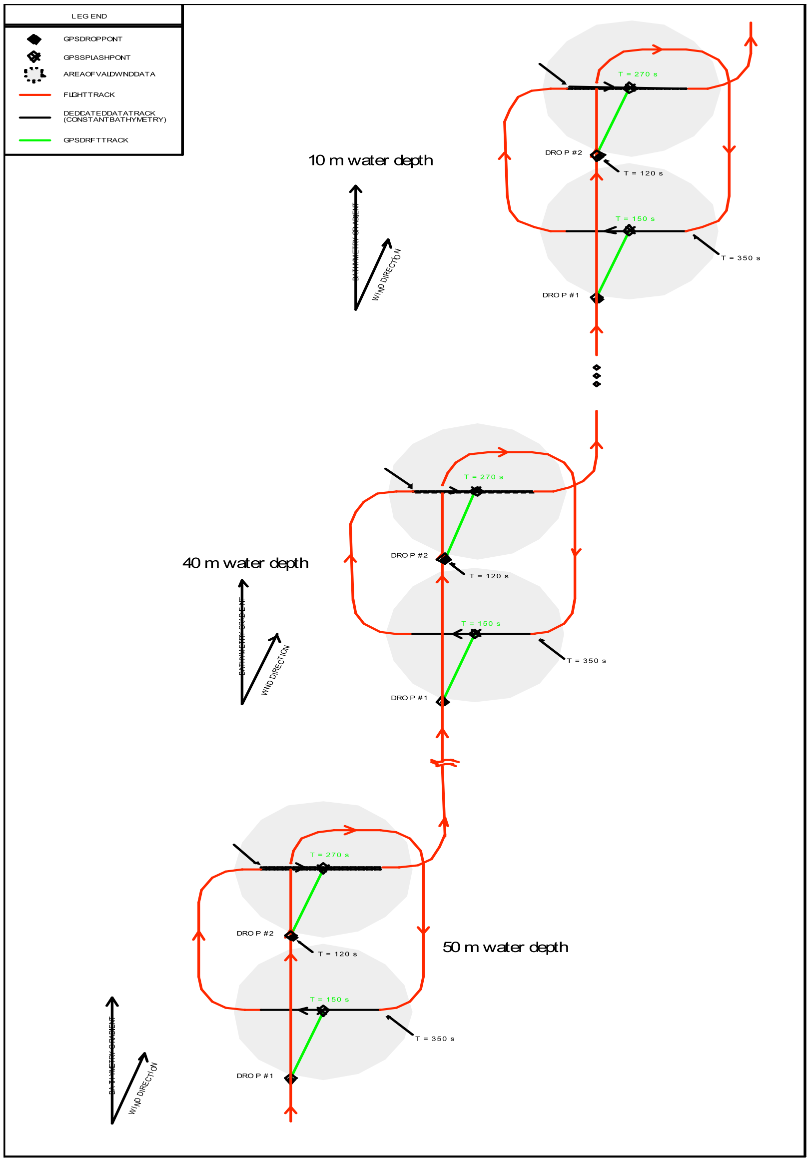


Figure 6-3: Shallow Bathymetry Module. Single aircraft dedicated bathymetry flight track is shown. Each submodule (Fig. 6-1) is executed at water depths of approximately 50 m, 40 m, 30 m, 20 m and 10 m. See notes for Fig. 6-1.

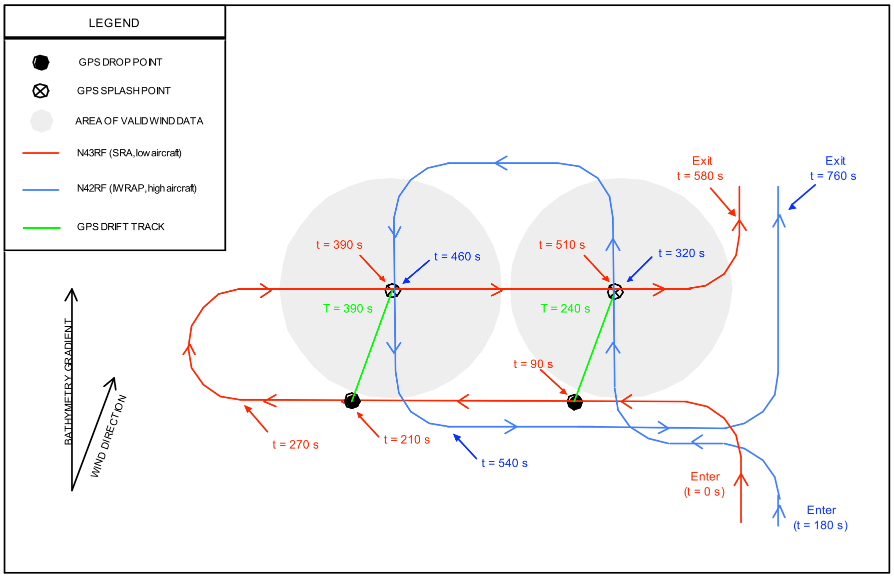


Figure 6-4: Dual aircraft SFMR bathymetry module.

Notes for low P-3 (5000 feet):

1. P-3 enters pattern heading in the direction of increasing or decreasing bathymetry gradient. If the bathymetry gradient is not known, this pattern is still recommended as the orthogonal cross pattern will allow the determination of whether the bathymetry was changing and in which direction.
2. At time t = 0 s the aircraft executes a 90-degree turn (30-degree bank) and then holds level flight. At time t = 90 s, dropwindsonde 1 is launched.
3. Dropwindsonde 2 is launched 2 min later (t = 210 s).
4. P-3 maintains level flight until the splash location of the dropwindsonde 1 is determined (~t = 270 s). The P-3 executes a 180-degree turn to overfly splash location of dropwindsondes 1 and 2. Splash location of dropwindsonde 2 is estimated from splash location of dropwindsonde 1. Since the release points are separated by approximately 12 to 15 km, both dropwindsondes should advect similarly.
5. The P-3 maintains level flight as it overflies the splash locations of dropwindsonde 2 and dropwindsonde 1 at approximately t = 390 s and t = 510 s, respectively. After flying a minimum of 4 km past the splash location of dropwindsonde 1, the P-3 then executes a 90-degree turn to resume the original flight track exiting this module at t = 580 s.

Notes for high P-3 (AWRAP, 7000 to 10,000 feet):

1. The high altitude P-3 enters the pattern at the same location as the low P-3 but delayed by 180 s.
2. With knowledge of the splash location of dropwindsonde 1, a box pattern is executed to overfly the splash locations of dropwindsondes 1 and 2. Each leg over each splash location is a minimum of 8 km centered on the splash location. The length can be extended in order to keep the timing of both P-3s aligned at the exit of the flight pattern. During the 8-km legs, the P-3 must maintain level flight. In this case the splash location of dropwindsonde 2 will already be known and therefore does not need to be estimated.
3. After completing the box pattern, the P-3 executes a 90-degree turn to resume the original track with the lower P-3.

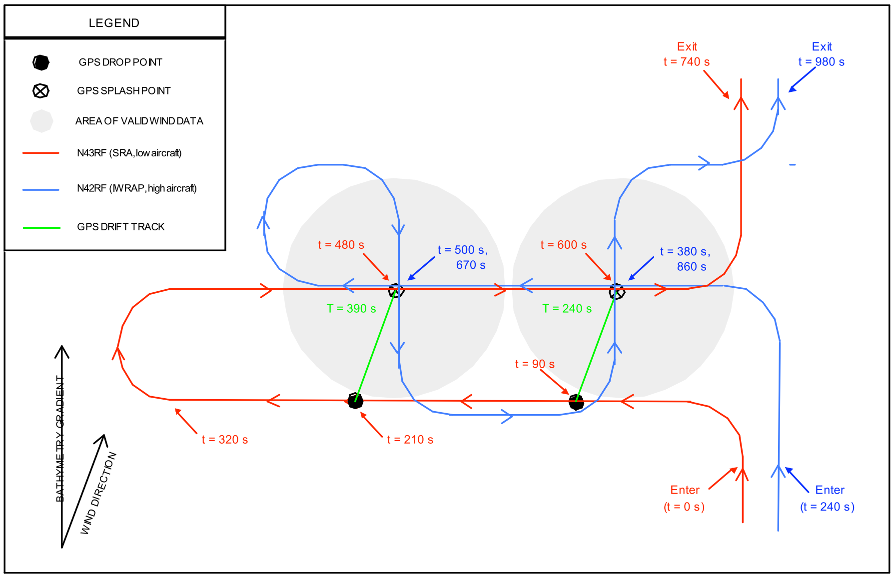


Figure 6-5: Alternative dual SFMR bathymetry module.

Note: The high P-3 executes orthogonal cross patterns over each location and over flies the same track as the low P-3 as it overflies the two splash locations.

6c. Off-nadir SFMR Experiment . The Hurricane Imaging Radiometer (HIRad) is currently under development by NASA and NOAA and is intended to follow the SFMR concept and extend its spatial coverage by providing a wide swath measurement. It is intended to be the next-generation scanning SFMR intended to reduce surface wind uncertainty by extending the SFMR measurement swath in the cross –track direction. In order to design HIRad and to retrieve wind speed and rain rate over its full swath, an ocean surface emissivity model is required that covers wind speeds over the full SFMR range of greater than 70 ms^{-1} and over the full HIRad swath of approximately ± 60-degree incidence angle. Existing models cover high wind speeds at nadir only (SFMR) and cover large incidence angles only during turns at less than hurricane force. Therefore, a new surface emissivity model is being developed under the HIRad project to meet future needs in radiative transfer analyses.

The HIRad surface emissivity model is being developed using SFMR algorithms for nadir incidence and using SFMR brightness temperature measurements in aircraft banks and turns for off-nadir modeling. Aircraft turns in past hurricane flights have typically produced maximum bank angles of 30 – 35 degrees or less. Therefore, there is a critical need for brightness temperature data in hurricane-force wind speeds at incidence angles greater than 35 degrees in order to complete the HIRad surface emissivity model. The Off-Nadir SFMR Experiment is intended to fill this need.

Flight Pattern Description

A full pattern consists of six complete circles. The first three turns should be performed with the aircraft banked at a 30 deg. angle, and the final three turns at 45 deg. bank. Turns are to be performed in relatively clear air, free of convection. When executing these rolls it is preferable to turn downwind for Lagrangian continuity in high wind speeds, however turning upwind can provide useful data as well. These patterns are to be flown when situation and time dictate. Dropwindsondes (2) should be released at both the beginning and end of the pattern, and one AXBT should be deployed at the beginning. It is important throughout this pattern for the rolls to be accomplished during the turns to be at constant pitch insofar as possible, as changes in pitch will translate to changes in SFMR brightness. An example of the optimal location for obtaining measurements is shown in Fig. 6-6 from Hurricane Gustav (2008). The open eyewall yielded hurricane-force surface winds with little or no convection present.

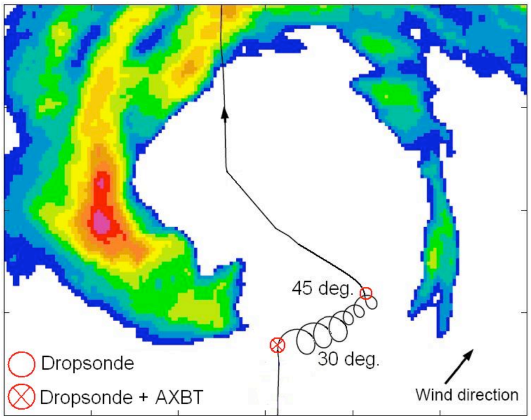


Figure 6-6: SFMR off-nadir module. Upon entering the pattern, a GPS dropwindsonde and AXBT are deployed. The first three of six full turns are performed at a constant roll angle of 30 deg., and the second three turns are at 45 deg. roll angle.

6d. SFMR High Rain-Rate Experiment It has been found that under certain conditions, the SFMR has a tendency to over-estimate the surface wind speed. One such situation is in heavy rain and weak-to-moderate wind speeds. This issue is particularly troublesome when a tropical storm is very near hurricane intensity (65 kts or 33 m/s). The reason for this problem lies with the assumptions about how the rain-induced microwave absorption is modeled in the SFMR's retrieval algorithm. To address the uncertainty about SFMR surface wind accuracy, a module has been developed to obtain in situ surface wind speed estimates in such conditions. It is hoped that improved statistics in these conditions will lead to an improved rain model, and ultimately more accurate wind speed retrievals.

Flight Pattern Description

The pattern consists simply of deploying a series of 3 closely spaced (30 seconds or less) GPS dropwindsondes within a rain band *outside of the eyewall*, along a radial leg (Fig. 6-7). Radar reflectivity levels of 20 dbZ and higher are of particular interest. Desired altitude is standard reconnaissance levels (700 mb, 10,000 ft), with flight level winds optimally between 30 and 80 kts (15 to 40 m/s).

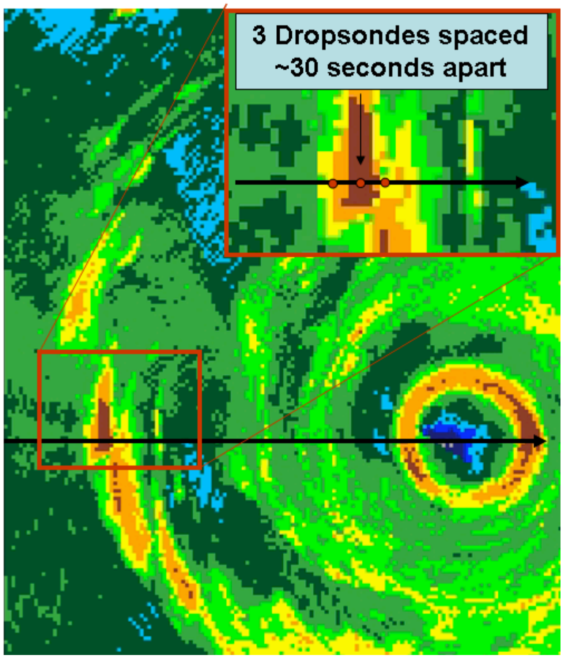


Figure 6-7: SFMR heavy rain module. Three dropsondes are deployed in rapid succession (every 30 s) across a rain band (or other convective region) outside of the primary eyewall region.

7. Tropical Cyclone/AEW Arc Cloud Module

Program Significance: 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 (~600-800 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 7-1), 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 (2009) 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 (2009) 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 gravity waves at midlevels that originate from the convective core of the tropical disturbance.

It is hypothesized that these arc cloud features can significantly impact an AEW or TC (particularly smaller, less developed systems) via three mechanisms. First, as arc clouds race away from the convective core region, they create low-level outflow in the quadrant or 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. Second, the formation of substantial arc clouds resulting from convectively-driven downdrafts indicates that significant downdrafts may be/may have been present in the periphery of the inner core environment. Again, this is counter to the typical updrafts that are vital for TC formation and maintenance. Third, assuming arc clouds are primarily manifestations of convectively-generated density currents, the cool dry air injected into the boundary layer may act to stabilize the lower troposphere and limit subsequent convection.

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 first mechanism (enhanced low level outflow) is likely occurring at the time of satellite identification, while the latter two mechanisms (downdrafts and cooling/drying of the boundary layer) have already occurred (though they may still be 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 on the periphery of AEWs or TCs using aircraft flight-level data and GPS dropsondes to improve our understanding of the physical processes responsible for their formation and evolution, as well as how these features may limit short-term intensification.

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

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

Mission Description: This multi-option research module is designed to utilize the WP-3D [flight-level (flying at multiple levels above 1500 feet) and GPS dropsonde data], G-IV (GPS dropsonde data), or Aerosonde UAS aircraft [flight-level (flying at 1,000-5,000 ft) data]. Although this module is not a standalone experiment, it could be included as a module within any of the following HRD research missions: Saharan Air Layer Experiment, TC Genesis Experiment, Aerosonde Experiment, or TC Landfall and Inland Decay Experiment or as part of operational G-IV Synoptic Surveillance and NHC-EMC-HRD Mature Storms Experiment 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. Also, the 200-850 hPa shear vector may be an additional indicator of where and when arc clouds might form. 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.

Option #1: G-IV aircraft. Once an arc cloud feature has been identified, a GPS dropsonde sequence (preferably running perpendicular to the arc cloud) should be made between the convective area where the arc cloud originated to at least 20 nm 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 ~20 nm 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 7-2 and 7-3 provide example G-IV flight patterns across arc cloud candidates. This option can be easily incorporated into pre-existing flight patterns with minimal additional time requirements.

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

Figures 7-2, 7-3, and 7-4 show sample flight patterns for this multi-level option.

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

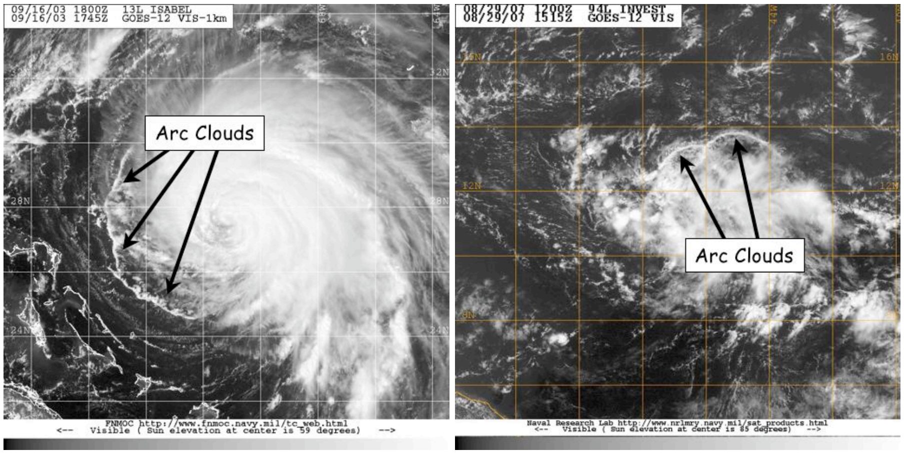


Figure 7-1: GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2003 Hurricane Isabel and (right) 2007 Pre-Tropical Depression Felix.

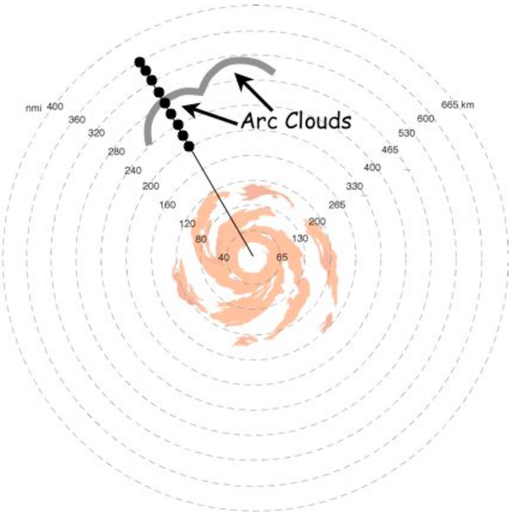


Figure 7-2: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and

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.

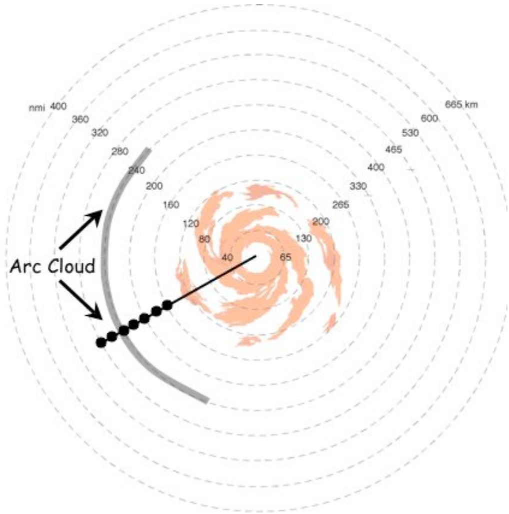


Figure 7-3: The G-IV (or WP-3D) flight track inbound or outbound to/from the TC/AEW. Azimuth and length of GPS dropsonde sequences during G-IV missions will be dictated by the pre-determined flight plan. For these cases, any G-IV flight legs that transect through the trailing and leading edges of the arc cloud are candidates for this module.

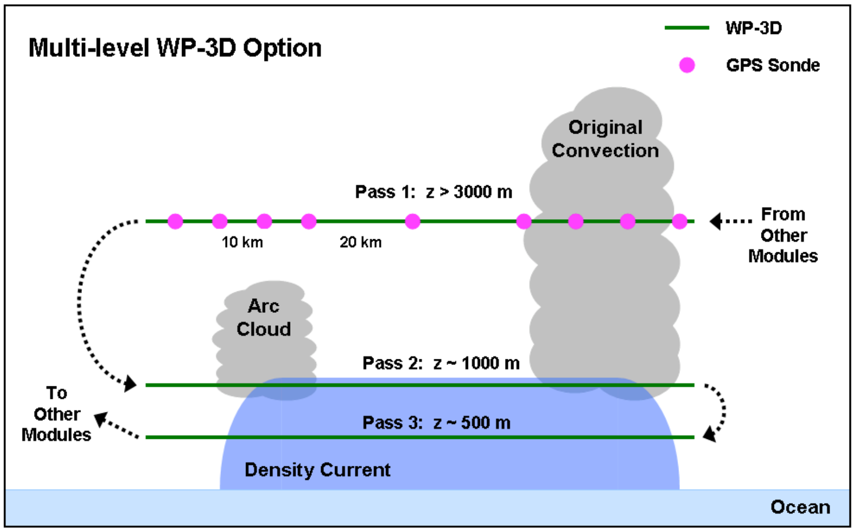


Figure 7-4: The WP-3D flight track for the multi-level option. Azimuth and length of initial midlevel pass with GPS dropsonde sequence will be dictated by the pre-determined flight plan. Lengths of the

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).

Hurricane Boundary Layer Entrainment Module. 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 thermodynamic 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.

Entrainment of dry air from above boundary layer or convective exchanges counters the surface enthalpy flux transport, reducing theta-e in the boundary layer (Powell 1990b). On the other hand, shear induced entrainment of high theta-e near radially outward of a strong rain band could led to increase in the energy content of the inflow layer (Barnes and Powell, 1995). Recently, Smith et al. (2008) revisited the Emanuel's hurricane potential intensity theory for tropical cyclones and pointed out that the interactions between the eye and eyewall region through shear instability, and the energy entrainment processes from the top of the boundary layer in the outer region are very important physical processes associated with hurricane intensity change, and should be accounted for in the theory. A better understanding the entrainment processes near the top of the boundary layer is also very crucial to the improvement of model parameterizations of the turbulent fluxes and vertical mixing in the hurricane boundary layer.

Background

Entrainment processes near the top of the boundary layer have been extensively studied in the ordinary atmospheric boundary layer outside hurricanes, especially in the convective boundary layer. Entrainment of midlevel air in the wake of a quall line brings cool and dry air into the mixed layer and reduces the theta-e even when theta is increasing, overwhelming the sensible and latent heat fluxes transferred from the ocean (Zipser 1977; Nicholls and Johnson 1984; Barnes and Sieckman 1984). Hurricane rain bands are a type of mesoscale convective systems that could entrain lower theta-e air into the inflow and potentially inhibit the storm intensity (Barnes et al. 1983; Powell 1990b). Betts and Simpson (1987) reexamined a trajectory analysis for the inflow into Hurricane Daisy which was first studied by Malkus and Riehl (1960), and argued that the inflow layer could receive energy from a number of mechanisms indicating the importance of study the processes at the top of the inflow.

Entrainment processes could also bring energy into the inflow from the boundary layer above. Numerical studies by Anthes and Chang (1978), and a budget analysis by Frank (1984), show that the entrainment of high potential temperature can contribute to the maintenance of an isothermal subcloud layer. Barnes and Powell (1995) showed that there are conditions shear induced entrainment of higher theta-e from a radially outward rain bands overlaying the inflow layer can led to increase in the energy content of the inflow. This is counter to the typical situation where the flux of energy is out of the layer and into the middle troposphere. These fluxes can rival the fluxes at the air-sea interface as well.

Till now, the understanding of the fluxes at the top of either the mixed layer or the thicker inflow layer in hurricanes is very limited due to the lack of in-situ measurements. There are only results from budget studies and simple numerical models that identify the mixing at the top of inflow layer, such as those given by Barnes and Powell (1995), and Wroe and Barnes (2003). During the Coupled Boundary Layer Air-sea Transfer (CBLAST) - Hurricane experiment, instruments including Rosemount gust probe and LICOR hygrometer, have been successfully tested and utilized to directly measure turbulent fluxes in the hurricane boundary layer (Black et al. 2007; Zhang et al., 2008). These instruments with capability of high quality of turbulent flux observations can be also used to study the entrainment processes near the boundary layer top by directly measuring the fluxes there.

Objectives

- To perform direct measurements of momentum and enthalpy flux near the top of the inflow layer.
- To use the measured high-quality flux to estimate the rate of entrainment and entrainment velocity
- To study the temporal and spatial variability of fluxes near the boundary layer top by storm quadrant and location respect to the storm center.
- To study the effects of entrainments on the hurricane intensity change.

Links to IFEX

It supports the following NOAA IFEX goals:

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

Experiment Description

This is a multi-option, single-aircraft experiment which is designed to directly measure momentum and enthalpy fluxes near the top of the inflow layer using the Rosemount turbulent gust probe, Rosemount fast response temperature sensor and LICOR-7500 hygrometer that are installed on both NOAA P-3. Turbulence probes need to be calibrated at the start of the field season during the turbulence calibration module described below. Except this module, this experiment can be included within any of the following missions: Aerosonde Experiment, or TC Landfall and Inland Decay Experiment or Arc cloud experiment, or genesis experiment or NHC-EMC-HRD Three-dimensional Doppler Winds Experiment missions. Specific effort will be made to gather fast response (40Hz) flight level wind, temperature and humidity data at altitude of around 1km - 2km within the region adjacent to the eyewall or rain bands, regions between the eyewall and rain bands, or regions between the outer rain bands. The goals are to better understand the entrainment processes near the top of the inflow layer, to estimate the magnitude of entrained turbulent fluxes in different regions and to investigate how the entrainment fluxes into or out of the inflow layer are related to TC intensity change. The P-3 aircraft can be flown in either along-wind or cross-wind directions. Maintaining the aircraft at a nearly constant altitude as longer as possible is desirable.

Turbulence Calibration Module. The calibration module was executed on separate flights at the start of the field season. The following maneuvers are requested for turbulence sensors calibration:

1. Dynamic Yaw--2 sets:
   First set, vary sideslip angle (beta) by +/- 4 degrees. This maneuver requires 5 full sinusoids, with one consisting of left 4 degrees, back through center, right 4 degrees, back to center--one sinusoid. Second set, set angle variation, and perform faster roughly +/- 2.5 degree variation with 25 sec period.

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

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

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

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).

8. Saharan Air Layer Experiment (SALEX)

Saharan Air Layer Experiment: This is a multi-option, multi-aircraft experiment which uses GPS dropwindsondes and flight-level data from the NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) and NOAA WP-3D (flying at ~500-700 hPa/19,000-10,000 ft) to examine the thermodynamic and kinematic structure of the Saharan Air Layer (SAL) and its potential impact on tropical cyclone (TC) genesis and intensity change. The GPS dropwindsonde drop points will be selected using real-time GOES SAL tracking imagery from UW-CIMSS and mosaics of microwave-derived total precipitable water from the Naval Research Laboratory and the UW-CIMSS MIMIC product. 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 the SAL's 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. Additionally, two new in situ measuring instruments have recently been installed on NOAA 43RF that will allow for the observation of suspended mineral dust in the SAL. When possible, HRD's Saharan Dust Microphysics Module should be conducted with the WP-3D Orions as part of SALEX. This module uses a stepped ascent pattern to collect in situ information on mineral dust concentration and particle size distribution from the CCP Probe and CAS instrument (described below):

1) **CCP Probe**: measures cloud and precipitation particles in the size ranges 3.0-47 μm and 0.25-1.6 mm;
2) **Cloud Aerosol Spectrometer (CAS)**: uses both forward and backward scattering of laser light to size particles in the ~0.5-50 μm diameter range. With the addition of the Particle-by-Particle Module, this instrument can also distinguish between solid and liquid particles (e.g. water droplets vs. Saharan dust);

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^{o}C in the central/western North Atlantic and ~5-10^{o}C in the eastern North Atlantic) than a typical moist tropical sounding. Additionally, the RH (mixing ratio) in the SAL is ~50-55% (~28-33% RH, ~1.3-3.3 g kg^{-1}) drier than a typical moist tropical sounding. 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 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 are to:

- Better understand how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change;
- Include the moisture information from the GPS dropwindsondes 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.

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

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

Mission Description: The NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) and NOAA WP-3D (flying at ~500-700 hPa/~19,000-10,000 ft) GPS dropwindsonde 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, and the UW-CIMSS MIMIC TPW product. Specific effort will be made to gather atmospheric information within the SAL, 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/or 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. Several SAL/TC interaction scenarios are candidates for SALEX missions:

Option 1:

Single TC located along the southern edge of the SAL (Fig. 8-1). Depending on the proximity of these two features, the SAL's dry air may be wrapping into the TC's low-level circulation (western semicircle).

G-IV: The G-IV **IP** will be in west of the TC (preferably west of the SAL's leading edge) and the initial portion of the 1st leg (**IP-2**) will focus a GPS dropwindsonde sequence across the high gradient region of humidity at the SAL's leading edge. The spokes of this 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 ~-55°C). 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**). 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**).

WP-3D: The WP-3D **IP** will be in the SW quadrant of the TC and the initial portion of the 1st leg (**IP-2**) will focus on sampling the ambient moist tropical environment south of the TC. The 2nd leg (**2-3**) will include sampling the ambient moist tropical environment east of the TC as well as focusing a GPS dropwindsonde sequence across the SAL's southern boundary to capture gradients of humidity and wind shear (associated with the SAL's mid-level easterly jet). The 3rd leg (**3-4**) will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will focus on sampling the intrusion of low humidity SAL air into the TC circulation and how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. The final leg (**4-FP**) will include a penetration of the TC center of circulation followed by GPS dropwindsonde sequences targeting the SAL west of the TC. The final GPS dropwindsonde sequence will sample the SAL's leading edge ("rooster tail") west of the TC.

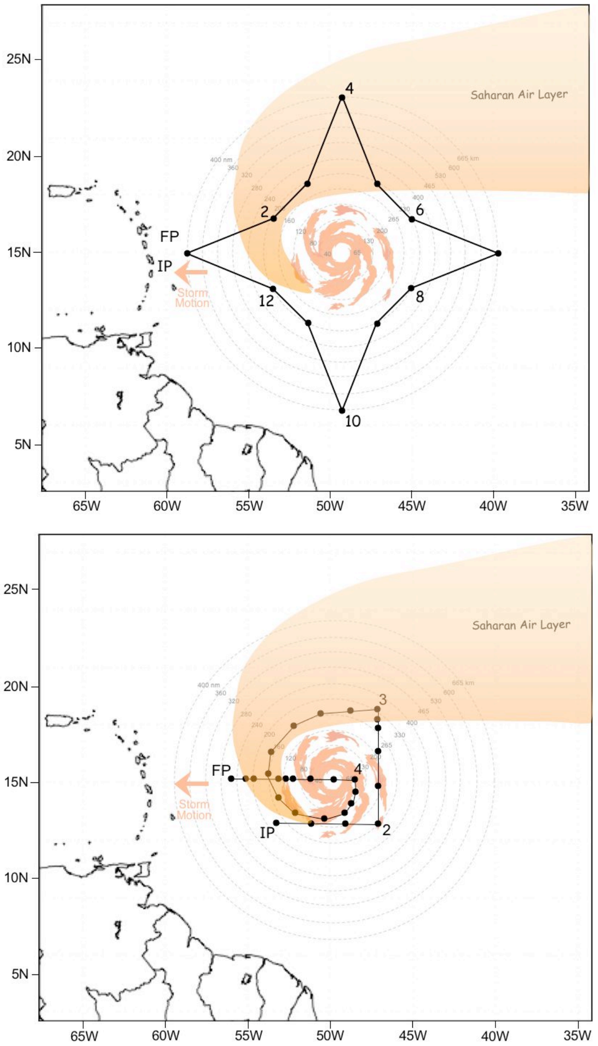


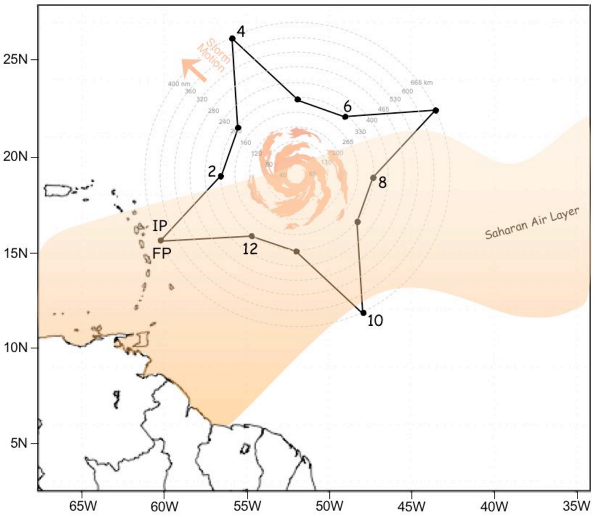
Figure 8-1: Sample (top) G-IV and (bottom) WP-3D flight tracks for a TC positioned along the southern edge of the SAL.

- *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. The WP-3D Orion should climb to the pre-determined flight-level (e.g. ~10,000-19,000 ft) as soon as possible.
- *Note 2*: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2**, **2-3**, and **4-5-6**; WP-3D: **2-3**, and **4-FP**) and possible penetration of dry air and vertical wind shear toward the inner core (G-IV: **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 dropwindsondes dropped near the SAL's southern boundary (G-IV: **2-3-4 and 4-5-6;** WP-3D: **2-3** and **3-4**).

Option 2: Single TC is embedded within the SAL and intensifies upon emerging (Fig. 8-2). These systems are often candidates for rapid intensification.

G-IV: The G-IV **IP** will be southwest of the TC. The first few legs (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL. This dropwindsonde sequence will focus on sampling the large humidity gradients across the northern edge of the SAL. The next several legs of the flight pattern (**2-3-4-5-6-7-8)** will intermittently sample the moist tropical environment out ahead of the TC and north of the SAL. The next few legs will include a GPS dropwindsonde transect across the northern boundary of the SAL northeast of the TC (**7-8**), intermittent GPS dropwindsondes within the SAL (**8-9**), and a GPS dropwindsonde transect across the southern boundary of the SAL (including the SAL's mid-level easterly jet) southeast of the TC (**9-10**). The last few legs will largely sample the SAL environment from which the storm is moving away from (**10-11-12-FP**). The spokes of this 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 ~-55°C). 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**).

WP-3D: The WP-3D **IP** will be southwest of the TC. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL. This dropwindsonde sequence will focus on sampling the large humidity gradients across the northern edge of the SAL. The 2nd leg (**2-3**) of the flight pattern will sample the boundary between moist tropical air north of the TC center and the SAL to the south and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core. The 3rd leg (**3-4**) will include a GPS dropwindsonde transect across the northern boundary of the SAL to sample the humidity gradients at the SAL's northern boundary. The 4th leg (**4-FP**) will sample the boundary between moist tropical air north of the TC center and the SAL to the south and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.



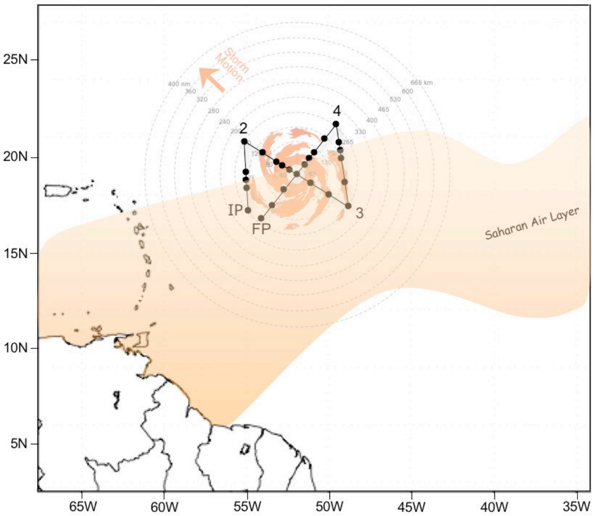


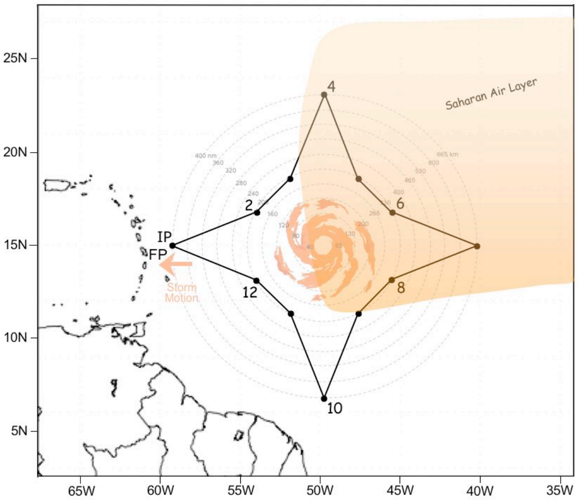
Figure 8-2: Sample (top) G-IV and (bottom) WP-3D flight tracks for a TC emerging from the SAL.

- *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. The WP-3D Orion should climb to the pre-determined flight-level (e.g. ~10,000-19,000 ft) as soon as possible.
- *Note 2*: The TC may undergo a period of rapid intensification as it emerges from the SAL.
- *Note 3*: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2-3**, **7-8** and **9-10-11;** WP-3D: **IP-2** and **3-4**).
- *Note 4*: The SAL's mid-level easterly jet (~20-50 kt at 600-800 hPa/14,500-6,500 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **8-9-10-11-12**).

Option 3: Single TC embedded located along the leading edge of the SAL (Fig. 8-3). These systems are often struggle to intensify as they are overtaken by the SAL surge, but do occasionally separate from the SAL and intensify. These systems are often characterized by their low-level circulations racing out ahead (west) of their mid-level convection.

G-IV: The G-IV **IP** will be west of the TC. The first two legs (**IP-2-3**) will include intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL. The 3rd (**3-4**) leg will sample the moist tropical environment north of the TC and west of the SAL followed by a GPS dropwindsonde transect across the leading edge of the SAL (north of the TC). The next several legs of the flight pattern (**4-5-6-7-8-9**) will intermittently sample the SAL with specific focus on sampling the gradients associated SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 8th and 9th legs (**8-9-10**) will include intermittent GPS dropwindsonde sampling of the SAL, followed by a transect across the SAL's southwest leading edge. The last few legs (**9-10-11-12-FP**) will include intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL. The spokes of this 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 ~-55°C). 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**).

WP-3D: The WP-3D **IP** will be west of the TC. The 1st leg (**IP-2**) will include intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL. The 2nd leg (**2-3**) of the flight pattern will sample the boundary between moist tropical air west of the TC center and the SAL to the east and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core. The 3rd leg (**3-4**) will include intermittent GPS dropwindsonde sampling within the SAL with specific focus on sampling the gradients associated SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 4th leg (**4-FP**) will sample the boundary between the SAL to the east of the TC center and the moist tropical air to the west and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.



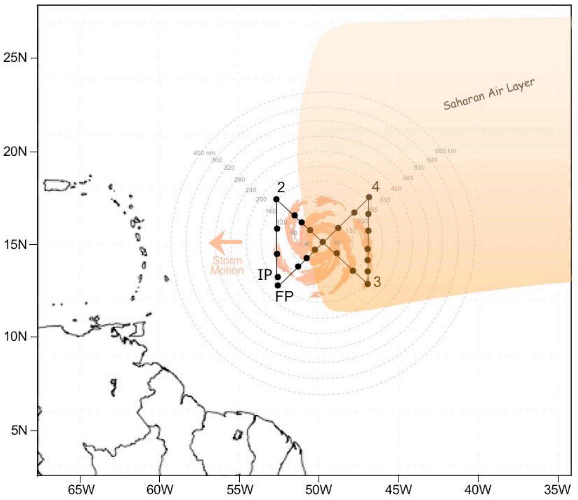


Figure 8-3: Sample (top) G-IV and (bottom) WP-3D flight tracks for a TC along the leading edge of the SAL.

- *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. The WP-3D Orion should climb to the pre-determined flight-level (e.g. ~10,000-19,000 ft) as soon as possible.
- *Note 2*: The TC will likely struggle to intensify as it is overtaken by the SAL. Slow intensification is possible if the TC is able to separate from the SAL.
- *Note 3*: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **2-3-4** and **8-9-10**; WP-3D: **2-3** and **4-FP**).
- *Note 4*: The SAL's mid-level easterly jet (~20-50 kt at 600-800 hPa/14,500-6,500 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **5-6-7-8-9**; WP-3D: **2-3** and **3-4**).

Option 4: Single TC embedded within the SAL throughout most or all of its lifecycle (Fig. 8-4). These systems struggle to intensify and are often characterized by their low-level circulations racing out ahead (west) of their mid-level convection. Depending on the proximity of these features, the SAL's dry air may be wrapping into the TC's low-level circulation (western semicircle).

*G-IV***:** The **IP** will be west of the TC and preferably west of the SAL. The first four legs (**IP-2-3-4-5**) will include GPS dropwindsonde transects across the western and northern boundaries of the SAL. These dropwindsonde sequences will focus on sampling the large humidity gradients across the SAL boundaries. These scenarios (TC embedded within the SAL) are typically cases where the TC is under the influence of a strong SAL easterly jet. The next several legs of the flight pattern (**4-5-6-7-8**) will intermittently sample the SAL environment northeast and east of the storm as well as the SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The last several legs (**7-8-9-10-11-12-FP**) will sample the moist tropical environment south and west of the SAL. The spokes of this pattern (**IP-2/12-FP**, **2-5**, **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 ~-55°C). The tangential legs at ~200 nm will observe the variability of possible dry air and shear that has penetrated close to the inner core (**5-6**, **8-9** and **11-12**).

*WP-3D***:** The **IP** will be NW of the TC and preferably north of the SAL. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL and will focus on sampling the large humidity gradients across the SAL. The 2nd leg (**2-3**) of the flight pattern will intermittently sample the moist tropical environment south of the SAL and will include a GPS dropwindsonde transect across the southern boundary of the SAL as well as the SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 3rd (**3-4**) and 4th (**4-5**) legs will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will sample the intrusion of low humidity SAL air into the TC circulation and help to define how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. The final leg (**5-FP**) will sample the boundary between moist tropical air west of the TC center and the SAL to the east and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.

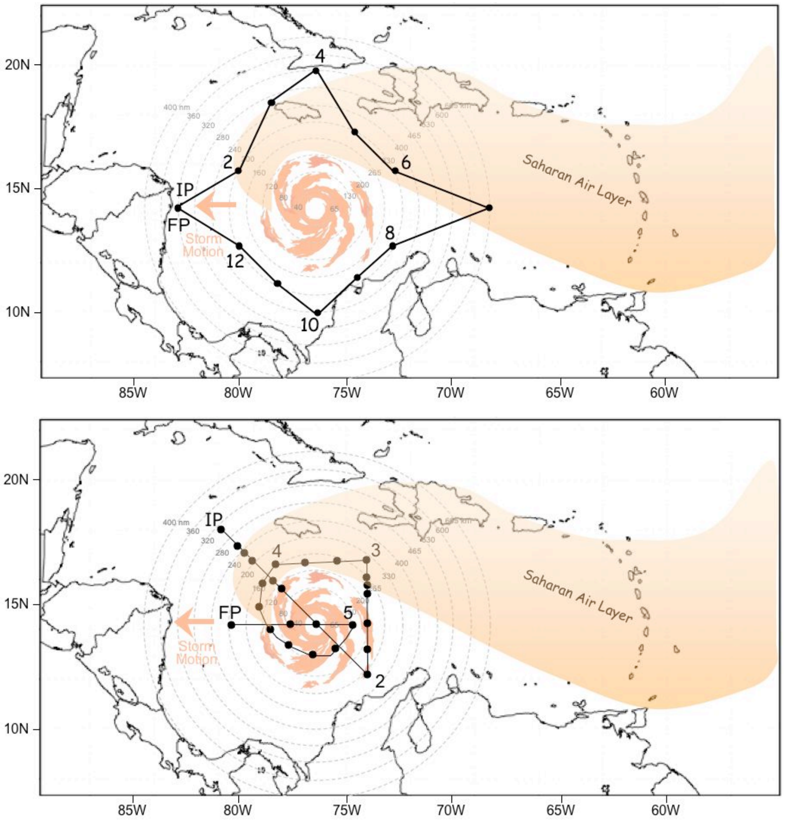


Figure 8-4: Sample (top) G-IV and (bottom) WP-3D flight track for a TC embedded in the SAL for most or all of its lifecycle.

- *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. The WP-3D Orion should climb to the pre-determined flight-level (e.g. ~10,000-19,000 ft) as soon as possible.
- *Note 2*: In order to capture the SAL structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2-3-4-5** and **7-8**; WP-3D: **IP-2**, **2-3 and 5-FP**).
- *Note 3*: The TC's low-level circulation may race ahead of its mid-level convection due to the influence of the SAL's mid-level easterly jet.
- *Note 4*: The SAL's mid-level easterly jet (~20-50 kt at 600-800 hPa/14,500-6,500 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **IP-2**; WP-3D: **2-3**).

Saharan Dust Microphysics Module

Program Significance: The Saharan Air Layer (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 mb (~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 western North Atlantic and ~5-10°C in the eastern North Atlantic) than a typical tropical sounding. Additionally, the RH (mixing ratio) in the SAL is ~50-55% (~28-33% RH, ~1.3-3.3 g kg^{-1}) drier than a typical moist tropical sounding. The SAL is often associated with a 20-50 kt mid-level easterly jet centered near 600-800 mb (~4,500-14,500 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:

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

5) 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;

6) **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;

Until recently, the NOAA WP-3D Orions lacked the necessary microphysical instrumentation to investigate the mineral dust component of SAL outbreaks. Two new in situ measuring instruments have recently been installed on NOAA 43RF that will allow for the observation of suspended mineral dust in the SAL:

3) **CCP Probe**: measures cloud and precipitation particles in the size ranges 3.0-47 µm and 0.25-1.6 mm;

4) **Cloud Aerosol Spectrometer (CAS)**: uses both forward and backward scattering of laser light to size particles in the range ~0.5-50 µm diameter range. With the addition of the Particle-by-Particle module, this instrument can also distinguish between solid and liquid particles (e.g. water droplets vs. Saharan dust);

Although previous studies have indicated that the particle size of the SAL's suspended mineral typically ranges from 0.4 - 40 µm, these studies sampled the SAL's mineral dust in the eastern North Atlantic. Given the typical operating area of the NOAA research aircraft (central and western North Atlantic), we anticipate that the mineral dust that will be sampled by the WP-3D Orions will likely be on the smaller side of that size range distribution (e.g. ~0.4 – 10 µm).

Objectives: The main objectives of Saharan Dust Microphysics Module are to:

- Investigate the capabilities of the new CCP Probe and CAS instrument to detect concentrations and particle size distributions of suspended mineral dust in the SAL;
- Investigate the horizontal/vertical concentrations and particle size distributions of the SAL's suspended mineral dust;

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

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

Mission Description: This multi-option research module is designed to utilize the WP-3D Orions (NOAA 43RF) flying at multiple levels from ~500-19,000 feet. Although this module is not a standalone experiment, it could be included as a module within any of the following HRD research missions: Saharan Air Layer Experiment or TC Genesis Experiment, or as part of operational NHC-EMC-HRD Mature Storms Experiment missions. GOES SAL imagery and total precipitable water (TPW) satellite imagery (≤45 mm TPW) will be used to identify SAL outbreaks in the operating area of the WP-3D Orion. The targeted region of the SAL outbreak can be well outside (several 100 km) of the TC environment and the module can be conducted during the inbound or outbound ferry to/from the storm. For fuel considerations, the outbound ferry is preferable. This module includes constant level atmospheric sampling at 5 discreet levels (10 min at each level). The WP-3D Orion will begin the pattern at ~500 ft and conduct a 10 min in situ sampling of the atmosphere. A succession of stepped ascents will then be made with 10 min of in situ sampling at ~5,000 ft (~850 mb, the approximate SAL base), ~10,000 ft (~700 mb, the approximate vertical center of the SAL), ~14,500 ft (~600 mb) and ~19,000 ft (~500 mb, the approximate top of the SAL). Due to the characteristics of the two microphysical instruments, the sampling should always involve a stepped ascent. While the 10 min constant level sampling at each level is important for this module, sampling during the ascents to each new level is not vital. Therefore, the climb rate to each successive level can be carried out at the pilot's discretion. If time and fuel considerations prohibit sampling at all 5 levels, the module can be terminated at any point in the stepped ascent pattern.

<u>Option #1: WP-3D aircraft (NOAA 43RF)</u>: After a suitable SAL outbreak region has been identified for this module, the WP-3D Orion should proceed to the IP (~500 ft). After completing a constant altitude 10 min leg, the aircraft should ascend to the next level (~850 mb/5,000 ft) and conduct another constant altitude sampling for 10 min. This ascending pattern should continue with similar 10 min legs flown at ~700 mb/10,000 ft, ~600 mb/14,500 ft and ~500 mb/19,000 ft (Fig. 7-5). If time and/or fuel considerations are limited, the upper legs of the pattern can be omitted as needed and the module can simply be flown up to the highest level that time and/or fuel permits. Figure 1 shows a sample fight pattern for this multi-level option.

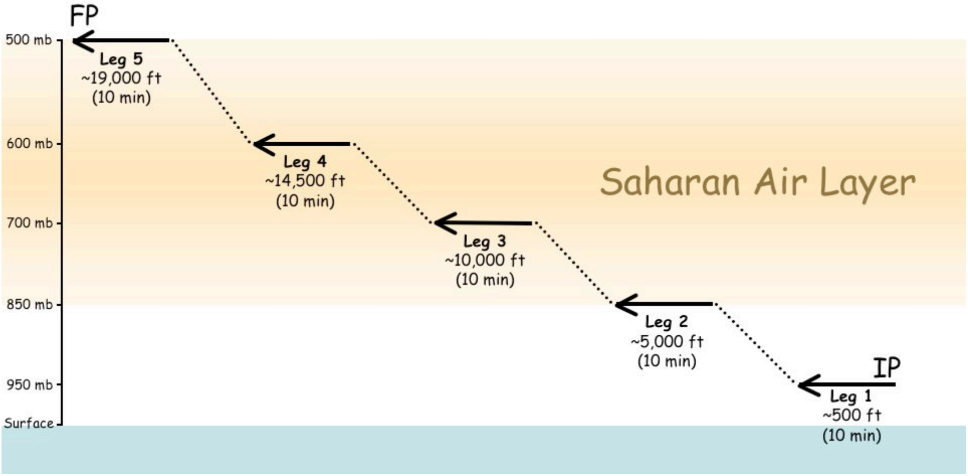


Figure 8-5: Sample fight pattern for the Saharan Dust Microphysics Module. The IP, FP and five 10 min legs are indicated in the figure.

9. Tropical Cyclone-Midlatitude Interaction Experiment

Significance: The poleward movement of a tropical cyclone (TC) initiates complex interactions with the midlatitude environment such that the symmetric distributions of winds, clouds, and precipitation concentrated about the mature TC circulation center develop asymmetries that expand. The asymmetric expansion of areas of high wind speeds and heavy precipitation may cause severe impacts over land without the TC center making landfall. Due to interactions between the TC and midlatitude circulation, regions of heavy precipitation may be embedded in large cloud fields that extend far ahead of the cyclone center. If the heavy precipitation associated with the primary structure of the TC then falls over the same region as the pre-storm precipitation, the potential for flooding is increased. 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. Away from the TC, low potential vorticity air in the upper-level TC outflow leads to downstream ridging on the tropopause. This may modify the tilt of a trough to the west of the TC, impacting the TC motion and rainfall distribution. Downstream, the modified tropopause structure may initiate explosive extratropical cyclogenesis or promote the formation of a cut-off low that may move back into the tropics exciting tropical convection or initiating tropical cyclogenesis. The downstream modification of the midlatitude flow can lead to significant forecast errors in the 3-14 day forecasts globally.

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 during the period in question, hereafter referred to as extratropical transition (ET). 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. This experiment will only be conducted at the end of a TC life cycle if that particular TC has been sampled previously.

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 examine whether the TC structure must be observed in order to forecast ET.

- 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.

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. 9-1). Aircraft will participate in staggered (12-hourly) missions because of the possible rapid changes in structure.

TC region: The G-IV and WP-3D will fly a modified figure-4 pattern as high as possible to avoid hazards such as convective icing. If conditions allow, both aircraft will make three passes over the center of the TC undergoing ET (Figs. 9-2, 9-3). The pattern will be skewed such that the legs to the north of the center will be longer than those to the south. The pattern will be oriented such that the aircraft will complement the pattern of the other. Both the G-IV and WP-3D will deploy dropwindsondes once they have entered their respective patterns. Dropwindsondes will be deployed at each waypoint and at evenly spaced intervals along each leg with optimal spacing near 60 n mi for the WP-3D (22 dropwindsondes) and 100 n mi for the G-IV (20 dropwindsondes). Furthermore AXBTs will be deployed from the WP-3D at each waypoint and at the midpoint of each leg north of the cyclone center (12 AXBTs).

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 the scanning radar altimeter (WSRA) to observe the ocean surface wave spectra. Flight level will be chosen to accommodate this instrument.

TC/Midlatitude interface: 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 during its pattern.

Pre-storm precipitation region: The pre-storm precipitation region ahead of the TC near the primary interface with the midlatitude circulation will be investigated (Fig. 9-4) by a WP-3D or G-IV aircraft as part of their patterns. A path across the region of warm frontogenesis (either aircraft) and potential significant wave heights (WP-3D only) will be completed.

Tropical Cyclone-Midlatitude Interaction Experiment

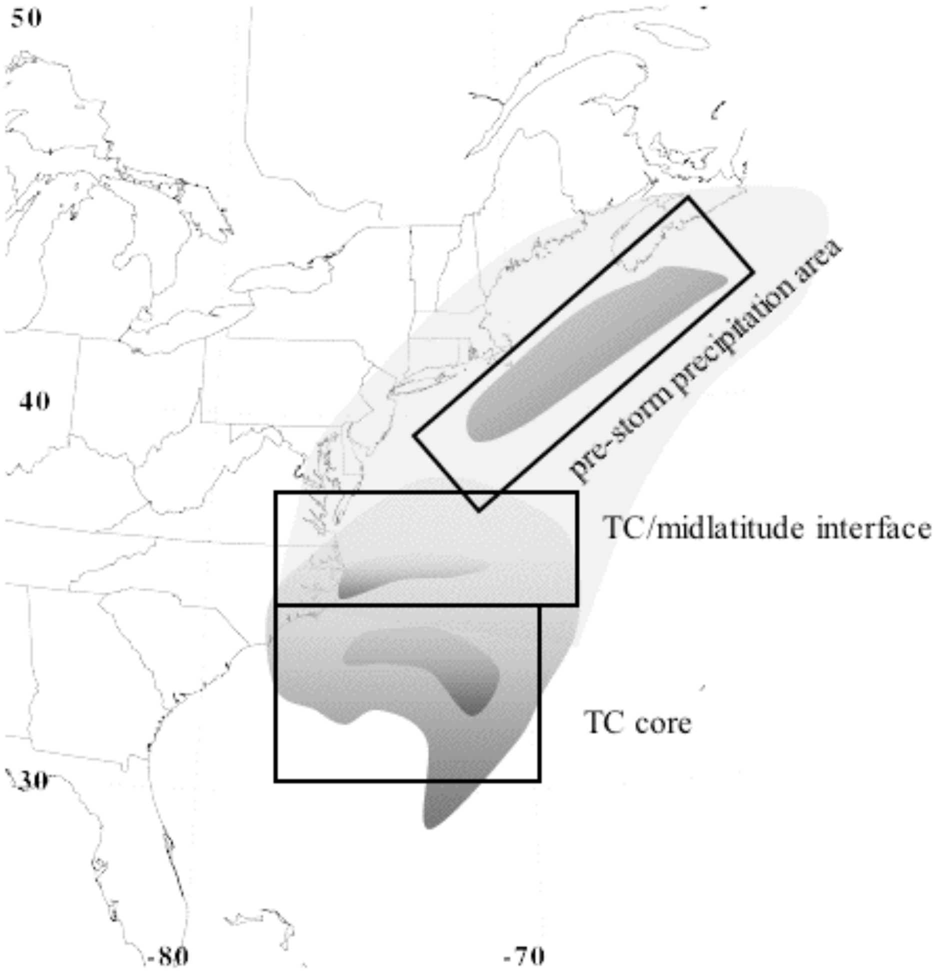


Figure 9-1: Schematic of Tropical Cyclone undergoing extra-tropical transition.

Tropical Cyclone-Midlatitude Interaction Experiment

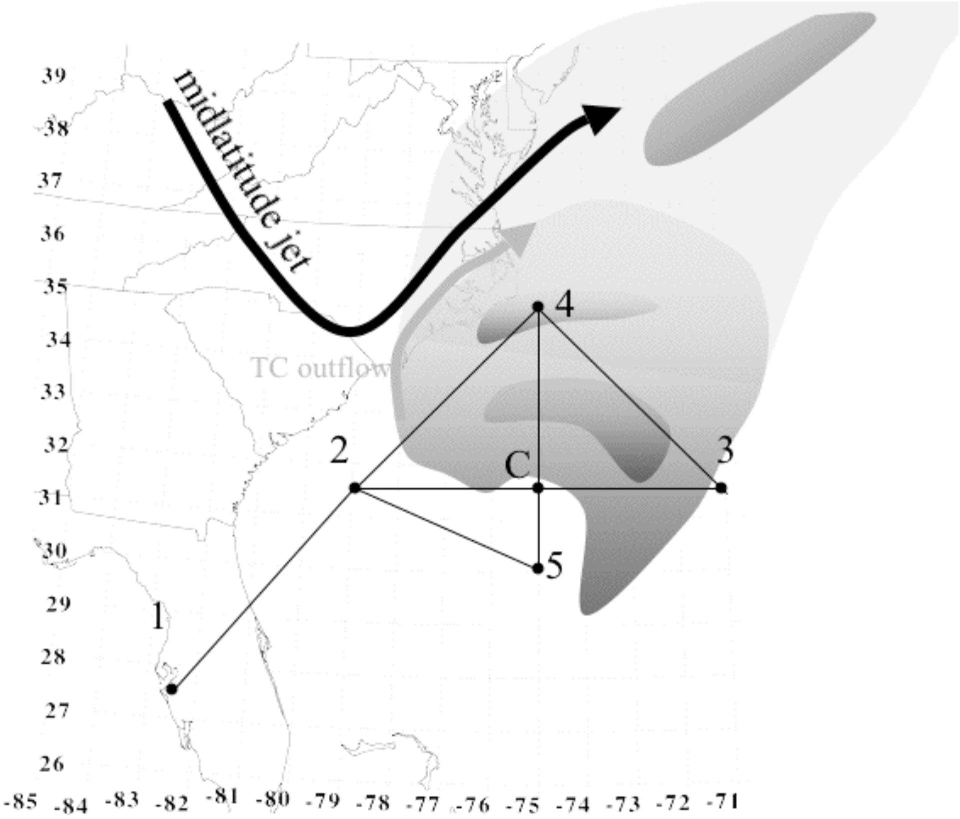


Figure 9-2: G-IV Flight Plan.

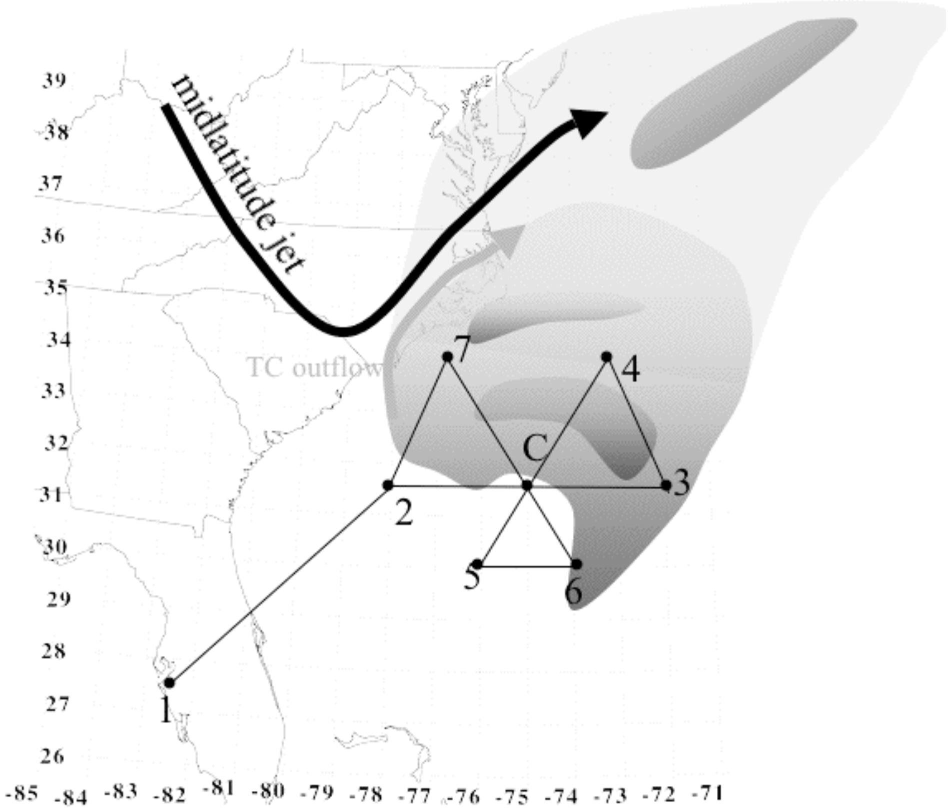


Figure 9-3: WP-3D inner core pattern.

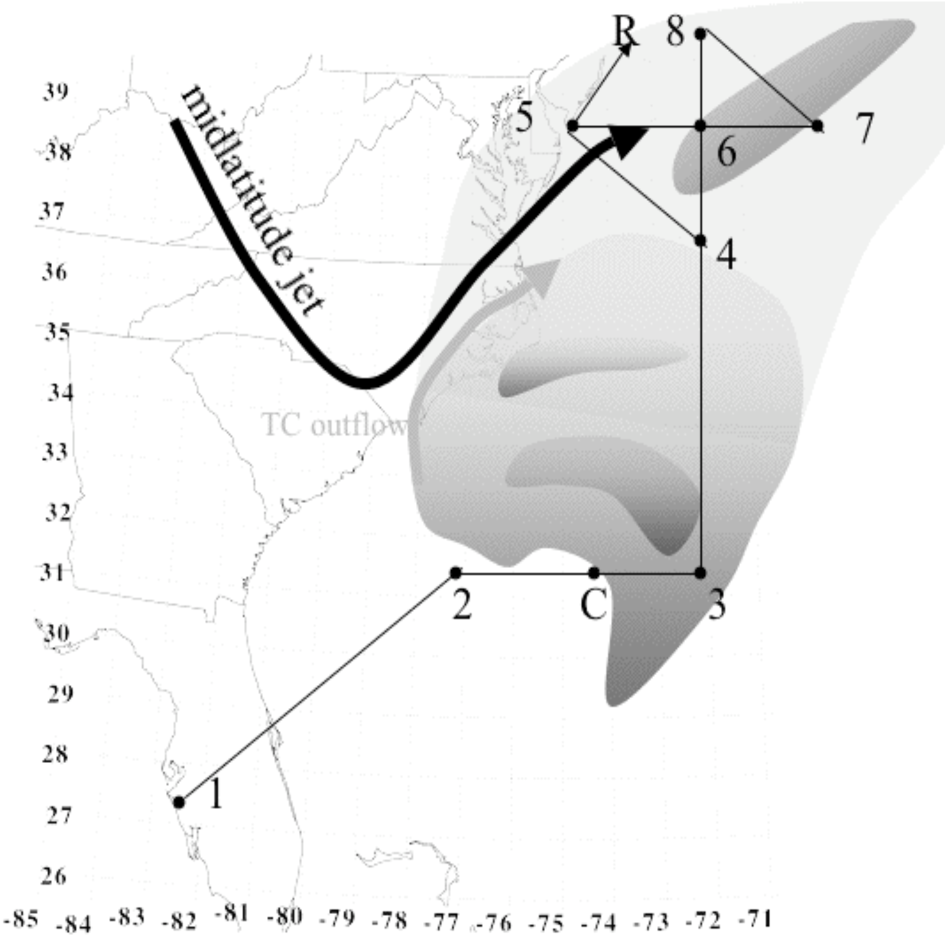


Figure 9-4: WP-3D or G-IV flight pattern to investigate pre-storm precipitation region.

10. Rapid Intensification Experiment (RAPX)

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. 2009) 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 inner-core, oceanic, and large-scale processes. The goal of this experiment is to collect datasets that can be utilized both to initialize 3-D numerical models and improve our understanding of RI processes with the overarching goal of improving our ability to the 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< 120 nm) and in the surrounding large-scale environment for systems that have been identified as having the potential to undergo RI (as determined using 3-D numerical and statistical forecast guidance) within 24-72 h.

Links to IFEX goals:

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

Mission Description:

The successful completion of this mission requires the use of both NOAA P-3 and G-IV aircraft. The P-3 aircraft will dispense AXBTs and GPS dropsondes and collect Doppler radar data while flying a rotating figure-4 pattern (see Fig. 1-4 for an example) in the inner-core with leg lengths of ~50-100 nm 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 ~15-20 nm to provide adequate coverage for deducing the radial variations in kinematic and thermodynamic storm properties. The G-IV should fly the environmental pattern shown in Fig. 10-1 at an altitude of ~ 42-45 K ft dispensing dropsondes at radii of 120, 180, and 240 nm 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. 10-1 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.

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 in the inner-core while the G-IV simultaneously flies the environmental surveillance pattern shown in Fig. 10-1 every 12 h. However, if one of the 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.

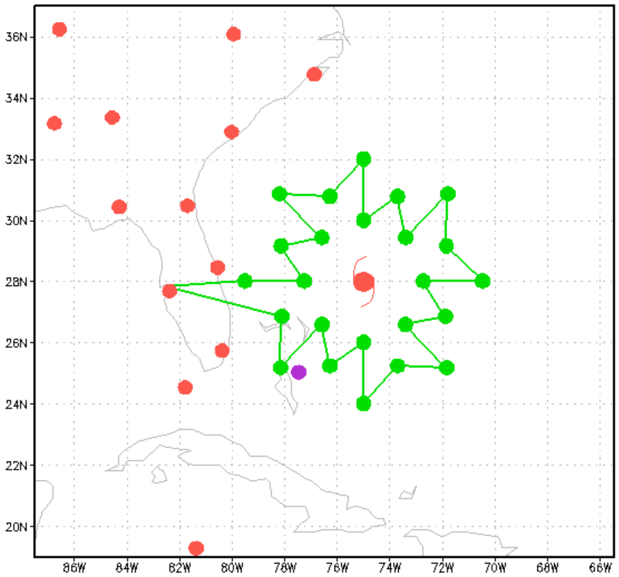
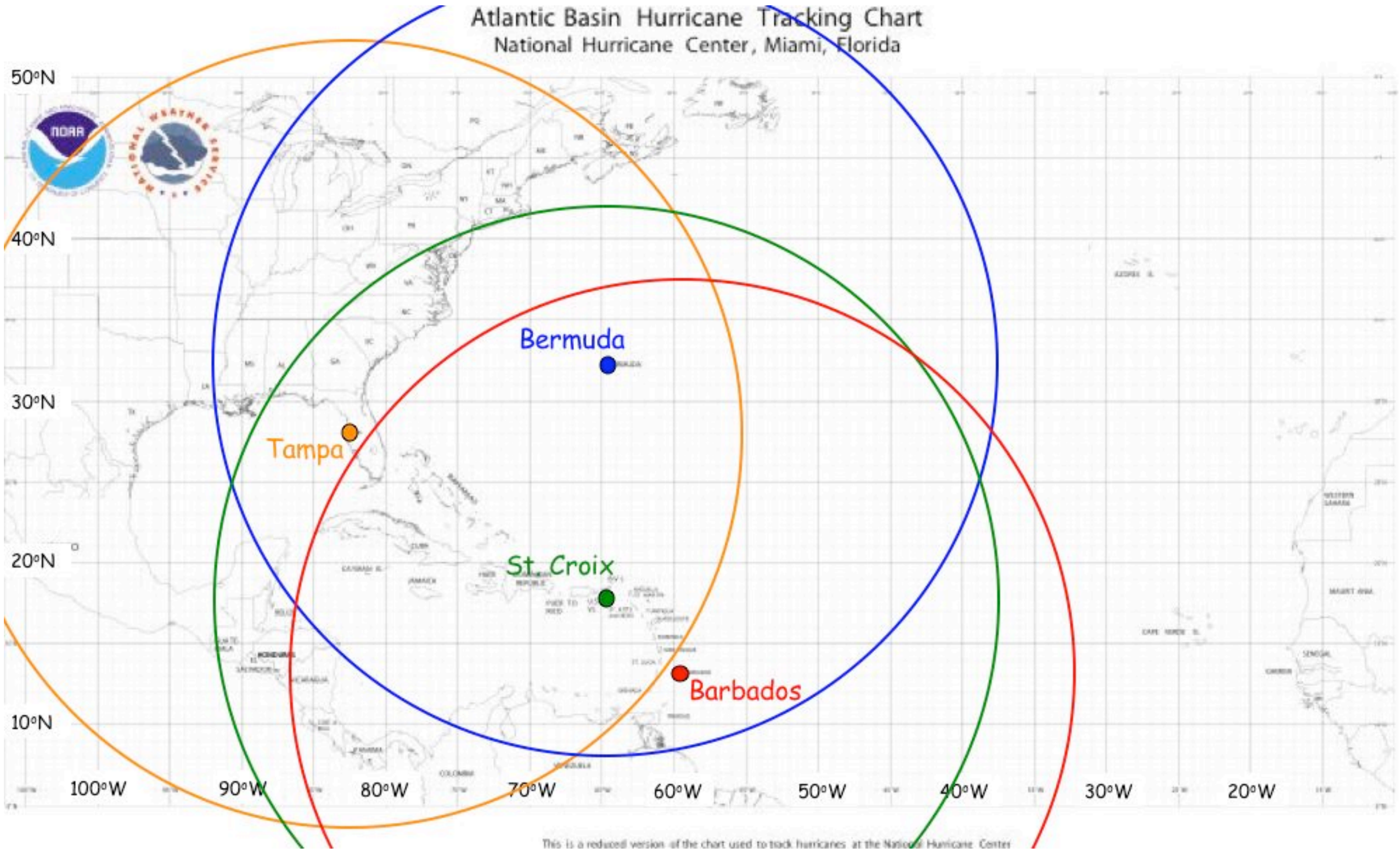


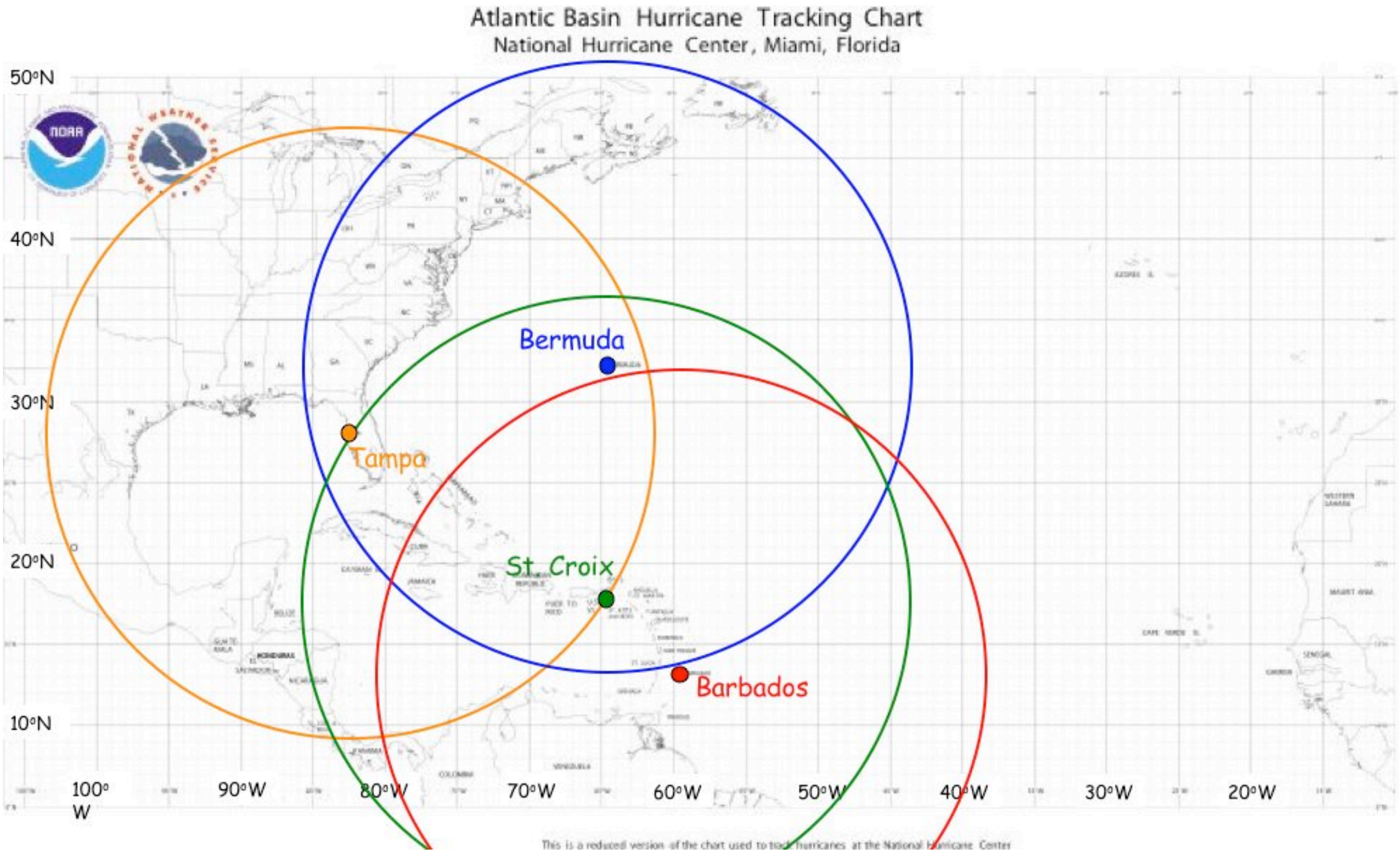
Figure 10-1: A sample G-IV flight pattern for the RAPX mission. The green dots denote the desired dropsonde locations at 120, 180, and 240 nm radius from the storm center. Note that the end points of each leg can be rounded slightly as required for aircraft flight considerations.

Supplemental: Operational Base Maps



Map 1: Primary Atlantic operating bases and approximate operating ranges for the NOAA G-IV.

Supplemental: Operational Base Maps (continued)



Map 2: Primary Atlantic operating bases and approximate operating ranges for the NOAA P-3.