2004 HURRICANE FIELD PROGRAM PLAN

CBLAST
OCEAN WINDS

DEPARTMENT OF THE NAVY ONR Science & Technology

AOML/HURRICANE RESEARCH DIVISION

2004 Hurricane Field Program Plan

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

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Cover:
Top Panel: eyewall of Hurricane Olivia on September 24, 1994 taken by P. Black from a NOAA WP-3D aircraft. Superimposed are photos of the NOAA aircraft and logos of organizations responsible for the sponsorship and execution of the Hurricane Field Program.

Bottom Panel: Photo of the sea-surface and eyewall cloud base of Hurricane Gilbert on September 13, 1988 by M. Black from a WP-3D aircraft at 10,000 ft altitude. Logos of some of the collaborators involved in CBLAST are superimposed on the photo.

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INTRODUCTION

The objective of the National Oceanic and Atmospheric Administration (NOAA) hurricane research field program is the collection of data that are required to support analytical and theoretical hurricane studies. These studies are designed to improve the understanding of the structure and behavior of hurricanes. The ultimate purpose is to develop improved methods for hurricane prediction.

Two major experiments have been planned by principal investigators at the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML) of NOAA for the 2004 Hurricane Field Program: Coupled Boundary Layer Air-Sea Transfer and Tropical Cyclone – Midlatitude Interaction experiments. In addition five other experiments are listed that might be flown if the opportunity arises. These experiments will be conducted with the NOAA/Aircraft Operations Center (AOC) WP-3D N43RF and Gulfstream IV-SP aircraft. Simultaneously, NESDIS will be conducting the Ocean Winds experiment with the second WP-3D, N42RF. In most cases the two WP-3D will fly coordinated patterns.

(1) Coupled Boundary Layer Air-Sea Transfer (CBLAST) Experiment This experiment is a *multi-option*, *single or dual aircraft* experiment designed to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical cyclones where swell, sea spray and secondary boundary layer circulations play a significant role. The experiment is composed of single or dual aircraft modules to be flown on *two successive days*. This experiment seeks to improve our understanding of the physical processed at and near the air-sea interface with in-situ aircraft data, GPS-sondes, air-deployed drifting buoys, AXBTs, Scanning Radar Altimeter (SRA), Ku-band scatterometer/profiler (SCSCAT/KSCAT, stepped frequency microwave radiometer (SFMR) and airborne Doppler radar observations on the meso- and convective- scales. There is also an option to test some rainband structure flight patterns.

(2) Tropical Cyclone – Midlatitude Interaction Experiment: This *multi-option, multi-aircraft experiment* is designed to study the interactions between a TC and midlatitude baroclinic environment. Specific objectives are to identify the physical mechanisms associated with the asymmetric expansion of wind, cloud, precipitation, and ocean surface wave fields during the initial stage of extratropical transition. To examine the relative roles of the TC and midlatitude circulation, aircraft will be used to monitor the changes in TC structure and the interface between the TC and midlatitude circulation into which it is moving.

(3) Hurricane Air-Sea Interaction Experiment: This experiment is a *multi-option*, *single or dual aircraft* experiment designed to determine the contribution of pre-existing and storm-induced ocean features to changes in TC intensity and surface wind field structure. This experiment seeks to address this issue through single-level aircraft penetrations using GPS-sondes, flight-level data, air-deployed drifting buoys, AXBTs, Scanning Radar Altimeter (SRA), K-SCAT and C-SCAT scatterometer/profiler, stepped frequency microwave radiometer (SFMR) and airborne Doppler radar observations on the synoptic, storm, and core scales. It will focus particularly on both thermodynamic and wind field transformations in the boundary and lateral interactions between the TC and its synoptic-scale environment.

(4) Tropical Cyclone Wind Fields Near Landfall: This experiment is a *multi-option*, *single-aircraft* experiment designed to study the changes in TC near surface wind structure near and after landfall. An accurate description of the TC surface wind field near and after landfall in real-time is important for warning, preparedness, and recovery efforts. HRD is developing a real-time surface wind analysis system to aid the TPC/NHC in the preparation of warnings and advisories in TCs. The analyses could reduce uncertainties in the size of hurricane warning areas. Flight-level and Doppler wind data collected by a NOAA WP-3D will be transmitted to TPC/NHC where they could result in improved real-time and post-storm analyses. Doppler data collected near a WSR-88D would yield a time series of three-dimensional wind analyses showing the evolution of the inner core of TCs near and after landfall.

(5) Hurricane Synoptic Surveillance: Hurricane Synoptic Surveillance: Since the arrival of the NOAA Gulfstream IV-SP high-altitude jet (G-IV) in 1997, the Hurricane Synoptic Flow Experiment has made the transition from a research program to operations. The missions seek to obtain accurate, high-density wind and thermodynamic data sets from the environment of tropical cyclones that are within 72 h of potential landfall in the mainland United States, Hawaii, Puerto Rico and the Virgin Islands. GPS-based dropwindsondes deployed from the G-IV provide these data over the normally data-void oceanic regions in objectively or subjectively derived target regions. Mandatory and significant level GPS-sonde data, transmitted in real time, are assimilated into numerical guidance at the Environmental Modeling Center (EMC) for use in preparing official forecasts at the Tropical Prediction Center/National Hurricane Center (TPC/NHC). In research mode, these data help improve targeting techniques, allow for study of the influence of synoptic-scale fields on track and intensity, and in studies of large-scale features such as the Saharan Air Layer.

(6) Saharan Air Layer Experiment: This is a multi-option, single aircraft experiment which uses GPS dropwindsondes launched from the NOAA WP-3D aircraft flying at ~500 mb to examine the thermodynamic structure and characteristic strong low-level wind surge of the Saharan Air Layer (SAL) and its potential impact on tropical cyclone genesis and intensity change. The GPS sonde drop points will be selected using information from the UW-CIMSS/HRD GOES SAL tracking product that can identify suspended dust silicates and dry lower tropospheric air that are characteristic of the SAL. The goal of this experiment is to better understand how the low-level wind surge, lower tropospheric dry air, and suspended mineral dust associated with the SAL affect Atlantic TC activity.

(7) Genesis Experiment*:* Thi*s multi-option, multi-aircraft experiment* is designed to study one of the most important unanswered questions in tropical meteorology: How does a tropical disturbance become a tropical depression with a closed surface circulation? This experiment seeks to answer the question through multilevel aircraft penetrations using dropsondes, flight-level data, and radar observations on the synoptic, meso, and convective spatial scales. It will focus particularly on both thermodynamic transformations in the mid-troposphere and lateral interactions between the disturbance and its synoptic-scale environment.

(8) NESDIS Ocean Winds and Rain Experiment: This *multi-option*, *single-aircraft mission* aims to improve understanding of microwave scatterometer retrievals of the ocean surface wind. The NOAA/ NESDIS Office of Research and Applications in conjunction with the University of Massachusetts' (UMASS) Microwave Remote Sensing Laboratory and the OMAO Aircraft Operations Center have been conducting flights as part of the Ocean Winds and Rain Experiment for the past several years. The Ocean Winds and Rain experiment is part of an ongoing field program whose goal is to further our understanding of microwave scatterometer retrievals of the ocean surface wind vector in high wind speed conditions and in the presence of rain for all wind speeds. This will 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.

OPERATIONS

1. Location

The primary base of operations for the NOAA aircraft will be Tampa, Florida, with provision for deployments to Bermuda, Barbados, Puerto Rico, and St. Croix for storms in the Atlantic basin (including the Atlantic Ocean and the Caribbean Sea).

The NOAA aircraft may deploy to U.S. coastal locations in the western Gulf of Mexico for suitable Gulf storms and to western Mexico for eastern Pacific storms. Occasionally, post mission recovery may be accomplished elsewhere.

2. Field Program Duration

The hurricane field research program will be conducted from 5 August through 31 October 2004.

3. Research Mission Operations

The decision and notification process for hurricane research missions is shown, in flow chart form, in Fig. A-1 (Appendix A in part II of the HFP). The names of those who are to receive primary notification at each decision/ notification point shown in Fig. A-1 are in Tables A-1 and A-2 (Appendix A in part II of the HFP). Contacts are also maintained each weekday among the directors of HRD/AOML, TPC/NHC, and AOC to discuss the "storm outlook."

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 "fix" requirements are accepted, the research aircraft must follow the operational constraints described in section 7.

4. Task Force Configuration

One NOAA/AOC WP-3D aircraft (N43RF), equipped as shown in Table B (Appendix B in part II of the HFP), will be available for research operations throughout the 2004 Hurricane Field Program (on or about 6 August through 31 October). The G-IV jet aircraft will be used during the Synoptic-Flow Experiment.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of HRD's 2004 Hurricane Field Program Plan is the responsibility of the field program director and CBLAST Chief Scientist, who is, in turn, responsible 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 HRD 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-2.10 (Appendix B in part II of the HFP) list the NOAA scientific crewmembers needed to conduct the 2004 hurricane field experiments. Actual named assignments may be adjusted on a case-by-case basis. Operations in 2004 will include completion of detailed records by each scientific member while on the aircraft. General checklists of NOAA science-related functions are included in E.2 through E.6 (Appendix E in part II of the HFP).

5.3 Principal Duties of the Scientific Personnel

A list of primary duties for each NOAA scientific personnel position is given in D.1 through D.12 (Appendix-D in part II of the HFP).

5.4 HRD Communications

The HRD/Miami Ground Operations Center (MGOC) will operate from offices at AOML on Virginia Key (4301 Rickenbacker Causeway, Miami, Florida) or from TPC/NHC (11691 S.W. 17th Street, Miami, Florida).

During actual operations, the senior team leader of the MGOC, or his designee, can be reached by commercial telephone at (305) 221-4381 (HRD/TPC/NHC) or at (305) 361-4400 (HRD/AOML). At other times, an updated, automated telephone answering machine [(305) 221-3679] will be available at the MGOC. In addition, MGOC team leaders and the field program director can be contacted by calling their cellphones or pager (phone numbers available at a later date).

MGOC, operating from AOML or TPC/NHC, will serve as "communications central" for information and will provide interface with AOC, TPC/NHC, and CARCAH (Chief, Aerial Reconnaissance Coordinator, All Hurricanes). In the event of a deployment of aircraft and personnel for operations outside Miami, HRD's field program ground team manager will provide up-to-date crew and storm status and schedules through the field program director or the named experiment lead project scientist. HRD personnel who have completed a flight will provide information to MGOC, as required.

6. Data Management

All requests for NOAA data gathered during the 2004 Hurricane Field Program should be forwarded to: Director, Hurricane Research Division/AOML, 4301 Rickenbacker Causeway, Miami, Florida 33149.

7. Operational Constraints

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 flight at the designated pre-take-off or "show" time will remain inoperative or be left behind to insure meeting scheduled operational fix requirements.

8. Calibration of Aircraft Systems

Calibration of aircraft systems is described in Appendix B in part II part II of the HFP (en-route calibration). 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).

EXPERIMENTS

9. Coupled Boundary Layer Air-Sea Transfer (CBLAST) Experiment

Program significance: Our primary goal is to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical cyclones where swell, sea spray and secondary boundary layer circulations play a significant role. In so doing, we plan to develop improved parameterizations for air-sea flux processes used in hurricane numerical models that will lead to improved forecasting of hurricane intensity change.

An ongoing collaborative effort, called Ocean Winds, will be conducted simultaneously by NESDIS to validate satellite scatterometer measurements in high-wind, hurricane environments. This effort uses and sponsors some of the same instrumentation systems used by CBLAST, especially the airborne scatterometer and radiometer systems.

The Hurricane Component of the Office of Naval Research (ONR) Coupled Boundary Layer Air-Sea Transfer (CBLAST) Departmental Research Initiative aims to measure, analyze, understand, and parameterize the air-sea fluxes in the tropical cyclone environment. Unlike mid-latitude cyclones where baroclinic processes are important, tropical cyclones draw their energy supply from the ocean. Fluxes of sensible heat and water vapor enrich the immediate atmospheric boundary layer (ABL). The momentum flux destroys the gradient balance and creates the cross-isobaric inflow transports the warm and moist air into the tropical cyclone inner region or rainbands to fuel the convective release of latent. Thus, the inward transport and air-sea fluxes ultimately determine the conversion of atmospheric available potential energy into kinetic energy of the storm. The significant air-sea flux exchanges greatly modify the near surface ocean temperature and current by mixing and three-dimensional transport. Under stationary or slow-moving hurricanes, the induced sea-surface temperature (SST) decrease can reach several degrees and the induced current can extend to great depths. The altered oceanic state can then feed back to modify the behavior of the overlaying tropical cyclone; they are indeed the most interesting and complex natural laboratory for air-sea interaction study.

The air-sea interfacial boundary under high wind is not well defined, and physical processes there are not properly quantified. The ocean surface waves and swell are characterized by limited fetch in the strongly forced regime. High winds and strong vertical wind shear mechanically form ocean spray, which is found to have significant effect on the thermal structure of ABL and may play an important role in hurricane thermodynamics, dynamics and intensity change. The ocean mixed layer is filled with air bubbles that can affect the air-sea exchange. This forms the basis for microwave and acoustic remote sensing of surface wind stress and allows inference of the surface wind. Standard boundary layer parameterizations, based on observations mostly taken at wind speeds below 20 m s^{-1} (39 kt), have not been validated for tropical cyclone conditions and highly disturbed sea states. Observation, understanding, and, eventually, the modeling of the structure and physical processes in the coupled hurricane-ocean boundary layer are the main objectives of the CBLAST Hurricane Component.

The research effort in the CBLAST Hurricane Component consists of re-examination of existing observations of hurricane-ocean boundary layer, wave conditions, and hurricane energetics. The effort also includes limited sensor development and calibration, and a refinement of observing strategies.

The objective of the work during the 2004 hurricane season is to conduct detailed measurements of the hurricane boundary layer, air-sea interface and ocean mixed layer using coincident airborne in-situ and remote sensing measurements, together with air-deployed drifting buoys and floats from AFRC WC-130J or other contract aircraft. The airborne turbulence measurements will be conducted with the two NOAA WP-3Ds, equipped with the Friehe radome-mounted gust probe. The lower WP-3D will also fly the NOAA/Field Research Division BAT (Best Atmospheric Turbulence) probe mounted on the nose-boom for direct measurement methods of momentum, heat and moisture fluxes via eddy correlation. Complementary vapor flux measurements will be provided by the NOAA/OAR, University of Miami/RSMAS LICOR vapor flux package and the NOAA/AOC TDL fast response hygrometer. Other instrumentation systems include the UMASS, HRD and AOC Stepped Frequency Microwave Radiometers (SFMRs) for bulk surface wind and rain estimation, University of Massachusetts (UMASS) IWRAP system consisting of range-gated CSCAT/KSCAT scatterometers operating alternately in scatterometer and Doppler mode for simultaneous surface wind and boundary layer wind profile retrieval with a range resolution of 15-30 m. A new particle spectrometer will be used to measure spray droplet size distribution down to flight levels of 200 ft (60 m) in the rain-free, high-wind ABL. Spray flux measurements will be obtained from the University of Washington/ Applied Physics Lab Particle Density Analyzer (PDA).

The surface-wind measurements will be supplemented with GOES, QUIKSCAT, TRMM, RADARSAT, TOPEX, ERS2 satellite observations.

The GPS-sondes and AXBTs will be deployed to obtain vertical soundings of atmospheric and oceanic structure along the flight path. TOPEX/POSEIDON satellite altimetry will be utilized to analyze ocean heat content changes during hurricane passage. An additional set of GPS-sondes will be densely deployed in the inner high-wind core regions of developed hurricanes to infer surface fluxes and momentum and enthalpy based on the budget technique of Hawkins and Rubsam. The NASA airborne Scanning Radar Altimeter (SRA) will provide measurements of wave topography in all quadrants of hurricanes over open water. Directional wave and swell spectra will be deduced in real-time during the field experiment from SRA wave topography. A Scripps laser altimeter will be utilized to measure one-dimensional wave spectra between rainbands in order to estimate the high-frequency portion of the ocean wave field not resolved by the SRA. A Scripps MASS high speed visual and infrared wave-following camera system will be utilized to document wave breaking processes and generation of foam and spray.

In addition to AXBTs, neutrally buoyant, Lagrangian floats from the University of Washington/APL will be deployed by AFRC WC-130J aircraft to measure three-dimensional mean ocean currents and large eddy turbulence properties in the upper ocean. Wave spectra and momentum fluxes will be obtained from these Lagrangian floats as well as measurements of surface wind speed and rain rate by ambient noise. Modified ARGO/SOLO floats from Scripps, to also be deployed, will carry additional sensors to measure surface wave heights, wave breaking, heat fluxes, rainfall, wind-speed, and thermal-salinity structure of the upper ocean. In addition an array of Scripps SVP and mini-met drifting buoys will be deployed ahead of the hurricane to obtain ocean temperature observations to 100m, surface current and surface wind, air temperature and sea temperature observations. The detailed planning of logistics and coordination of aircraft operations necessary for the multi-sensor, simultaneous, hurricane-ocean measurement program to be successful, will be conducted at HRD/AOML. The CBLAST hurricane field measurements will be complemented in experimental design and cross validation with the modeling component of CBLAST.

The CBLAST hurricane field experiment will be coordinated with the USWRP Hurricane Landfall Program. The CBLAST field measurements are closely coordinated with complementary studies sponsored by other federal agencies. NESDIS is supporting an Ocean Winds project to validate satellite scatterometer algorithms at high wind speed that will make use of UMASS remote sensing equipment developed in part by CBLAST. NESDIS is also supporting the testing of new, high-speed aircraft-satellite communication links. NASA is supporting an investigation of the structure of secondary circulations in the hurricane atmospheric boundary layer that are revealed in SAR imagery from RADARSAT, ERS-2 and other satellites. Testing of real time Doppler radar transmission to the Environmental Modeling Center will also be carried out.

Long-Term Objective: Our ultimate goal and prime motivation for this work is to improve the accuracy of hurricane intensity and intensity change prediction.

Short-Term Objectives: This work intends to use airborne platforms to develop new surface wave-dependent flux parameterizations for the high wind hurricane ABL containing secondary (roll-vortex) circulations over fetch limited seas in the presence of sea spray, one or more swell components and ocean boundary layer secondary (Langmuir) circulations. We propose to test the following hypotheses:

1. that surface momentum exchange coefficients increase with wind speed for moderate winds (>30 m s^{-1} or 58 kt), are enhanced by fetch-limited waves or opposing swell, but level off or decrease above a high wind threshold (>45 m s^{-1} or 87 kt), especially in quadrants where swell has a significant downwind component,
2. that compensating mechanisms for enhanced surface air-sea enthalpy fluxes over and above current parameterizations must exist for storm maintenance and growth above some high-wind threshold wind speed, and
3. that candidate physical mechanisms are separable and can be estimated, such as (a) enhanced turbulent fluxes due to wave interactions, (b) spray evaporation and (c) secondary flow circulations (roll-vortex type) in the ABL.

NESDIS Ocean Winds and Rain Experiment: This experiment aims to improve understanding of microwave scatterometer retrievals of the ocean surface wind. The NOAA/ NESDIS/ Office of Research and Applications in conjunction with the University of Massachusetts' (UMASS) Microwave Remote Sensing Laboratory and the OMAO/Aircraft Operations Center have been conducting flights as part of the Ocean Winds and Rain Experiment for the past several years. The Ocean Winds and Rain experiment is part of an ongoing field program whose goal is to further our understanding of microwave scatterometer 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 Integrated Wind and Rain Airborne Profiler (IWRAP) and the Stepped Frequency Microwave Radiometer (USFMR), both designed and built by UMASS, are the critical sensors for these experiments. IWRAP 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 IWRAP are essential in unraveling the effects of precipitation on scatterometer wind retrievals.

A secondary objective of the NESDIS experiments 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. Remotely-sensed surface data can be extremely useful to the hurricane analysts at the Tropical Prediction Center as has been demonstrated with the quasi-operational use of the SFMR on the NOAA P-3s over the past several years. For this experiment a near real-time processing system for IWRAP and SFMR is setup on N42 and integrated with a 9600 baud satellite phone.

Mission Description:

This experiment requires a minimal category 2 hurricane (winds>43 m s-1 or 84 kt) containing an identifiable eyewall structure. The primary measurement philosophy of this experiment is to treat the two WP-3D aircraft as a single "super" airborne platform. All phases of the initial CBLAST test flights will rely on the two WP-3D's flying 'in trail', with one aircraft following the other at safe horizontal and vertical separation. Our approach is to conduct an initial survey pattern with high-density dropsonde sampling in the eyewall. This survey would be followed by several flight segments in at least two quadrants of a storm. These flight segments should cover as many as seven levels ranging from just above the top of the primary wind maximum, located just above the top of the ABL, to as close to the surface as is considered safe by the aircraft commander (in the range of 60-180 m or 200-500 ft).

The experiment is viewed as a two-day mission. Day one would consist of a survey pattern plus ABL modules at two wind radii in a selected storm sector. Day two would consist of an abbreviated survey, most likely a single radial leg followed by ABL modules at two wind radii in two storm sectors.

These two missions will be conducted in coordination with deployment of drifting buoys and subsurface floats ahead of the storm by a WC-130J weather aircraft operated by the Air force Reserve Command (AFRC) 53rd Weather Reconnaissance Squadron and a C-130J cargo aircraft operated by the 815 airlift squadron, both under the 403 Wing at Keesler AFB. These systems will be deployed over a target area normal to the forecast hurricane track, roughly 24-36 h in advance of the storm. The first two legs of the initial survey pattern on day one would be oriented to over-fly as many buoy and float positions as possible during the initial survey pattern. AXBTs would be deployed at buoy/float positions along the flight track in coordination with GPS-sonde deployments.

Pre-Storm Float and Buoy Deployment: The float and drift buoy deployments are expected to be done as follows in 2004:

Three days, or 72 hr, prior to launch, an IP is identified that is projected to be 120 nm ahead of the NHC 72 hour forecast storm position (near the 96 hr forecast position) and 120 nm right or 60 nm left of track, depending on where the operating base is relative to the storm. Revise the IP the next day when any deployment would have to take place (T0-48 hr). On the third day, finalize the IP to be at or just beyond the gale force wind radius in the clear normal to the forecast 24 hour position, or the nominal 120 nm ahead of the storm.

Define a leg length of 180 nm normal to the storm track with 4 drop points outbound from the IP at 60 nm spacing and 4 points along the inbound leg displaced 30 nm further along the storm track and staggered to be in between the outbound drop points. There would be 8 drop points all together.

We want to carry 8 SVP/minimet boxes, 4 Lagrangian boxes and 4 Argo/Solo boxes, in one flight if this is logistically feasible. Otherwise a second flight would need to be scheduled immediately after the first with a second crew. Two options are envisioned. In the first option (Fig. 1a), we would drop one SVP box (2 buoys inside), one Lagrangian box and one Argo box at each outbound drop point (points 1-4). Then on the inbound leg, we would drop only the 4 remaining SVP boxes at points 5-8. The second option will be required if the C-130 is unable to deploy three boxes at one point. Two possible patterns are shown in Fig 1b and 1c . In the pattern shown in 1b we would drop one SVP box (2 buoys inside) and one Lagrangian box at each drop point on the outbound leg. (points 1-4) Then on the inbound leg, we would drop one SVP box and one ARGO box at each drop point 5-8. In the pattern shown in 1c we would drop one SVP box (2 buoys inside) and one Lagrangian box at each drop point on the outbound leg. (points 1-4) Then on the inbound leg, we would drop one SVP box and one ARGO box at each drop point 5-8. We *require* the deployment of the 2 or 3 buoy types at each drop point within 10 miles of each other.

CBLAST Day 1:
In route to the survey pattern Initial Point (IP), or alternatively, on return to base from the end of the flight pattern, a series of calibration maneuvers will be executed by the WP-3D aircraft (N43RF) that are designed to ensure proper post-flight calibration of aircraft turbulence sensors. These maneuvers are described in the turbulence calibration module. It is anticipated that these maneuvers may require about 30 min of flight time. If done in route to the start of the survey pattern, which would be the first choice, then N42RF would then delay takeoff by 30 min to rendezvous together at the IP.

For the initial survey pattern, nominal constant radar altitude (RA) for N43RF for the first penetration is 5,000 ft (1.5 km. Conditions permitting, N43RF would then descend to 2,500 ft (750m) for the remainder of the flight. N42RF would fly at 7,000 ft (2.1 km). For category 4 or 5 storms with intense turbulence, constant pressure altitudes would be flown with N43RF flying at 8,000 ft (2.4 km) and N42RF flying at 12,000 ft (3.6 km). AFRC WC-130H reconnaissance aircraft would most likely be flying at 10,000 ft (3 km). N43RF would lead N42RF to ensure a clear vertical path for dropsondes and AXBTs.

The nominal short survey pattern will be a figure-4 pattern that is designed to be flown on two successive days (Figs. 2 and 3) in coordination with maximum radial distances for N43RF of XX nm (XXX km) and for N42RF of 119 nm (220 km). The pattern is designed to be flown in 2.5 h. Should the storm be close to a staging base, and more time is available for the survey, a three-legged long ‘butterfly’ pattern will be flown with maximum flight legs of 97 nm (180 km) for N43RF and 109 nm (200) km for N42RF, and requiring 4 h, as shown in Fig. 4.

The prime purpose of the survey pattern (Figs. 2 or 4) is to record data that will (1) allow the large scale structure of the storm to be analyzed, (2) allow bulk aerodynamic flux estimates to be computed using a variety of existing parameterizations and (3) to deploy sequences of GPS-sondes at short time intervals during eyewall penetration. Alignment of the pattern will depend on storm direction of motion, ABL shear orientation and distribution of pre-storm floats/buoys. We are proposing to use an 8-channel dropsonde receiving system on N42RF, where 8 GPS-sondes at 10-20 s intervals will be deployed following 4 GPS-sondes from N43RF to obtain a sequence of up to 12 GPS-sondes along four radial legs through the eyewall. Three AXBTs, at the beginning, middle and end of the 12-sonde sequence, will be deployed from N43RF. Four additional sondes and AXBTs will be deployed from N42RF at 27 nm (50 km) intervals for the outer portion of each flight leg. The primary purpose of this measurement strategy is to diagnose the surface drag and enthalpy exchange coefficients at high winds using budget methods developed at the Massachusetts Institute of Technology (MIT).

Along the final leg of the survey pattern on day one, two relatively clear areas between rainbands will be determined in the right-rear quadrant of the storm relative to the storm motion vector. Three sectors representative of differing wave/swell conditions have been defined: (1) the rear quadrant representative of steep growing waves, (2) the right and right-front quadrants representative of mature swell moving approximately with the wind, and (3) the left-front and left quadrants where the swell that is moving at approximate right angles to the wind. The right-rear quadrant is also characterized by maximum ocean mixed layer currents, current shears at the base of the mixed layer and minima in SST, which are factors that may influence surface fluxes. The right quadrant typically contains the strongest inflow and active outer band convection. The downshear left quadrant typically contains the strongest eyewall convection.

Upon exiting from the initial survey pattern, the two aircraft will then proceed to the closest selected rain-free sector of interest at the 34-50 kt wind radius. First, a radial boundary layer flight leg normal to the wind will be flown, the boundary layer *crosswind* module (Fig. 5), prior to the *alongwind* module (Fig.6). Alternatively, the combined *crosswind and alongwind* module could be flown (Fig. 7). The purpose of these observations is to identify the structure of ABL secondary circulations.

Following the first completed ABL flight module at the 34-50 kt (17-26 m s^{-1}) wind radii, the two aircraft would proceed to the second rain-free sector at a hurricane force wind radius of 64-80 kt (33-41 m s^{-1}) in the same sector and repeat the sequence. Once the second ABL pattern is completed on day one, the aircraft would return to base with the N43RF executing the calibration maneuvers if they had not been done on the inbound flight.

CBLAST Day 2:
On day two, following the in-route calibration maneuvers an initial radial leg will be flown, which will simply be a single leg of the survey pattern at an RA of 5,000 ft (750 m). The aircraft would again select a region free of convection in the right-front quadrant and repeat the ABL pattern at the two wind radii. Following the initial pair of ABL patterns, the aircraft would proceed to a second sector in the left or left-rear quadrant which is identified as clear of strong convection. The ABL sequence should then be repeated for the two wind radii. The aircraft would then return to base.

Boundary Layer multi-level modules:

The **crosswind module**, shown in Fig. 5, will consist of an out and back 5.5 min, 19 nm (35 km) leg (11 min, 38 nm (70 km) total) with N43RF flying 3500 ft (1.0 km) outbound and 2000 ft (600 m) inbound, while N42RF flies near the top of the ABL at 7,000 ft (2.1 km). N42RF will conduct a 5 sonde drop sequence on the outbound leg. AXBTs will be deployed from N42RF at the beginning, middle and end of the outbound radial flight leg, and 43 will deploy sonobuoys at the beginning and end of the first leg. 43 will then fly a stepped descent pattern, as shown in Fig.5, with cross-wind legs at 1,000 ft (300 m), 600 ft (180 m), 400 ft (120 m), and if possible at 200 ft (60 m). Each level will be limited to 7 min flight time, including the 180° turn and descent. Completion of the six levels will require 0.8 h flight time.

The **alongwind module**, shown in Fig. 6 , consists of roughly 27 nm (50 km) flight legs parallel to the wind, which will be about 6 min downwind and 9 min upwind in 34-50 kt (17-26 m s^{-1}) winds (5 min down wind, 11 min upwind in 64-80 kt (33-41 m s^{-1}) winds) at each level. N42RF will deploy 6 GPS sondes at 5.4 nm (10 km) intervals along the first flight leg from 7,000 ft (2.1 km). N43RF will commence its first leg at 3,500 ft (1 km). Flight legs will then be flown at 2,000 ft (600 m), 1,000 ft (300 m), 600 ft (180 m), 400 ft

(120 m)and if possible at 200 ft (60 m). Each level will be limited to 5-11 min flight time, including the 180° turn and descent. Completion of the six levels will require 1.0 h flight time.

The **combined alongwind and crosswind** module is shown in Fig. 7. In this case NOAA 43 will fly out-and-back alongwind and crosswind modules at 600 ft (180 m), 400 ft (120 m)and if possible at 200 ft (60 m). Each level would require 11 minutes crosswind, and 14 minutes up/ downwind, including turns, for a total of 1.2 h per module.

Ocean Winds module: This module (Fig. 8) consists of a series of pie-shaped wedges originating in the eye and extending outward to just beyond the eyewall and high wind inner core nominally 50 km (37 nm), and which rotate downwind with time. These pie slices will be concentrated in the high wind right and front quadrants of the storm and be flown with the two WP-3D aircraft flying 'in trail', maintaining sage lateral and vertical spacing.

Turbulence Calibration Module: For calibration of the BAT probe, this module should be executed on separate flights at the start and end of the CBLAST filed program. The following maneuvers are requested for turbulence sensor calibration:

- Pitch Up/Down maneuvers: One series, with pitch variations of ±8-10°, containing 10-20 complete sinusoids. Sinusoids in the series will have periods of roughly 5-6 s (the plane should actually react to this, i.e., change altitude).
- Dynamic sideslip: 1/2- to full-ball sideslips with 10-20 complete sinusoids. Series slow (5-6 s period).
- Steady-state Yaw: 1/2-ball, held for 10-15 s, full-ball held for 10-15 s, 1/2-ball, held for 10-15 seconds. Repeated on other side.

NOTE: above maneuvers should be done while trying to hold everything else constant (i.e. during side-slips and yaws, pilot should allow plane to lose altitude instead of increasing attack angle).

- 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'.
- Acceleration/Deceleration runs (AC/DC): Start at slowest possible flight speed, accelerate to fast flight speed, decreasing attack angle. Then decelerate to slow flight speed. Two runs.
- Wind box: Straight and level box, 2 min on each side, standard rate 90° turn on the corners.

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

Hurricane Rainband Modules

These modules test proposed flight patterns and data analysis plans with a NOAA P3 to prepare fully for a rainband experiment proposed for 2004 when the ELDORA system is incorporated into the plans. Our emphasis is on rainbands outside the eyewall . The testing accomplished in the first year should allow us to go in the field in 2004 with lested flight patterns. The deployment of aircraft will be done according to a set of generic flight modules:

i. The concentric eyewall module will use 1-2 aircraft to investigate an existing double eyewall structure.
ii. The single-aircraft rainband module will be flown by 1 aircraft, to investigate the principal rainband or another major rainband that appears likely to be interacting with the eyewall region of the storm.
iii. The dual-aircraft rainband module will investigate the principal rainband or another major rainband that appears likely to be interacting with the eyewall region of the storm.

These modules are designed so that they can be applied to whatever eyewall and rainband pattern is present when the aircraft arrive in the vicinity of a hurricane. Since the development of a concentric eyewall is a rare but important event, the highest priority will be given to flying the concentric eyewall module. The second highest priority will be the 2-aircraft band module, which will probably be the most common flight situation. The hypothesis is that the Stationary Band Complex (SBC), and the principal band in particular, constitute a stationary heat source whose structure varies from convective on its downshear end farthest from the eyewall to stratiform on its upshear end nearest the eyewall. One of our primary goals is to map the convective-stratiform variability along the principal band and other features of the SBC. The third priority is the single-aircraft module, which is the optimal pattern to achieve our objectives when only one aircraft is available.

The three flight modules can be executed either singularly or in combination In a storm with a concentric eyewall, the concentric eyewall pattern can be flown in combination with one of the rainband modules. Flown simultaneously, these modules would give the best indication of interaction between the eyewall and rainband region. The modules are robust enough that they can be adapted to whatever combination of aircraft and storm structure occurs. Any module should provide some useful information on the mesoscale structures and interactions affecting storm intensity changes. When the aircraft are on station, the plan is to "mix and match" the three flight modules according to which aircraft are in the air as well as the actual eyewall/rainband pattern. The NOAA aircraft have lower fuselage radars and are better prepared to direct multi-aircraft missions in hurricanes. Accordingly, one NOAA aircraft will always be designated as the lead aircraft and the lead scientist on that crew will use the lower fuselage radar to direct all the aircraft in real time.

All the modules require GPS-sondes, and lower fuselage and Doppler radars. In this study, dual-aircraft options require ~40 sondes (20 for each aircraft), single aircraft options require 20 sondes, and the rainband module requires 10-15 sondes. The next sections give detailed description of the modules.

Concentric eyewall module: This module will be flown only by the NOAA aircraft since it has the lower fuselage radar to guide the penetration of the eyewall To execute this module with the two NOAA aircraft, the planes will stagger their takeoffs. The first aircraft (AC1) will take off ~30-60 min before the second aircraft (AC2) and fly a figure-4 pattern at 3 km (10,000 ft) with 150 km (~80 nmi) legs to document the general reflectivity and wind structure of the storm (1-2-3-4 in Fig. 30). AC2 will fly 150 km (~180 nmi) legs at 4 km (~14,000 ft) and rendezvous near AC1 at point 4 (Fig. 30). GPS-sondes should be dropped inside and outside of the concentric rainband, and the tail Doppler radar should always scan in fore/aft scanning technique (F/AST). While it is preferred that both aircraft drop sondes and fly legs through the storm, it is essential that the two aircraft arrive at 4 at roughly the same time. To meet this requirement drops can be eliminated and legs can be shortened if necessary.

Single aircraft rainband module: For a single aircraft investigation of either the principal band or another outer rainband, a “figure-four” pattern with 150 km (~80 nmi) legs will be flown between 3 and 4 km (10,000-14,000 ft) to identify the overall structure of the storm and to choose a rainband for investigation. The Doppler radar should always scan in F/AST. Then a zigzag or sawtooth pattern (Fig. 9a) should be flown across the rainband of interest with GPS-sondes dropped on both sides of the band. At 9, the aircraft may fly downwind around the storm (flight option 1) or fly upwind to repeat the investigation of the rainband (flight option 2). In either case, GPS-sondes should be dropped along the flight track to gather information on the hurricane environment.

Dual-aircraft rainband module: This module uses two NOAA aircraft. AC1 will be at 3 km (10,000 ft) and begin its pattern inside the rainband (Fig. 9b). AC2 will continue to fly at 4 km (14,000 ft) and begin its segment of the pattern outside the rainband. At 5 the inside aircraft (AC1) will fly across the band to the outside, and AC2 will move to the inside. The aircraft will continue to switch from inside the band to outside the band while dropping sondes as seen in Fig. 9b until both aircraft have flown completely around the storm and arrive at 10. This pattern is designed to obtain kinematic and thermodynamic data inside and outside the band. Alternating which aircraft is inside the band assures that neither aircraft proceeds too far ahead of the other while traveling around the storm. It also allows flight level data to be gathered in the band itself. With careful coordination, insuring safety at all times, it may be possible to fly the band-crossing legs to create Doppler opportunities in several portions of the secondary eyewall.

CBLAST EXPERIMENT

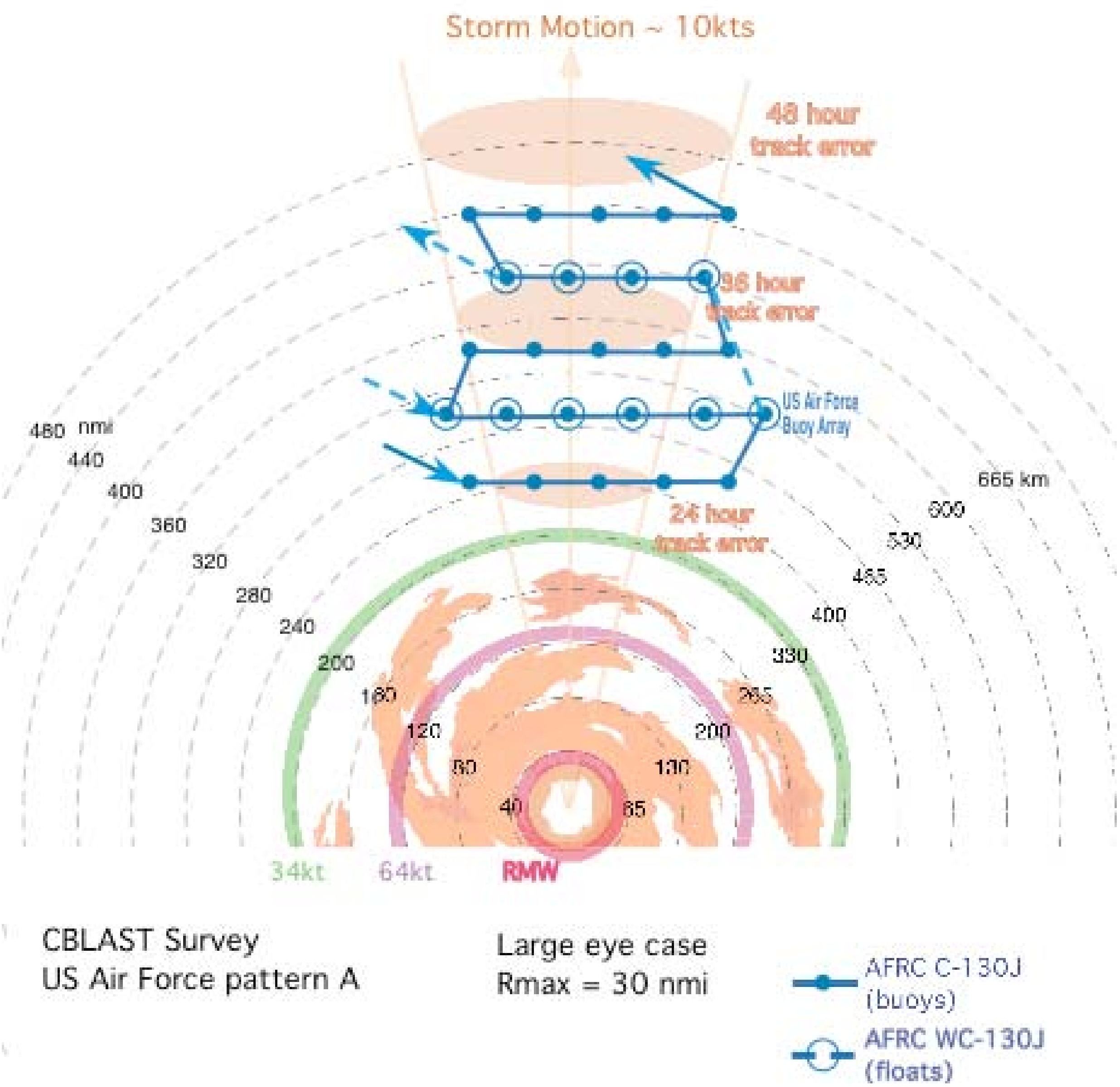


Figure 1a. Buoy drop pattern across forecast storm track relative to 34-kt and 64-kt winds and the RMW for a large storm. Flight pattern for WC-130J weather and command/ control aircraft deploying only CBLAST floats is shown together with C-130J ‘slick’ aircraft deploying only drifting buoys.

CBLAST EXPERIMENT

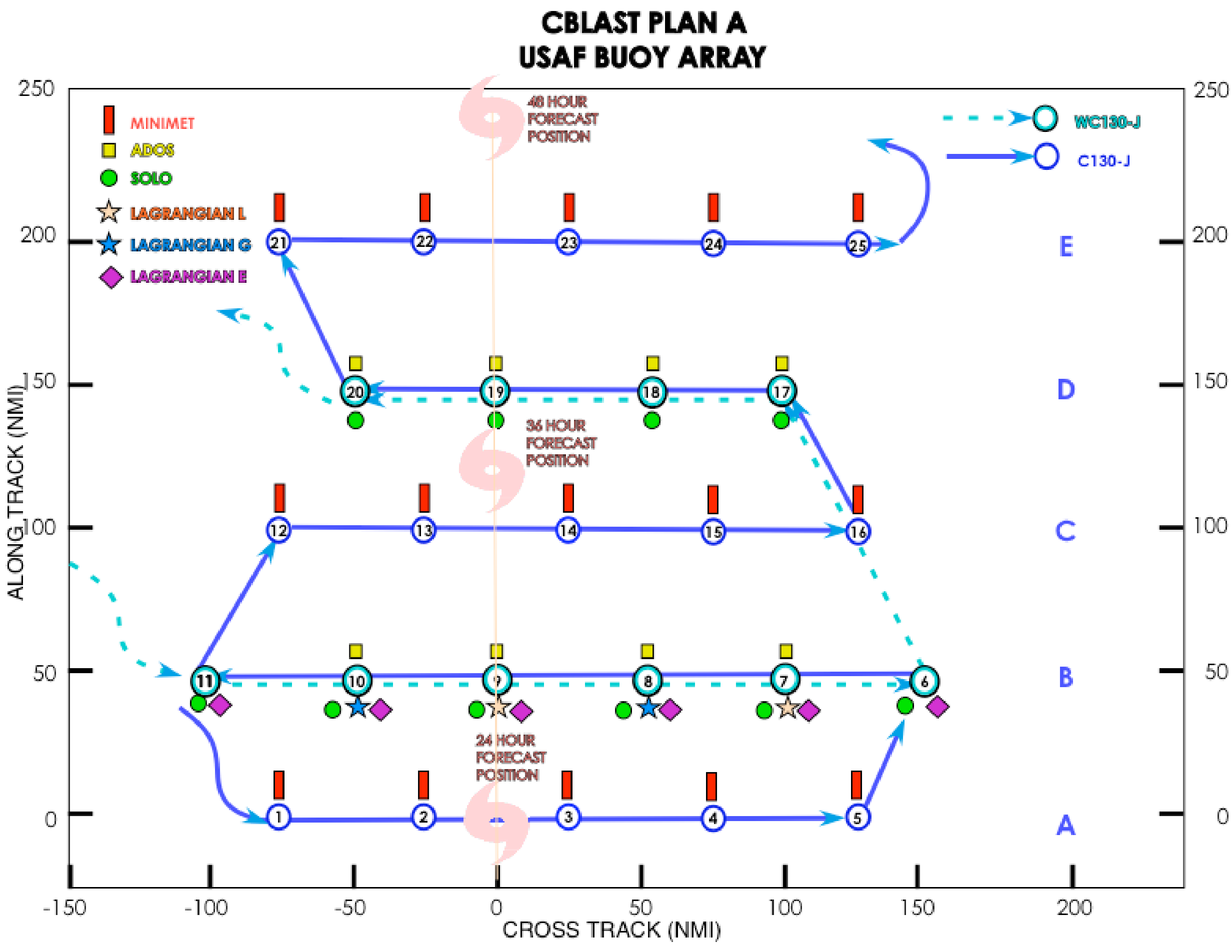


Figure 1b. Detail of buoy and float deployment drops. Grid points are labeled from 1-25 and lines identified as A through E.

CBLAST EXPERIMENT

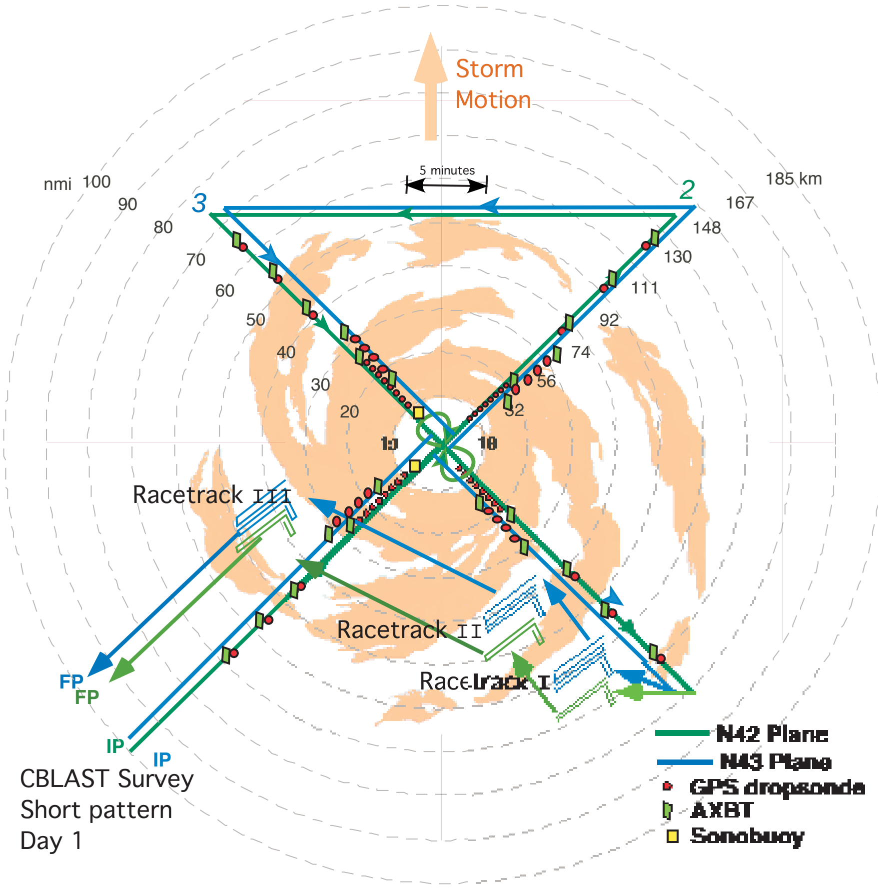


Fig. 2. CBLAST short pattern, Day 1.

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

CBLAST EXPERIMENT

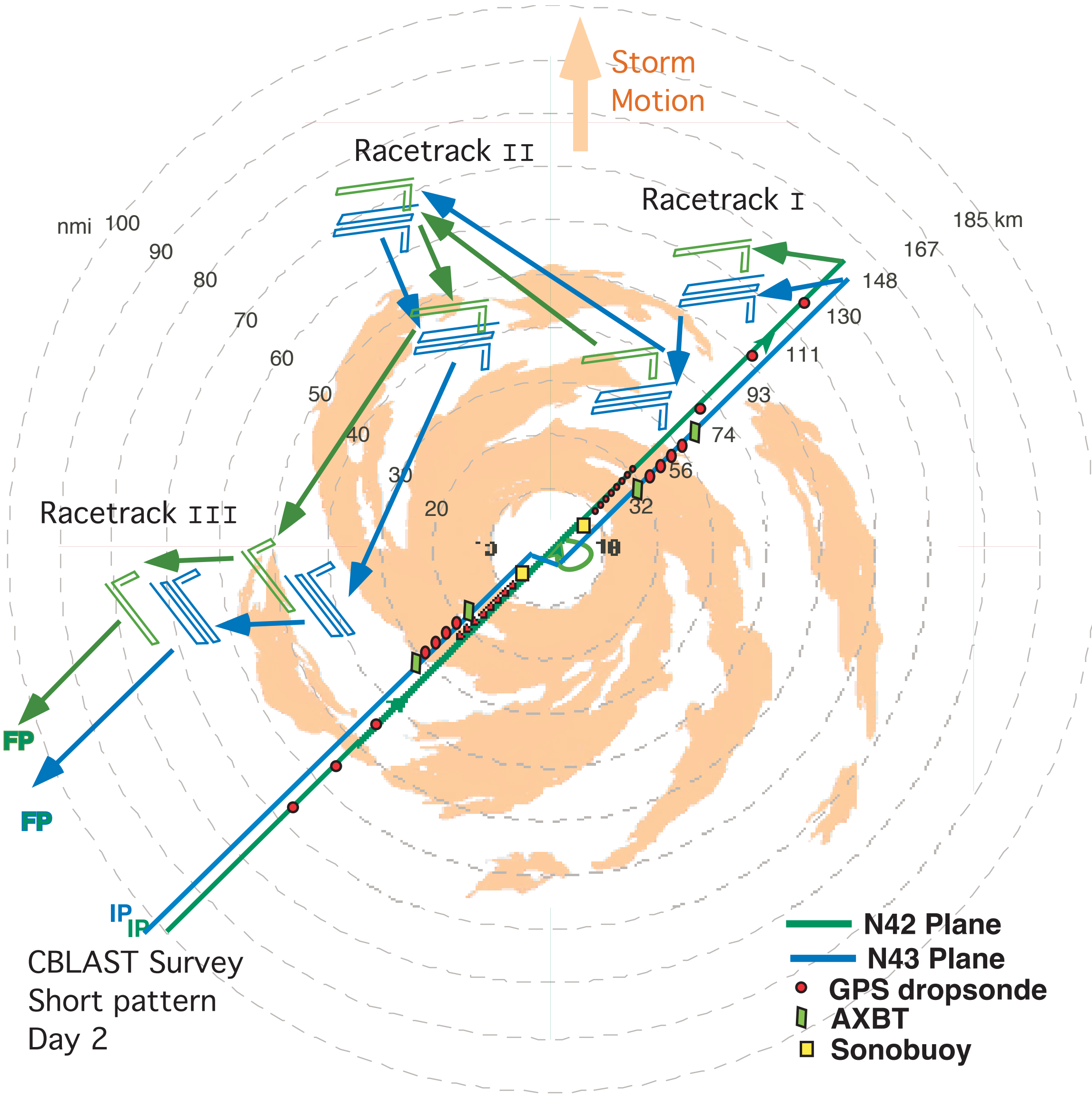


Fig. 3. CBLAST short pattern, Day 2.

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

CBLAST EXPERIMENT

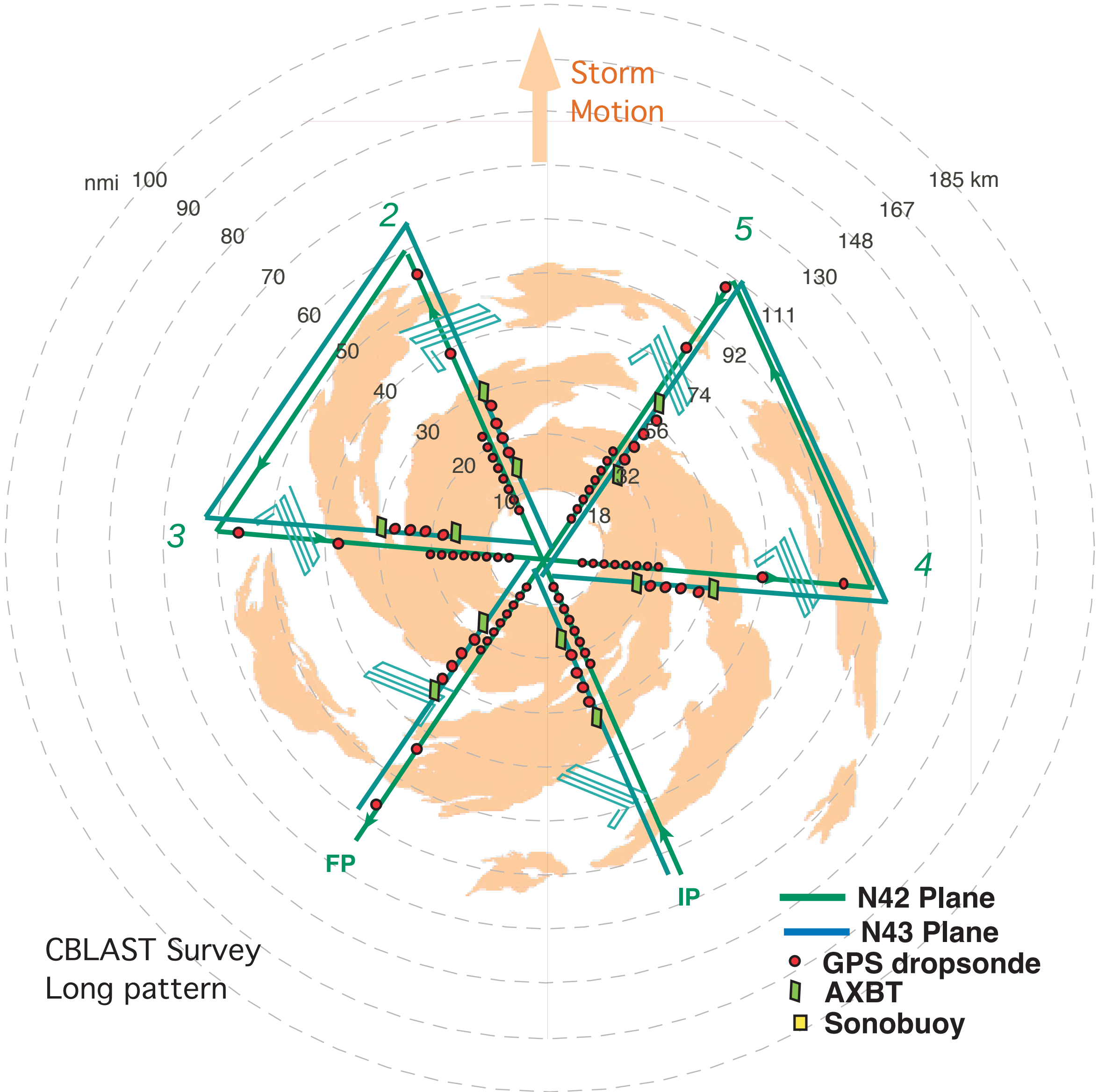


Figure 4. CBLAST long pattern.

• Note 1.	The pattern should be aligned 30° from storm heading. Preferred **IP** is in left-rear quadrant, but can be in any quadrant.
• Note 2.	The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
• Note 3.	Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 108 nm, and the **IP** for the lower WP-3D at a radius of 97 nm.
• Note 4.	The high WP-3D will commence a sequence of six eyewall drops on inbound legs at approximately 1.5RMAX or near the outer edge of the eyewall, ending at inner edge of eyewall. Reverse the sequence on the outbound legs.

CBLAST EXPERIMENT

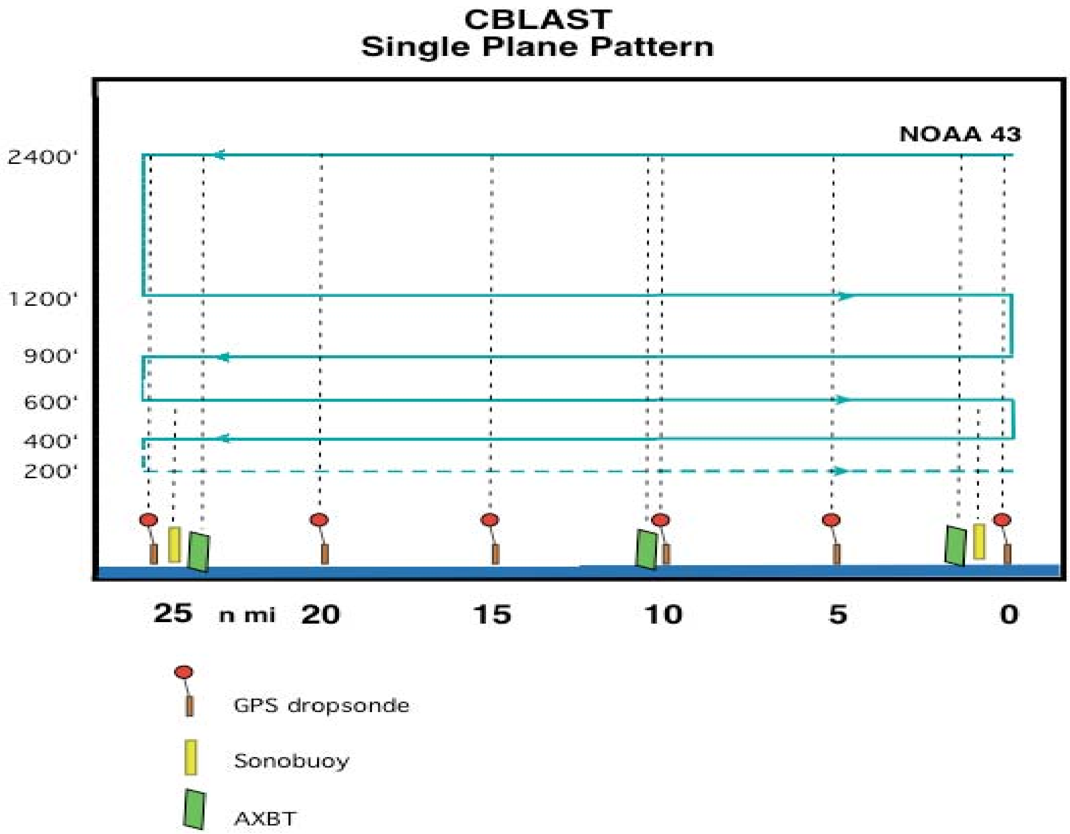


Figure 5 Single aircraft CBLAST stepped descent pattern (racetracks) in upwind-downwind or cross wind direction.

• Note 1. Each level will be limited to 7 min flight time, including the 180° turn and descent.

CBLAST EXPERIMENT

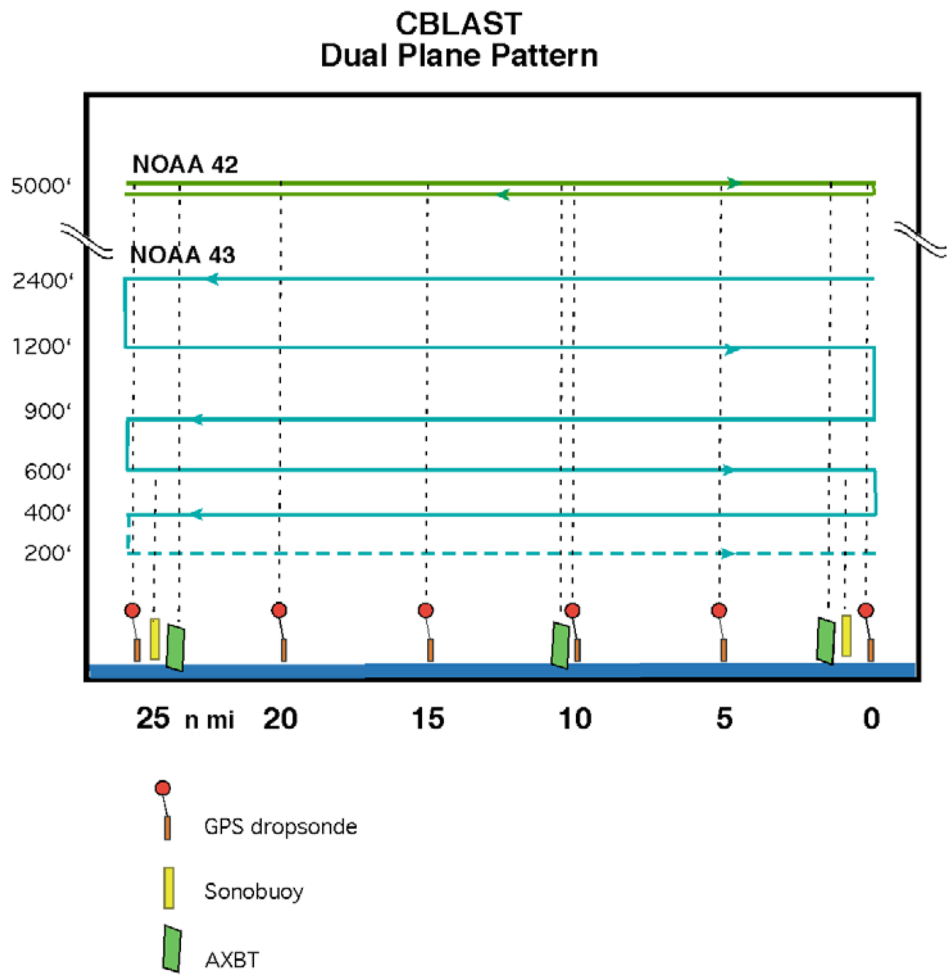


Figure 6. Dual- aircraft CBLAST stepped descent pattern (racetracks) in upwind / downwind direction.

• Note 1.	The high WP-3D flies at 7,000 ft deploying six sondes along the track of the low WP-3D for the first leg. The low WP-3D leads and orbits past the endpoint until the last sonde has splashed.
• Note 2.	A spiral descent is executed at the end of each leg.
• Note 3.	27 n mi legs will require 6 min downwind and 9 min upwind in 34-50 kt (17-26 m s^{-1}) winds (5 min down wind, 11 min upwind in 64-80 kt (33-41 m s^{-1}) winds).

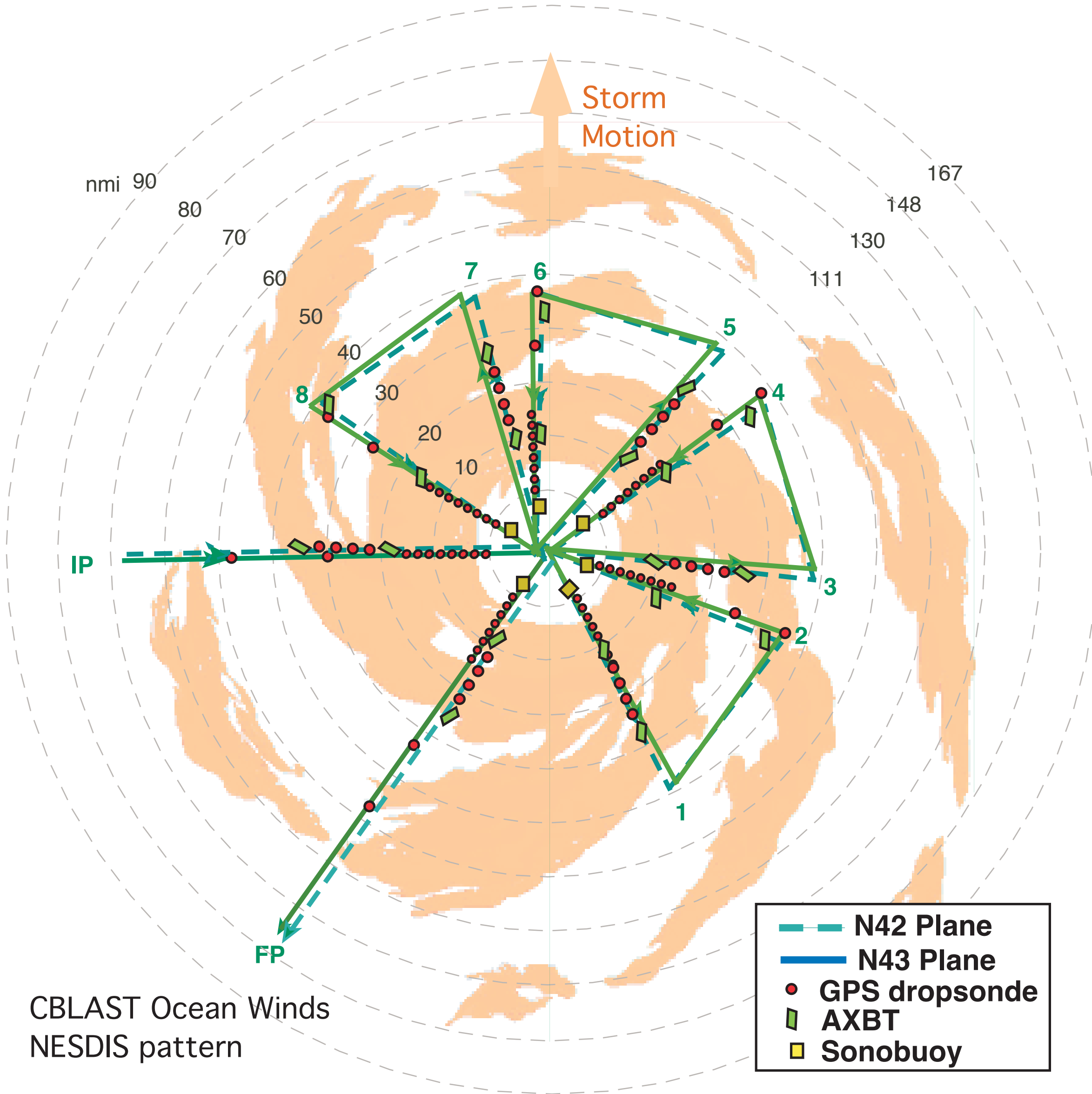


Figure 8. Ocean Winds Pattern

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

CBLAST Rainband module

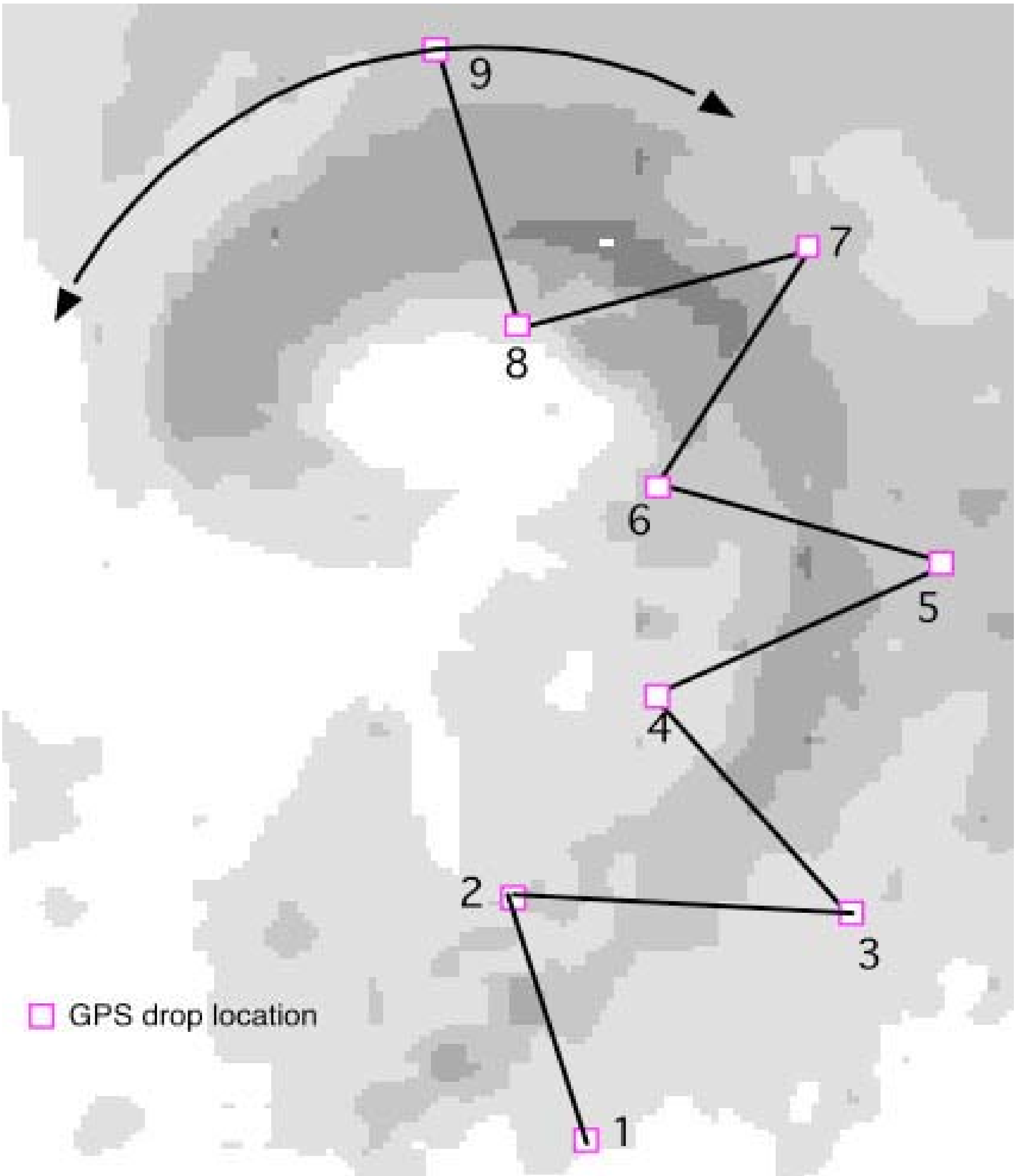


Figure 9a Rainband test pattern: Single Aircraft Option

• Note 1.	True airspeed calibration required.
• Note 2.	WP-3D Tail Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt

CBLAST Rainband module

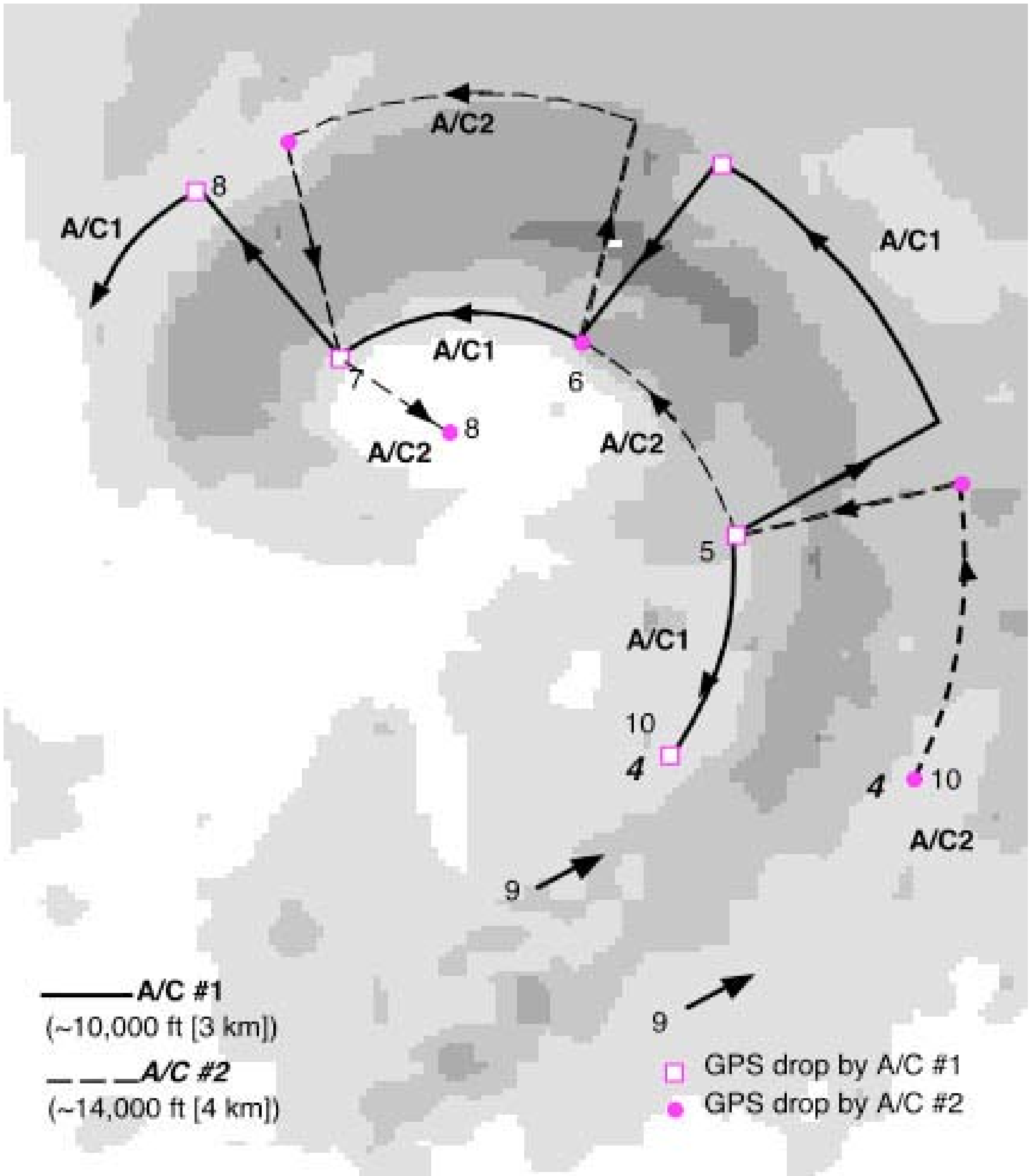


Figure 9b Rainband test pattern: Dual Aircraft Option

• Note 1.	True airspeed calibration required.
• Note 2.	Both aircraft should operate their Tail Doppler radars in F/AST mode at a single PRF ≥2400 and 20° tilt

10. Hurricane Air-Sea Interaction (ASI) Experiment

Program Significance: The importance of the ocean for tropical cyclone (TC) genesis and maintenance has been well-known for decades. Through air-sea interactive processes, the ocean provides the necessary energy required to establish and maintain deep convection. Recent studies conducted by Shay et al. (2000) and Bosart et al. (2000) showed that in some instances, warm upper-ocean features may act to significantly impact TC intensity. While findings from these case studies are significant, the results do not present a clear understanding of how (and to what extent) storm-to-storm variations in upper-ocean thermal structure directly impact changes in storm intensity.

However, recent (multi-storm) findings clearly depict a statistical linkage between upper ocean temperature change and subsequent Tropical Cyclone (TC) intensity change. For a 23-storm (1975-2003) sample, it was shown that the magnitude of SST change (high wind inner-core SST minus ambient SST ahead of the storm) was statistically linked to subsequent changes in TC intensity. Findings from this study also illustrate that relatively small changes in inner core SST can dramatically alter sea-air fluxes within the high wind storm environment. In fact, inner core SST change (or inaccurate representation of actual SST conditions) by as little as ±1.0° C can result in total enthalpy flux errors on the order of 40% or more.

These findings highlighted the importance of accurately (and routinely) documenting inner core SST change (relative to the ambient SST environment ahead of the storm) and provide the basis for the motivation for developing an HFP experiment designed to regularly and systematically document “SST change” for as many HFP hurricanes as possible in order to dramatically increase our storm sample size over a relatively short period of time. Research over the last two decades suggests that several environmental controls influence the change in TC intensity and structure, including wind shear, upper ocean heat potential and upper-tropospheric interactions. Also important are the internal physics of the vortex, including dynamic and thermodynamic characteristics.

The ASI experiment is designed to collect data from a single TC using two NOAA WP-3D aircraft, which involves capturing complete snapshots of a TC's structure, horizontally within 170 nm (300 km) of the center and vertically from the top of the boundary layer to at least 300 m below the ocean surface, for use in intensification studies. By combining NOAA's aircraft resources (two WP-3D and a supplemental G-IV) from the Hurricane Field Program, ASI provides a unique opportunity to obtain a thorough depiction of the storm and its environment through a coordinated interagency effort that employs a greater variety of instruments than is usually available during the Hurricane Field Program.

One of the primary atmospheric instruments utilized is the GPS-sonde. In this experiment, GPS-sondes are capable of being deployed from the ASI aircraft to measure pressure, temperature, relative humidity, and winds every 0.5 s as they descend (~5 m vertical resolution near the surface). Since their introduction in 1996, reliability has proven to be outstanding and observational accuracy is quite high; the average error is less than 0.5° C for temperature, within 10% for humidity, and 1-2 m s^{-1} for winds. Most notably, the probes have helped to document extremely fine thermodynamic and kinematic variations in vertical structure, particularly in the boundary layer, and have permitted highly accurate point measurements near the surface in turbulent conditions.

The ASI experiment will add context to the airborne Doppler observations often made in TCs. Recent studies using Doppler radar data collected by two WP-3D aircraft flying simultaneous orthogonal tracks have found that the wind structure in a TC can change drastically in as little as three hours. ASI experiment combines many dropsonde observations in the TC inner core and rainband regions out to 170 nm (300 km) from the center with Doppler radar observations within ~22 nm (40 km). The drops will be particularly dense immediately outside the Doppler coverage area but will be spaced farther apart at larger radial distances. This data distribution will help us to verify our present theories concerning both the interaction of the vortex with environmental shear and the modification of the vortex by upper-tropospheric interactions. The data may also be supplemented with other environmental observations within 540 nm (1000 km) of the center, including sondes dropped by the G-IV.

Of particular interest is to relate modifications of the TC wind and pressure fields to oceanic thermodynamic influences are accomplished in two general fashions. First, pre-existing ocean temperature and circulation features modify the fluxes at the air-sea boundary as the storm passes over them. Such features include permanent currents, such as the Gulf Stream and Gulf Loop Current; semi-permanent circulations, such as the Gulf of Mexico Warm Eddies; and transitory features, such as cold wakes from previous storms. Second, immediate modifications of SST and ocean mixed layer depth under the storm itself will affect the surface fluxes. To address these issues, the ASI patterns will be used to map upper oceanic thermal structure by deploying Airborne Expendable Bathythermographs (AXBTs) from N43RF and N42RF. To fully understand the ocean's impact on intensity, pre-storm, storm and post-storm missions are required.

In addition to the aircraft expendables, Lagrangian ocean mixed layer floats and surface drifters may be deployed during the pre-storm mission with the ocean grid in conjunction with CBLAST objectives. These profiling floats add turbulence measurements to the current, temperature and salinity fields and provide very high-resolution measurements within the Oceanic Mixed Layer (OML). These floats were deployed in Hurricane Dennis with reasonably good success.

It is important to separate other environmental influences from those of the ocean. Surface and tropospheric wind field measurements from instruments including the GPS-sondes, Doppler radar, the vertically-pointing Doppler wind profiler, Ku/C-band Scatterometer (Ku/CSCAT), and Stepped Frequency Microwave Radiometer (SFMR) out to several hundred km from the center will help achieve this. Finally, surface-wave observations will be made by a Scanning Radar Altimeter (SRA) to provide information on the distribution of low-frequency swell.

Rainbands and outer eyewalls are internal components of the TC that modify the thermodynamic characteristics of the boundary layer air flowing into the storm. Their circulations tend to suppress convection and the secondary circulation in the inner eyewall. They may also protect the inner eyewall from the full effect of environmental wind shear. The large number of GPS-sondes dropped both in the inner core and rainband regions should help to monitor the effects of rainbands and the degree to which surface fluxes are able to restore the warm moist properties of the inflow air modified by regions of storm-induced SST decreases. Additionally, the near-surface inflow will be determined from Doppler profiler, SFMR and Ku/CSCAT data collected along the flight tracks.

Goal: The long-term goal of this experiment is to improve our understanding of the mesoscale ocean processes in modifying the tropical cyclone intensity structure and wind field by the air-sea interactions. Main research themes are isolating physical effects such as vertical mixing, and horizontal advection on the upper ocean's three-dimensional heat, momentum and haline budgets, and the net effect of these processes on feedback to the atmospheric boundary layer as tropical cyclones encounter warm ocean features. A TC undergoing a period of rapid intensification or weakening will be a prime candidate. Combined with GPS-sonde observations from a simultaneous G-IV synoptic surveillance mission, observations of opportunity, and heat potential estimates from the satellite radar altimeters, a comprehensive snapshot of these mesoscale interactions will be obtained within ~170 nm (300 km) of the center.

Specific objectives are:

- To examine the relationship of environmental wind shear with TC structure, evolution, and intensity change;
- To examine the forcing by warm upper ocean features on enhanced surface stresses, fluxes and waves in the ABL.

These are the requirements for the ASI experiment:

- A hurricane category 1 or strong tropical storm within 540 nm (1000 km) of land, which is a threat to the U.S. coast, but is not expected to make landfall for 48-72 h.
- Both WP-3D aircraft must have operational tail and lower-fuselage radars, and be fully equipped to launch and monitor GPS-sondes, and AXBTs.
- Upper WP-3D (N43RF) must have working Doppler profiler, Ku/C-SCAT, and USFMR,
- Lower WP-3D, N43RF, (which will also be the pre-storm ocean survey aircraft) must have working SFMR, SRA, BAT probe or radome-mounted gust probe.
- If AFRC WC-130 operational reconnaissance missions are carried out concurrently, coordination will be required particularly if the WC-130 is deploying floats/drifters in the pre-storm mission..
- If available, profiling floats and drifting buoy platforms should be deployed by AFRC WC-130 aircraft prior or during the pre-storm ocean survey.

Mission Description:

ASI Track-Dependant SST-Change Experiment

This module is simple enough that it can also be used in most other HFP experiments as a one-plane, single mission module (as time and resources permit). The two basic components to the experiment are: (1) the "out ahead" module (Fig. 10); and (2) the inner core verification module (Figure 11). Depending on resources and flying opportunities, there are several possibilities that can be executed ranging from a single day one-plane mission (out ahead module only) to a three day mission that includes a one-plane "out ahead" mission on day one, a two-plane effort on day two (inner core verification with a concurrent out ahead module), and an inner core verification flight on day three. The two basic flight missions that make up this experiment are described. AXBTs and GPS dropwindsondes are all that are required. Assuming an average 220 kt airspeed, on-plane mission duration should range between 3.4 h (for the full "inner core" module) and 4.6 h (for the full "out ahead" module). Flight level is assumed 10,000 ft (3 km) unless stated otherwise. The "out ahead" module could be flown at lower altitude (i.e. likely 5,000 ft (1.5 km)) if necessary (weather permitting).In the ASI experiment, two to three aircraft provide simultaneous, coordinated observations of the TC. The aircraft involved are the two NOAA WP-3D as well as the NOAA G-IV during operational synoptic surveillance flights, which will provide most of the observations between 200 and 500 nm (300 and 800 km) from the storm center. The experiment consists of the pre-storm ocean survey and coordinated in-storm modules. Other optional modules are also presented here.

Ocean Feature Experiment:

Pre-Storm Survey Module: This module should be executed approximately 24-36 h prior to the storm module. The patterns shown in Fig. 12 and 13 correspond to full mission options designed to accurately measure the undisturbed structure of a (predetermined) asymmetric or a symmetric ocean feature, respectively, just prior to encountering the storm. A single WP-3D aircraft, i.e. N43RF, with AXBT launching capability maps the undisturbed ocean boundary and mixed layer structure of the ocean feature at least one day before TC/ocean feature interaction occurs. These patterns should be flown with the initial leg parallel to a TOPEX/Poseidon or Jason satellite altimeter ground track (±32° inclination from true north) if possible. A constant altitude of 5,000 ft (1,500 m) RA should be maintained throughout the mission. Doppler radar should be set to F/AST mode on all legs if there is any precipitation present. A single aircraft experiment in the TC inner core using the high level aircraft (N42RF) should ideally be conducted simultaneously with either of these options to measure internal storm structure prior to interaction.

A) **Asymmetric Ocean Feature Option:** This is best suited for an elongated or irregularly-shaped ocean feature, such as the Gulf Stream in the Atlantic or the Loop Current in the Gulf of Mexico. The "lawn mower" pattern (Fig. 12) consists of flying four 135 nm (250 km) transects, bisected by the feature's major orientation axis and spaced apart by 54 nm (100 km) intervals. Depending on the location of the grid, it may be spread out a bit more to encompass a wider swath to accommodate any track changes. These are followed by a return leg approximately 216 nm (400 km) aligned with the feature's major axis. 10 GPS-sondes and 50 AXBTs should be launched at regular intervals as shown in Fig. 12. The time on station needed to complete this option is about 5.5 h. Lagrangian ocean mixed layer floats should be deployed during this experiment from a separate aircraft over a broad enough region to insure that the storm will pass over them. Coordination with these float deployments is necessary at least 72 h in advance of possible storm flights.

B) Symmetric Ocean Feature Option: If the ocean feature is circular in shape, such as a Gulf of Mexico Warm Eddy, the pattern in Fig. 13 should be executed. This pattern has six radial legs (three inbound and three outbound), and two downwind legs (**2-3** and **4-5** in Fig. 1b3; all have nominal length of 108 nm (200 km) and are spaced 60° apart azimuthally. During each radial leg AXBTs will be launched at 11-14 nm (20-25 km) intervals beyond the feature center. A GPS-sonde will be dropped concurrently at 54 nm (100 km) and 108 nm (200 km) from the center. Another set of simultaneous GPS-sonde and AXBT probes will be launched at the midpoint of the two downwind legs. An AXBT will be launched at 13.5 nm (25 km) from the center on each radial leg, and a GPS-sonde will be dropped in the center during the second pass. AXBTs will be deployed at 40 nm (70 km), 60 nm (120 km), and 90 nm (170 km) from the center during each radial leg; as well as at 30 nm (50 km) and 80 nm (150 km) from the center. The time on station needed to complete this option is about 5.5 h.

Primary Storm Survey Module: The CBLAST in storm flight pattern described in the previous section will be the flight pattern for this module.

ASI Experiment

SST CHANGE AHEAD OF THE STORM MODULE

(Single Plane Mission)

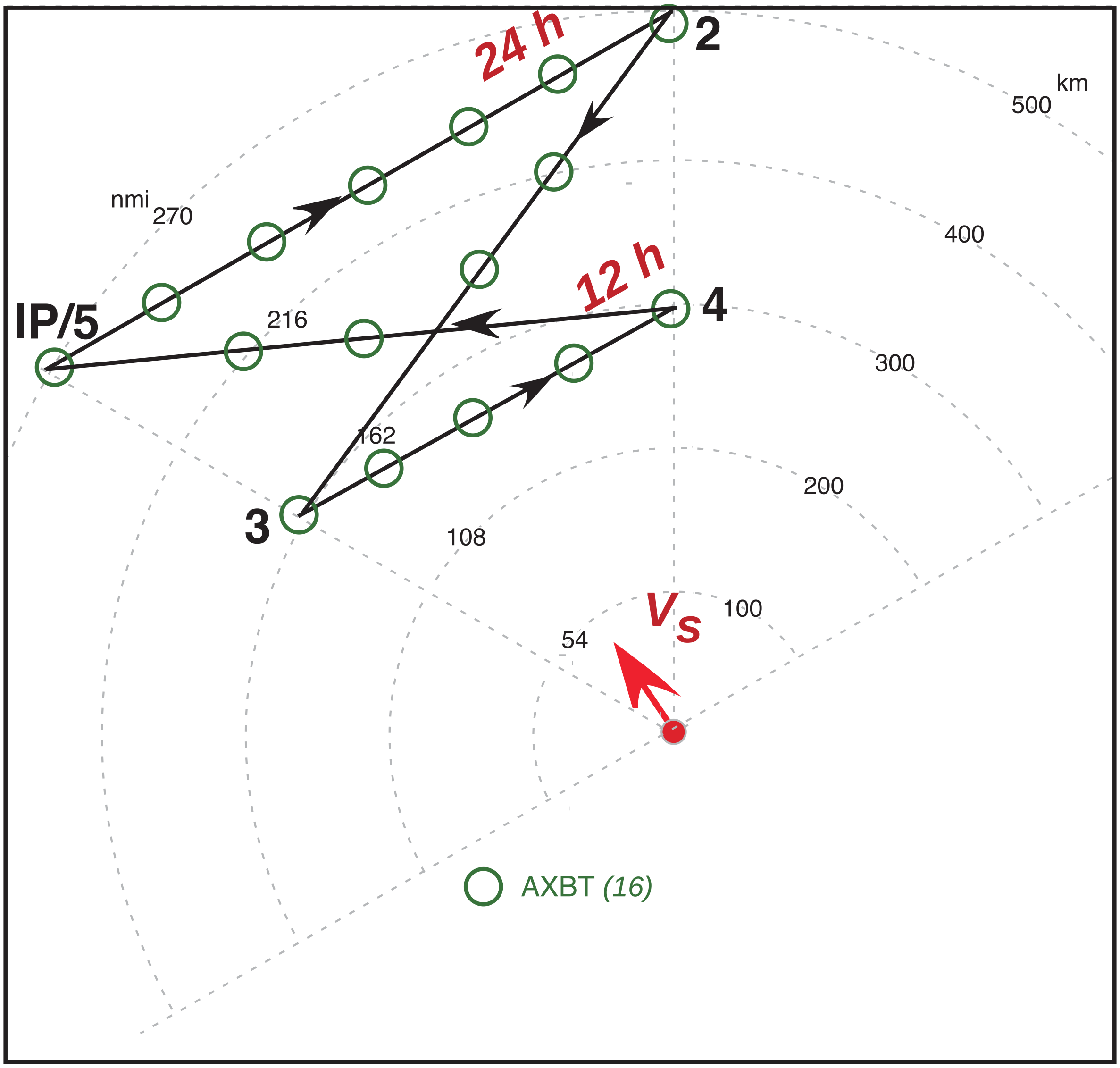


Fig. 10 ASI module ahead of projected storm track

• Note 1. GPS Sondes may be released with AXBTs, resources permitting.

AIR-SEA INTERACTION EXPERIMENT
SST CHANGE INNER-CORE VERIFICATION
(Single plane option)

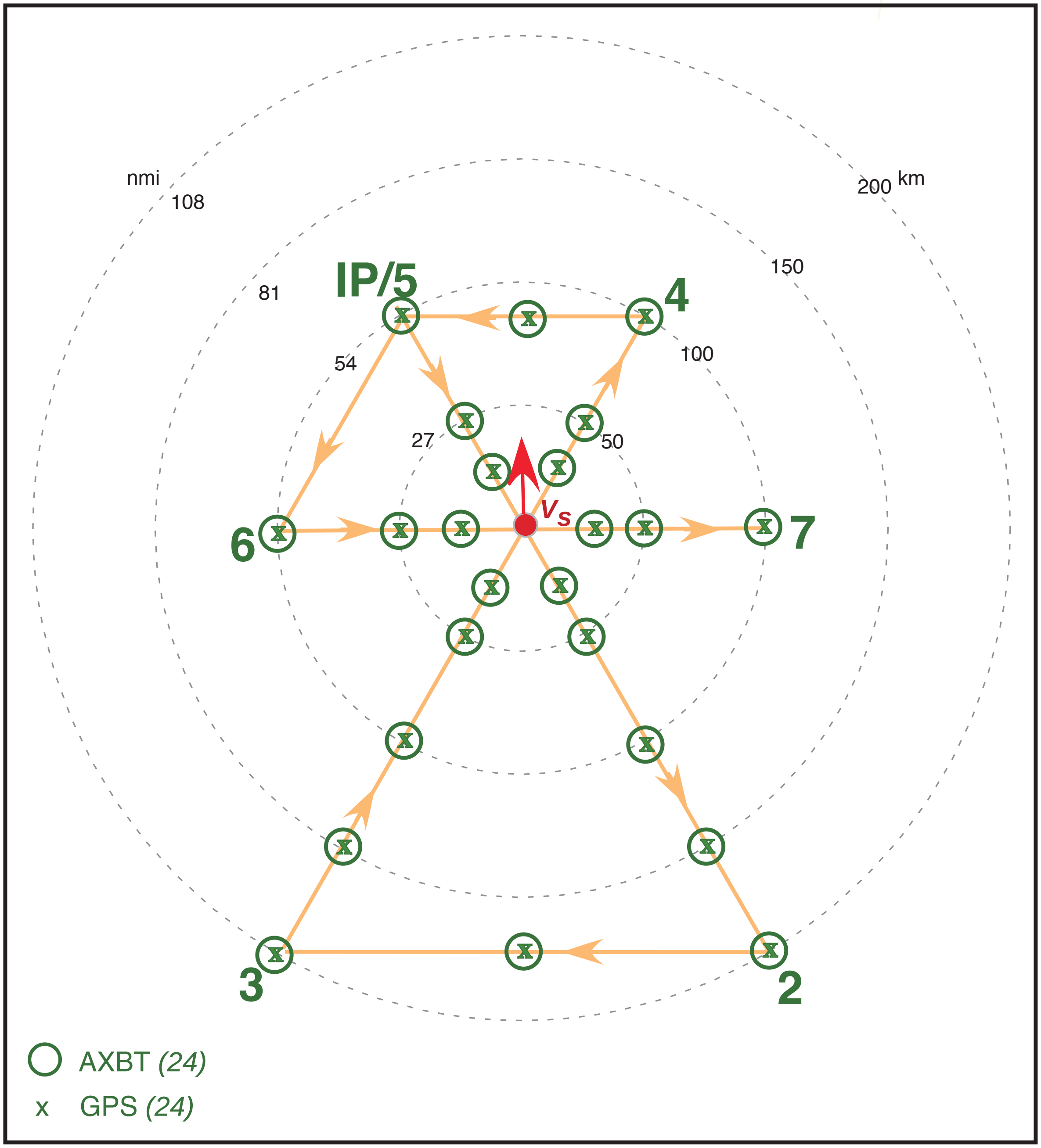


Fig. 11. Single plane in-storm module

• Note 1 . Pattern to be aligned with storm motion (arrow)

• Note 2 . Pattern may be flown IP-eye-3-2-eye-4-5-6-7 to avoid upwind leg in strong storms.

AIR-SEA INTERACTION EXPERIMENT

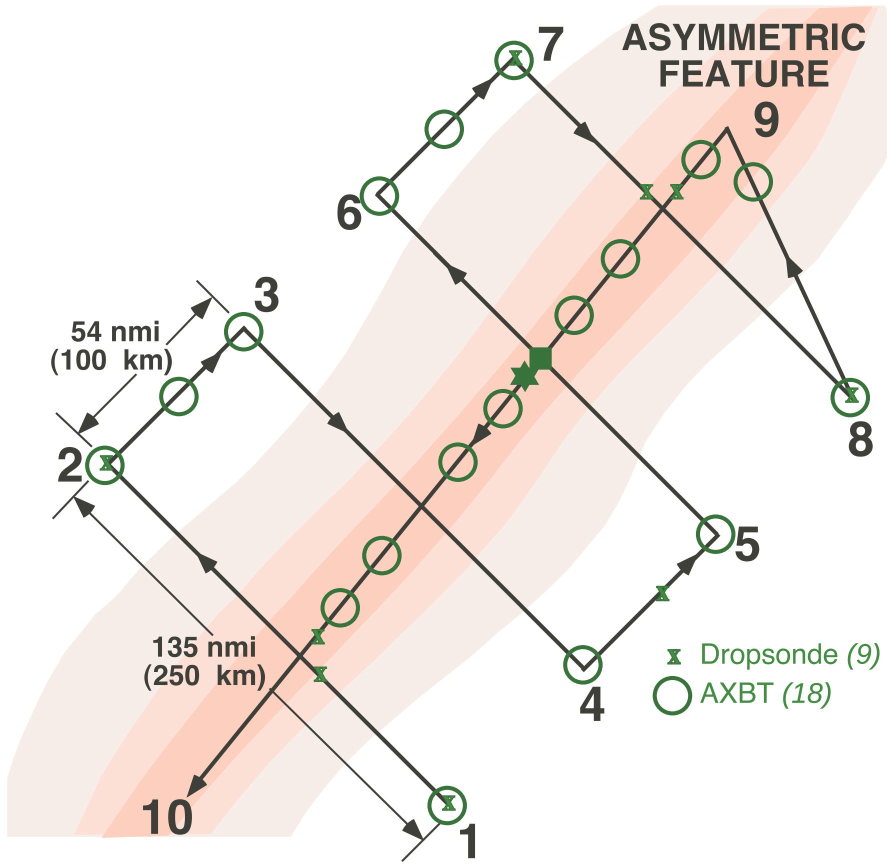


Fig. 12. Pre-storm Asymmetric Ocean Feature Survey Pattern

• Note 1.	Flight altitude should be 5,000 ft RA.
• Note 2.	Lagrangian ocean mixed layer floats should be deployed near the pre-storm ocean measurements from AFRC WC-130J aircraft.

AIR-SEA INTERACTION EXPERIMENT

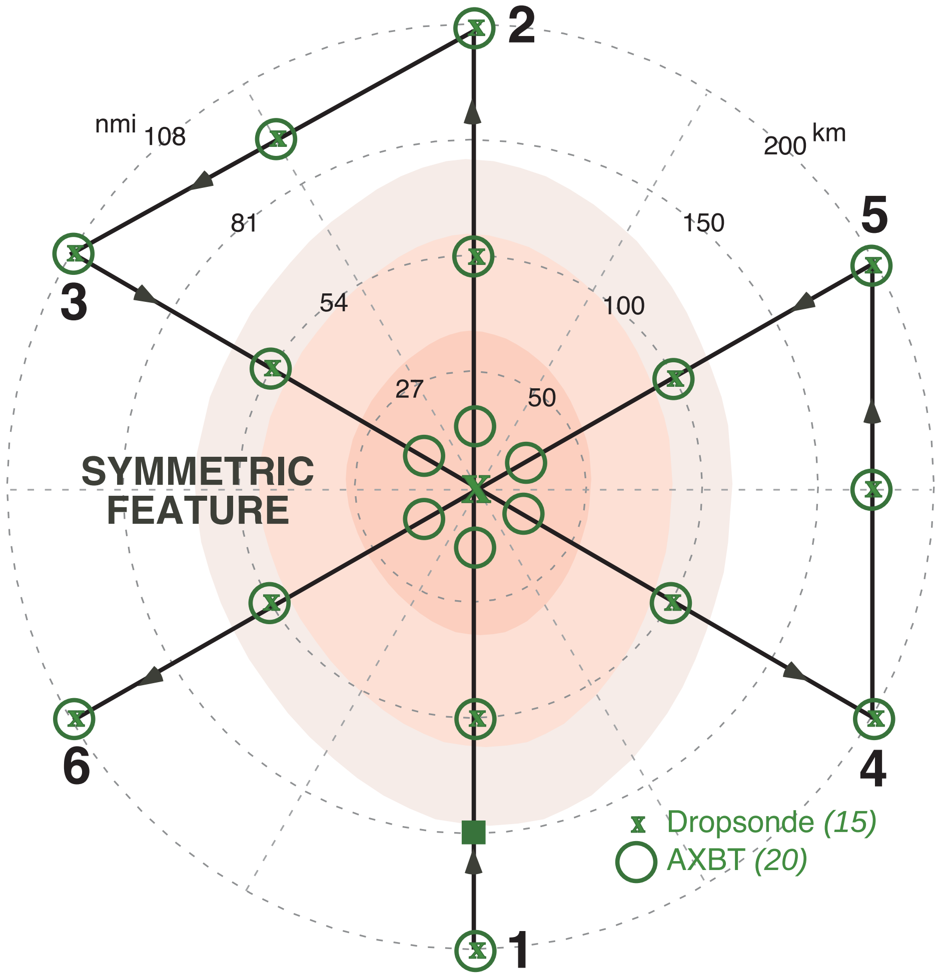


Fig. 13. Pre-storm Symmetric Ocean Feature Survey Pattern

• Note 1.	Flight altitude should be 5,000 ft RA

11. Tropical Cyclone Wind Fields at Landfall Experiment

Program Significance: An accurate real-time description of the TC surface wind field near and after landfall is important for warning, preparedness, and recovery efforts. 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 winds at the surface, evacuation lead-times, and the forecast of the storm's track. Research has helped reduce uncertainties in the track and landfall forecasts, but now there is an opportunity to improve the accuracy of the surface wind fields in TCs, especially near landfall.

HRD is developing a real-time surface wind analysis system to aid the TPC/NHC in the preparation of warnings and advisories in TCs. The real-time system was first tested in Hurricane Emily of 1993, and the system is now being evaluated by hurricane specialists at TPC for use in operational forecasts and warnings. The surface wind analyses should reduce uncertainties in the size of hurricane warning areas and are now used for post-storm damage assessment by emergency management officials. The surface wind analyses are also used to validate and calibrate an operational inland wind forecast model that HRD has developed under Federal Emergency Management Agency (FEMA) sponsorship. The operational storm surge model (SLOSH) could also be run in real-time with initial data from the surface wind analysis.

As a TC approaches the coast, surface marine wind observations are normally only available in real-time from National Data Buoy Center (NDBC) moored buoys, 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 Air Force Reserve aircraft flight-level winds are adjusted to estimate surface winds. These adjusted winds, 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 Hurricane Hugo's landfall in South Carolina and Hurricane Andrew's landfall 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 (1999), and Floyd (1999).

Dual-Doppler analysis provides a more complete description of the wind field in the inner core. While these techniques are still too computationally intensive for real-time wind analysis, the data are 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's environment. Another study used PDD data collected in Hurricane Hugo near landfall to compare the vertical variation of winds over water and land. The profiles showed that the strongest winds are often not measured directly by reconnaissance aircraft.

While collection of dual-Doppler radar data by aircraft alone requires two WP-3D aircraft flying in well-coordinated patterns, time series of dual-Doppler data sets have been collected by flying a single WP-3D 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 (WSR-88D) deployed by the National Weather Service (NWS), Department of Defense, and Federal Aviation Administration (Fig B-5 in the Appendix in part II of the HFP). Each radar archives (and will soon transmit in real-time) the base data (Archive Level II). In precipitation or severe weather mode the radars collect volume scans every 5-6 min.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

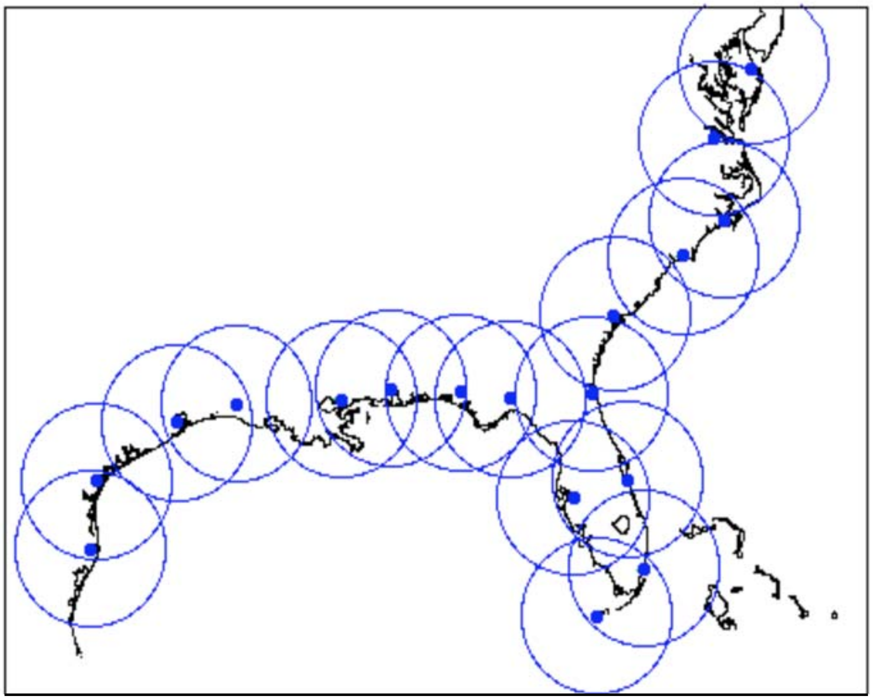


Fig. 14. The locations of the WSR–88D coastal radar sites. Range rings are at 125 nm (230 km) radius.

If a significant tropical cyclone moves within 215 nm (440 km) of the coast of the Eastern or Southern United States, then a WP-3D 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% forward and aft from the track during successive sweeps (the fore-aft canning mode: 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's inner core wind field and its evolution. The flight pattern for this experiment is designed to obtain dual-Doppler analyses at intervals of 10-20 min in the inner core. Unfortunately, these WSR-88D /aircraft dual-Doppler analyses will not be available in real-time, but the Doppler wind fields could be incorporated into post-storm surface wind analyses. The data set will also be useful for development and testing of TC algorithms for the WSR-88D. The Doppler data will be augmented by dropping GPS-sondes 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. GPS-sondes will also be dropped in the eyewall in different quadrants of the hurricane. To augment the inner 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%, sufficient for dual-Doppler synthesis of winds.

Recent GPS sondes dropped at and inside the flight-level radius of maximum winds (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 suggest 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. Careful observations during hurricane landfall could help document these changes, as well as help us better understand how the boundary layer adjusts at the coast in offshore flow. This could further help reduce uncertainties in reduction of flight level winds to surface (10 m) values in operational wind analyses of landfalling hurricanes.

Previous observational studies have shown that the primary mechanism responsible for the decay of TCs after landfall is the large reduction in latent and sensible heat fluxes. These post-landfall reductions in surface fluxes have been shown to be the result of decreases in land temperature beneath the storm. It also has been shown that these decreases in land temperature are due to the limited heat capacity of the soil subsurface. Several studies have also shown that the rate of TC decay after landfall is proportional to the landfall intensity and that the winds associated with landfalling TCs decrease rapidly within the first few kilometers of the coastline. However, the above findings have typically relied upon a relatively sparse observational network and/or compositing techniques that assume stationarity over a considerable length of time. Clearly, collecting high resolution landfall data sets against which the above findings can be verified is a worthwhile task, particularly in light of the substantial damage and loss of life that occurred in inland regions during Hurricanes Hugo (1989), Andrew (1992), Opal (1995), Fran (1996), and Floyd (1999).

There are outstanding questions on tropical cyclone rainbands and electrification that can be studied during a landfall mission. Spiral-shaped patterns of precipitation characterize radar and satellite images of tropical cyclones. The earliest radar observations of tropical cyclones detected these bands, which are typically 3-36 nm (5-50 km) wide and 55-160 nm (100-300 km) long. Nevertheless, many aspects of their formation, dynamics, and interaction with the symmetric vortex are still unresolved. The precipitation-free lanes between bands tend to be somewhat wider than the bands. The trailing-spiral shape of bands and lanes arises because the angular velocity of the vortex increases inward and distorts them into equiangular spirals. As the tropical cyclone becomes more intense, the inward ends of the bands approach the center less steeply approximating arcs of circles. A dynamical distinction exists between convective bands that spiral outward from the center and convective rings that encircle the center.

The lack of rainband observations leaves us to infer and assume critical elements of rainband structure that may be of fundamental importance to our understanding of the tropical cyclone. It seems clear that concentric eyewalls can affect hurricane intensity, and available evidence suggests that convectively-active non-concentric rainbands may play a role in the intensity changes in the hurricane core. It is extremely important that we understand the structure of rainbands and secondary eyewalls and how they may impact the hurricane environment. The rainband module is designed to address these issues by gathering kinematic data in and around hurricane rainbands. In addition, with the new GPS-sondes, it is possible to sample some of the thermodynamic aspects of the hurricane boundary layer. Our understanding of the fluxes at the top of either the mixed layer or the thicker inflow layer is not well known. There are no reliable measurements of the flux at the top of the inflow layer, nor are there reliable estimates of the depth of the inflow. This is despite the conclusions from budget studies and simple numerical models that identify the mixing at the top of these layers as a vital part of the hurricane circulation.

Recent analyses of an intense rainband in Hurricane Gilbert (1988) support the hypothesis that the fluxes at the top of the inflow layer are large and downward into the inflow layer. 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. There appeared to be regions in Gilbert where the inflow layer rapidly increased in $\theta_{e,}$ and other regions where the flux divergence of θ_e resulted in very slowly changing conditions. Rainband circulations have been implicated in this highly asymmetric input of energy into the storm's inflow layer. Strong rainbands like the one sampled in Gilbert are similar in circulation to an eyewall. We hypothesize that the eyewall circulation itself will have a profound affect on its own inflow, and may lead to a recycling of high $\theta_{e,}$ into the top of the inflow layer.

Neither the microphysical nor the electrical structure of TC clouds that exhibit lightning is known. Laboratory experiments have shown that more charge is separated when ice crystals collide with a rimed target in the presence of supercooled water than is separated without supercooled water. They also showed that the sign of the charge transferred reversed at about –20° C. Other laboratory experiments showed that the growing conditions encountered by the ice particles determined the sign of the charge that was transferred between them during collisions. Observations in continental thunderstorms support this hypothesis and suggest that charge separation occurs most rapidly on the boundary between the main updraft and the downdraft near –15° C. More recent observations showed that sublimating graupel acquire negative charge and graupel undergoing deposition acquire positive charge. As these processes depend critically upon the graupel temperature and cloud liquid water content, it is highly desirable to obtain suitable measurements in natural clouds.

In mature hurricanes, updraft velocities are usually low. In addition, graupel and ice particles are plentiful, but supercooled cloud water is rare in hurricanes at temperatures as warm as -5 C. Studies of two mature Atlantic hurricanes have shown that the little supercooled water present in the strongest eyewall updrafts was immediately adjacent to areas that contained high concentrations of small ice particles. When one considers the lack of supercooled water in mature hurricanes, it is not surprising that mature hurricanes are not always electrified. However, the National Lightning Detection Network (NLDN) detected lightning in several hurricanes and tropical storms as they approached land.

A recent investigation noted that there appeared to be a relationship between the occurrence of CG lightning in the eyewall and a subsequent intensification of the hurricane. A similar relationship was proposed by studies of lightning observations in two developing TCs. In each case, lightning was qualitatively associated with exceptionally strong convection, which occurred when the storms were rapidly intensifying. In addition, recent observational studies of CG lightning in TCs using data from the NLDN showed that CG lightning is most prevalent in the outer convective rainbands of hurricanes with little CG lightning near the eyewall. An apparent paradox is thus created as research shows that vertical velocities in rainbands are weaker than those in the eyewall. It is important to note, however, that rainbands >54 nm (100 km) outside of the eyewall remain virtually unsampled. Based upon the above findings, we hypothesize that supercooled water and charge separation occasionally occur in the strong convection in TCs. The recent additions of the four rotating vane field mills that measure the vector electric field and an induction ring that measures the charge on individual particles to the suite of instrumentation already on board the WP-3D aircraft will help to confirm or refute this hypothesis.

Objectives:

1. Collect flight level wind data and make surface wind estimates to improve real-time and post-storm surface wind analyses in hurricanes.
2. Collect airborne Doppler radar to combine with WSR-88D radar data in post-storm three-dimensional wind analyses.
3. Document thermodynamic and kinematic changes in the storm during and after landfall.
4. Determine the kinematic and thermodynamic characteristics inside (toward the eye) and outside of hurricane rainbands, including those that form convective rings.
5. Measure the characteristics of the middle troposphere and the hurricane boundary layer through utilization of GPS-sonde data.
6. Determine how different inflow trajectories that may pass over land, and warmer or cooler waters alter the energy content of the inflow.
7. Measure the sign and magnitude of the vector electric field near the eyewall and in an outer convective rainband.
8. Determine the polarity and magnitude of the charge on ice precipitation at several temperature levels above the melting level.
9. Estimate the transport of electrical charge in the storm.
10. Record the types and concentrations of all particle types observed in the electrically active portions of the storm.
11. Document changes in microphysics and rainfall characteristics in the storm during and after landfall.
12. Obtain a remote sensing database suitable for evaluation and improvement of satellite and ground validation rainfall estimation algorithms for landfalling TCs.

Mission Description:

This experiment is designed to be conducted by flying one or two single aircraft missions with a NOAA WP-3D aircraft 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 either the rainband , electrification , or post-landfall module. If the storm either moves parallel to the coastline or moves slowly inland and resources permit, the experiment may be repeated with a second flight. While the storm’s location relative to the coastline will dictate which combination of these modules will be ultimately flown, the real-time module will generally precede all of the other modules. In addition, the rainband and electrification modules will only be flown while the storm is still over water.

This mission requires that the aircraft have working lower fuselage and tail radars. The HRD workstation should be on board, so we can transmit GPS sonde and radar images back to TPC/NHC. Microphysical data should be collected, to compare rainfall rates with those used in the WSR-88D precipitation products. The SFMR should be operated, to provide estimates of wind speed at the surface. If the C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface winds. All efforts should be made to ensure that Level II data are recorded at the WSR-88D radars closest to landfall and the initial inland

If the portable Doppler radars (Doppler on Wheels DOW), portable profilers and portable wind towers are able to participate in the experiment then they should be deployed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. 13. 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 below (Fig. 15), 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.

The primary module of the experiment, the "real-time module", will support real-time and post-storm surface wind analyses. Two dual-Doppler options can be flown if the storm is near a WSR-88D radar. The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars.

Real-time module:
The real-time module combines passes over marine surface platforms with one or more figure four patterns in the core of the hurricane. The aircraft flies at or below 5,000 ft (1.5 km) (ideally at 2,500 ft [750 m]), so that flight level winds can be adjusted to 30 ft (10 m) to combine with measurements from marine surface platforms. Flight-level data and GPS-sondes dropped 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, or the rainband or electrification module could be flown.

The landfall flight pattern should take advantage of buoys or C-MAN sites nearby, if those platforms are expected to experience winds > 25 m/s.. 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. 15). 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. GPS-sondes would be dropped near the buoys or C-MAN sites, and additional sondes will be dropped at or just inside the flight level radius of maximum winds (RMW).

If the timing is such that the storm is farther off the coast than desired for landfall, then the aircraft can execute the Rainband Module (see Fig. 16 below) to map the thermodynamic structure of the inflow. The flight pattern should overfly any buoys or C-MAN sites that are in high wind regimes and include legs coordinated with a WSR-88D.

Dual-Doppler Option: If the TC moves within Doppler range of a coastal WSR-88D 125 nm (230 km), then we will fly a second module, to collect a time-series of dual-Doppler data from the storm's inner core. 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%.

The pattern will depend on the location of the storm relative to the coastal radar. Depending on safety and operational considerations, the aircraft could fly this portion of the experiment at a higher altitude, although 5,000 ft (1.5 km) would still be preferred. After completing the real-time module the aircraft flies to an initial point on the track intersecting the storm center and the coastal radar. The aircraft then makes several passes through the eyewall (A-B in Fig. 15). Depending on the size of the eyewall each pass should last 10-20 min. It is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage. After each pass the aircraft turns quickly and heads back along the same track, adjusted to keep the storm center and the coastal radar on the same line. In 2 h, 6-12 volume scans will be collected. The last pass should be followed by a pass through the eye perpendicular to the other legs, to provide data for dual Doppler analyses. If time permits, the real-time module could be repeated before returning home, or the coastal-survey, rainband, electrification, or post-landfall module could be flown.

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. On the first coastal pass the WP-3D would fly parallel 10-15 km offshore to obtain SFMR surface winds (1-2 in Fig. 16). 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. 16). 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 winds and drop GPS-sondes 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. 3-4 sondes would be dropped quite near the coast, followed by 3-4 sondes 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.

Rainband module:

The single aircraft rainband thermodynamic structure module has been designed to be flown with other experiments in "rainbands of opportunity" and last 30-60 min (Fig. 17a,b). The goal of the module is to gather data inside, outside, and across several rainbands of several storms over several seasons. While individual data sets will increase our understanding of the structure of rainbands, the primary objective here is to develop a database of rainband observations for future comprehensive study.

This module requires one WP-3D flying above the inflow layer (8,000 to 10,000 ft). The WP-3D deploys 6-8 GPS-sondes and an occasional AXBT along a curved track approximately 60 nm (100 km) long that roughly mimics the inflow trajectory for air in the subcloud and lower cloud layers. Deployment of the GPS-sondes occurs between the eyewall outer edge and the inner edge of any convective rainband found at greater radial distance. If there are no rainbands then sonde deployment may cease at approximately 60 nm (100 km) radial distance from the circulation center. Fig. 17a is a plan view of the experiment, Fig. 17b is a radius-height cross-section of the scheme. Note that shorter times between each GPS launch are preferred when the aircraft is near the eyewall. A sonde should also be deployed in the eye. A typical spiral path should be 20-40 from a tangent to a given radius. Flight time for 60 nm (100 km) is about 15-20 min.

GPS-sondes are deployed every 6-9 nm (10-15 km) starting from about 6 nm (10 km) from the outer edge of the eyewall to insure that the sonde falls outside of the main updraft and rain. After four sondes are in the air and the first sonde splashes down a new one may be deployed. The design assumes that 4 sondes may be in the air simultaneously and that the sonde descends at about 12 m s^{-1}.

A single spiral in or out will provide a view of how energy content changes along a trajectory for one portion of the storm. If several trajectories are sampled then energy content and cyclone intensity can be studied. Judicious choice of the inflow trajectories to be flown is made by the airborne mission scientist and would likely include sampling inflow from the southeast and from the northwest as shown in Fig. 17a.

Electrification Modules:

The aircraft must be equipped with the DRI electric field instruments in addition to the standard instrumentation. The PMS probes must be the best available, and the radars must be fully operational. The experiment is composed of three options. In all options, it is desirable to have 4 to 6 GPS-sondes to obtain soundings outside the convection in the inflow near the areas of interest.

Rainband option: If a convective outer rainband is available >80 nm (150 km) from the eye, it should first be surveyed for evidence of electric fields. The survey consists of flying along the band until the field mills register a space charge or the Doppler radar reveals the presence of vigorous convection. When an interesting area is located, the aircraft should either seek a clear area and climb to maximum altitude or descend to the 0 C (~16,000 ft [4.8 km]) altitude, whichever is closer, and start making passes downwind (Fig. 18a) through the middle of the band. Each downwind pass (Fig. 18a) should maintain a track along the axis of the band and be about 50 nm (93 km) long and 1,500 ft (500 m) higher (lower) than the previous one. During this portion of the pattern, the Doppler radar should make 360% scans normal to the aircraft track. After the downwind pass is completed, the aircraft should exit the band on the outer side, climb (descend), and return (Fig. 18a, 3-4) upwind to the start of the band. The Doppler data will be obtained on the upwind pass using the F/AST method. This pattern will require about 20 min to execute. Pass length may be altered as circumstances dictate. Repeat this pattern until the maximum altitude is reached, or seek a new area as desired. As an alternate, a zigzag path downwind through the convective band may be flown if necessary for flight safety.

Landfalling storm option: The purpose of this option is to investigate the relationship between cloud physics, vertical velocity, and the occurrence and location of CG lightning. Outer convective rainbands are of primary interest since they are the most likely features to be electrified. Vertically pointing Doppler rays are used to estimate vertical air motions during passes through active convection in both tropical storms and hurricanes. Along with the vertical velocities, coincident microphysics and electric field measurements are made at heights above the melting level.

The aircraft should initially fly a survey figure-4 pattern (Fig. 18b) at ~18,000 ft (5.5 km) altitude. The figure-4 pattern would be completed in 1.5-2.0 h with radial legs 80 nm (150 km) in length. The second part of this option (Fig. 18b) concentrates on rainbands that are located within the useful range of the NLDN. Upon exiting the eye at 4, the aircraft should climb as high as possible on the way to the rainband of interest (5). A sawtooth pattern is flown downwind (Doppler operating in standard mode) with repeated crossings of the rainband to 6. We prefer to fly directly down the band, but for reasons of safety, a sawtooth pattern may be flown. An upwind leg, flown outside of the band, is performed with the tail radar operating in the F/AST mode. The sawtooth pattern across the band is repeated with an exit toward the eye at 7. After entering the eye, the aircraft turns toward the second rainband at 8. The sawtooth crossings and the F/AST downwind leg are repeated as in the first rainband. About one hour should be spent in each of the rainbands. If only one rainband is present within the useful range of the NLDN, a second study of the same band can be performed after a circuit through the storm center.

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 of this module is to determine the kinematic and thermodynamic changes that occur after a hurricane makes landfall, throughout the depth of the lower troposphere.

The WP-3D will fly a coastal survey pattern followed by a figure-4 pattern (Fig. 19) over land with leg lengths ~150 km at an altitude of ~15,000 ft (5 km). The WP-3D tail radar should be in F/AST mode. These data will aid in rainfall estimation and will help document the changes in vortex and rainband 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 DOW radars 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. A profiler will 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 radar 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. Fig. 20 shows the estimated time after landfall that is required for the TC winds to decay to various wind threshold levels as determined using the HRD empirical inland wind decay model. 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 radius of maximum wind of the landfalling storm.

If the inland profilers are mobile, it will be possible to follow severe weather producing rainbands if safety and logistical considerations allow. The DOW Doppler radars should be placed roughly halfway between the two rear lines of mesonet and profiler stations. The DOW radars 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 winds within the PBL of a landfalling hurricane. Finally, the radars will aid in the measurement of the rainfall associated with the landfalling hurricane.

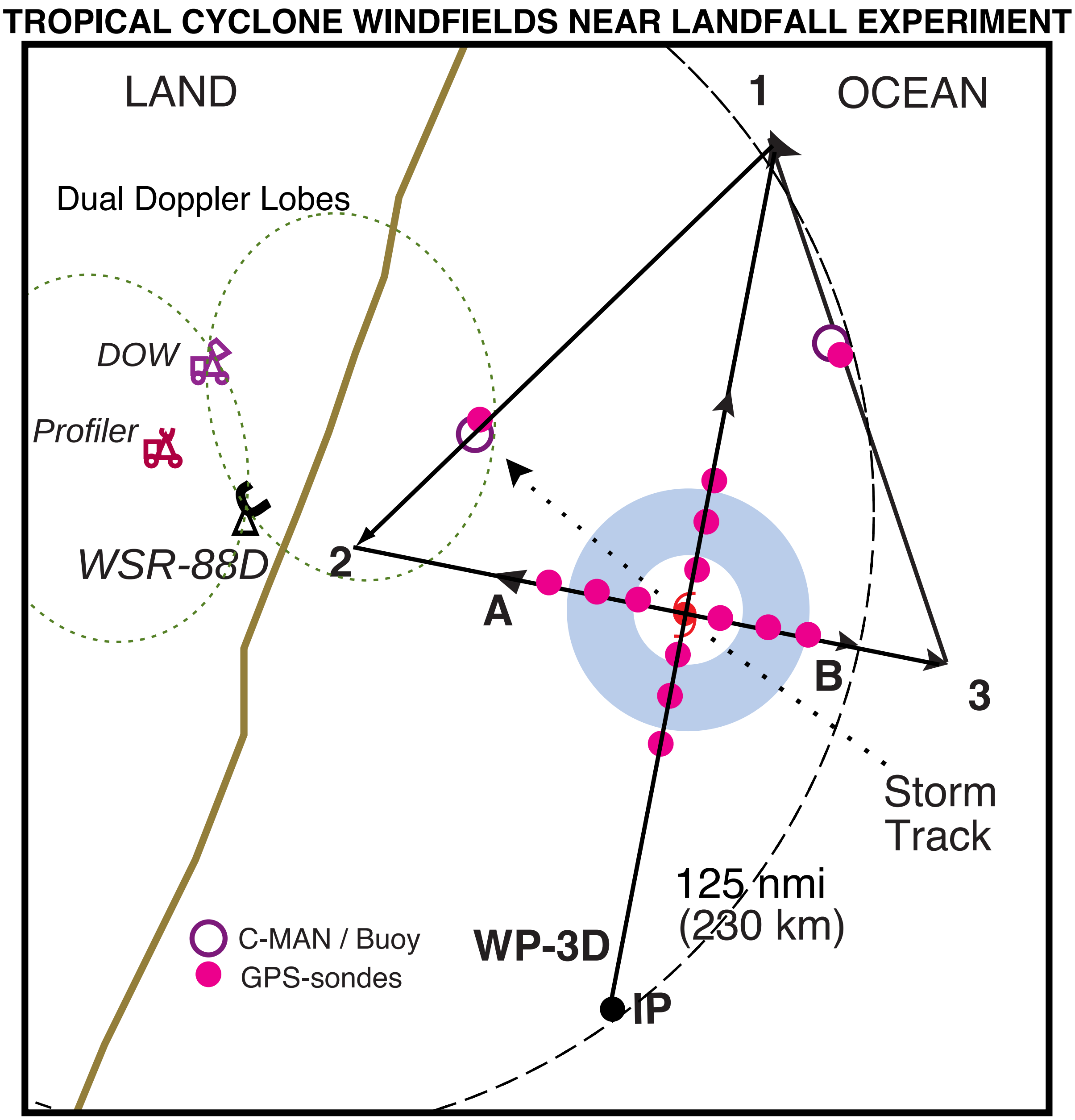


Fig. 15. **Flight track for the real-time module with over flights of moored buoys for a storm passing within range of a coastal WSR-88D.**

• Note 1.	True airspeed calibration required.
• Note 2.	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.
• Note 3.	If possible, the WP-3D should fly legs along the WSR-88D radials. Set airborne Doppler radar to F/AST scanning on all legs.
• Note 4.	All aircraft should avoid penetration of intense reflectivity regions (particularly those over land). Wind center penetrations are optional.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

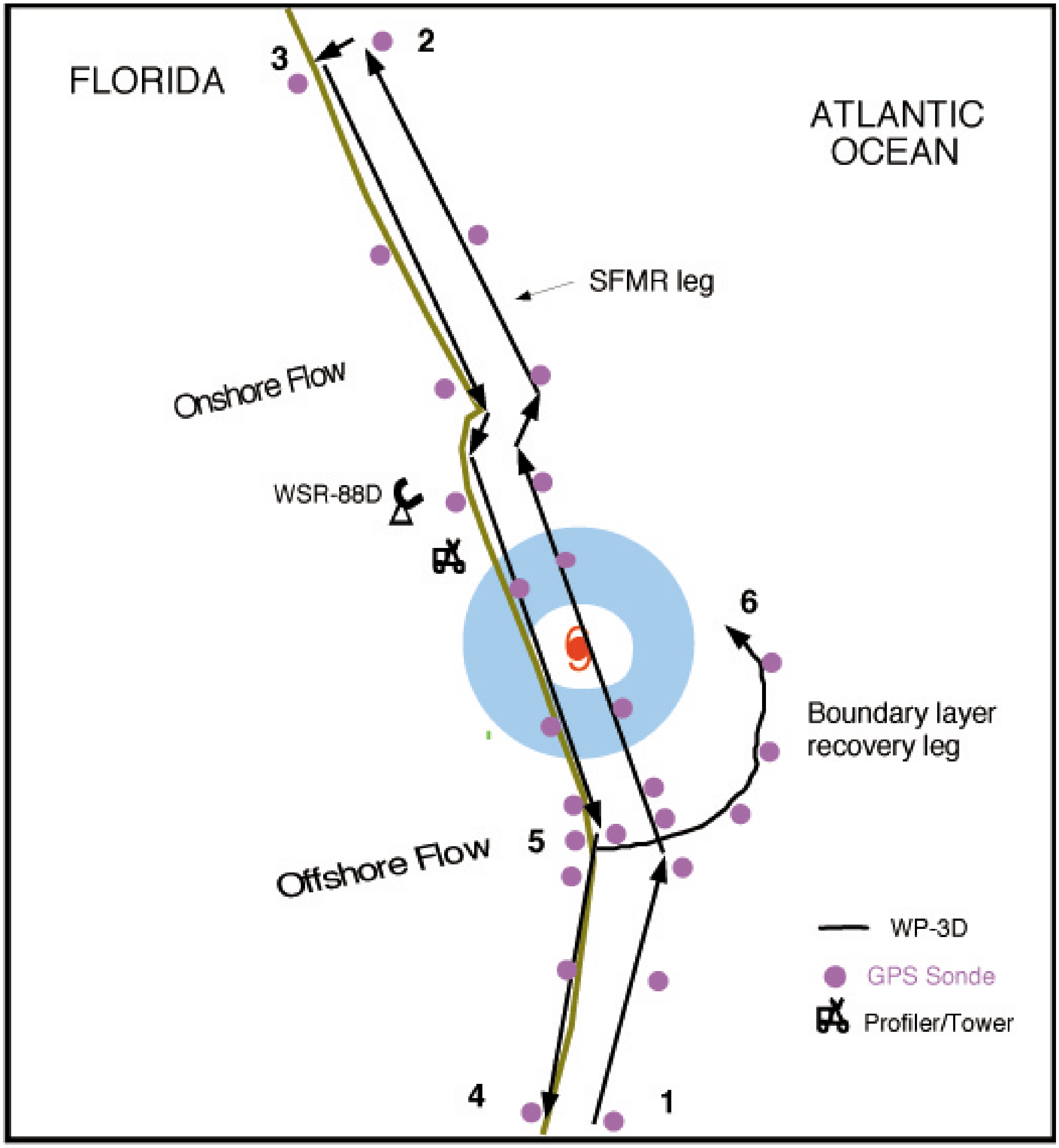


Fig. 16. Coastal Survey pattern.

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

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

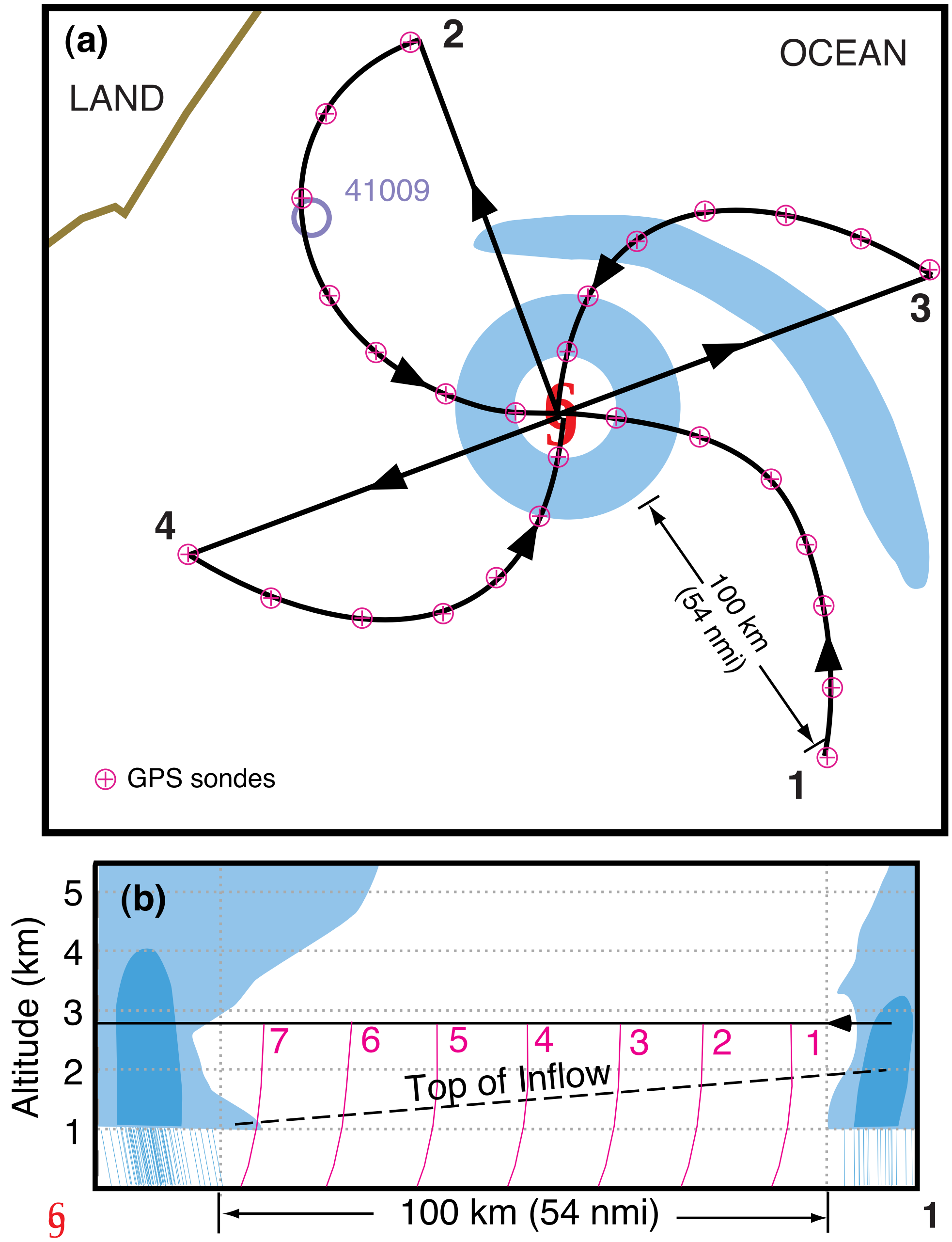


Fig. 17. Rainband Thermodynamic Structure Module (a) Plan view; and (b) track-height depiction.

• Note 1.	True airspeed calibration required.
• Note 2.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt

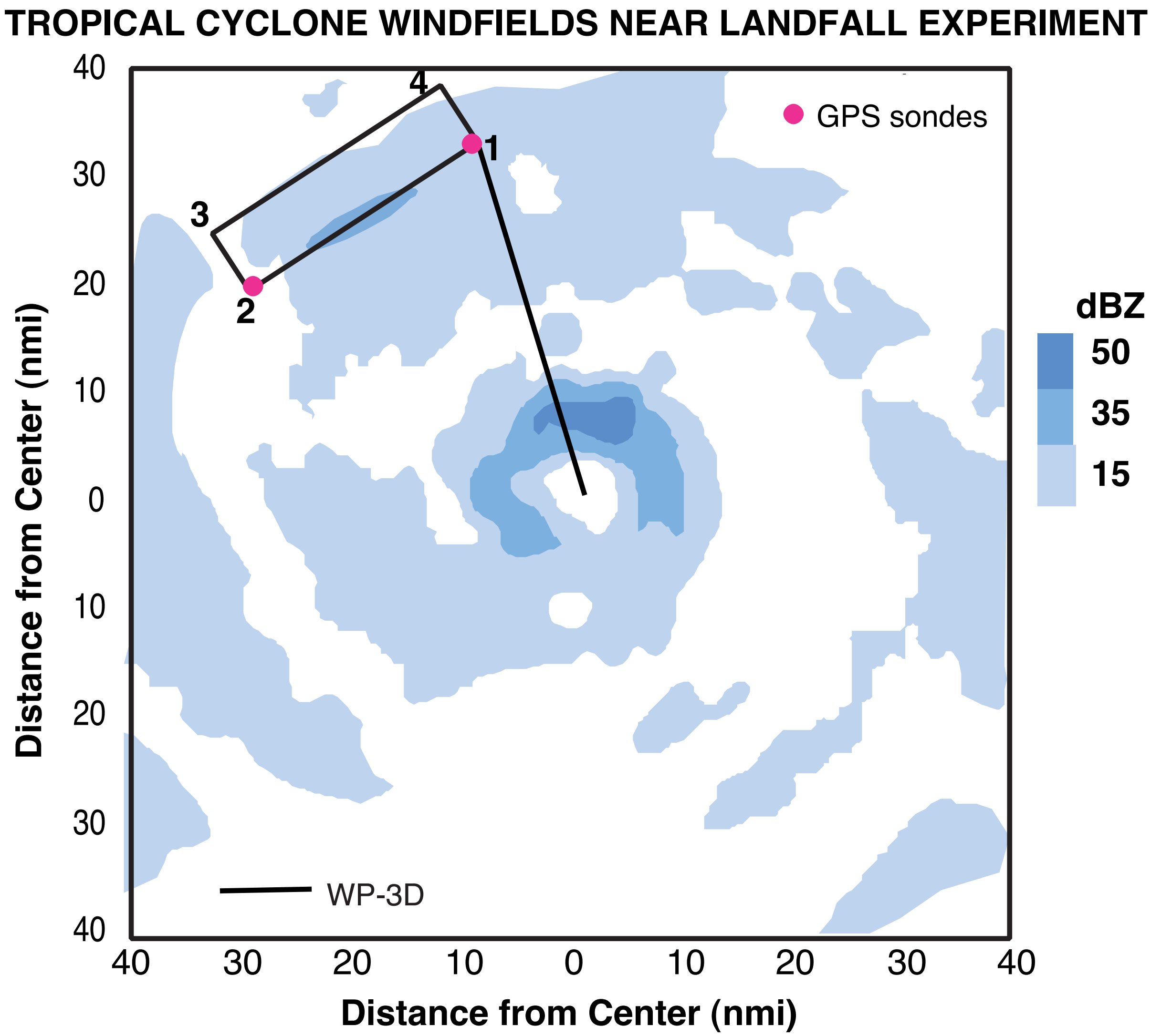


Fig. 18a. Electrification rainband module flight pattern.

• Note 1.	True airspeed calibration is required.
• Note 2.	The pattern may be flown along any compass heading.
• Note 3.	Rainband passes **1-2** are separated by 1500 ft (500 m) altitude. Climbs (descents) occur along **3-4** outside the convection.
• Note 4.	Set airborne Doppler radar to continuously scan perpendicular to the track from **1-2**, and in F/AST mode at a single PRF ≥2400 and 20° tilt on all other legs.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

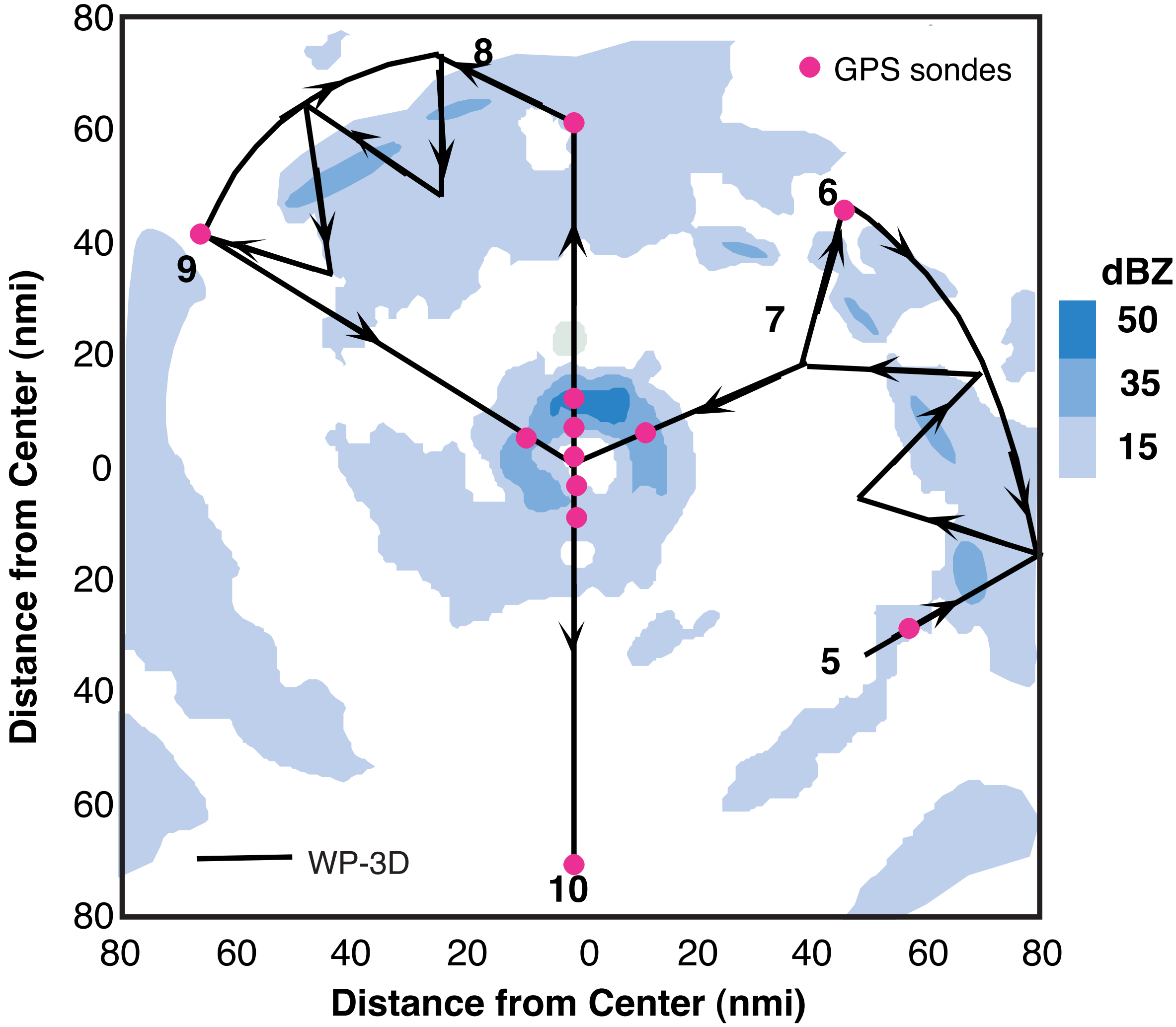


Fig. 18b. Electrification landfall module flight pattern.

• Note 1.	Fly zigzag legs **5-6** and **8-9** at highest possible altitude. Each leg is approximately 25 nm (45km) long. Outside turns of 270°-300° are at the end of each zigzag leg.
• Note 2.	At **6** and **9** fly upwind leg along rainband at highest possible altitude to a point near the beginning of the zigzag legs.
• Note 3.	Repeat pattern in different parts of the storm as time permits.
• Note 4.	Set airborne Doppler radar to scan in F/AST mode on all legs.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

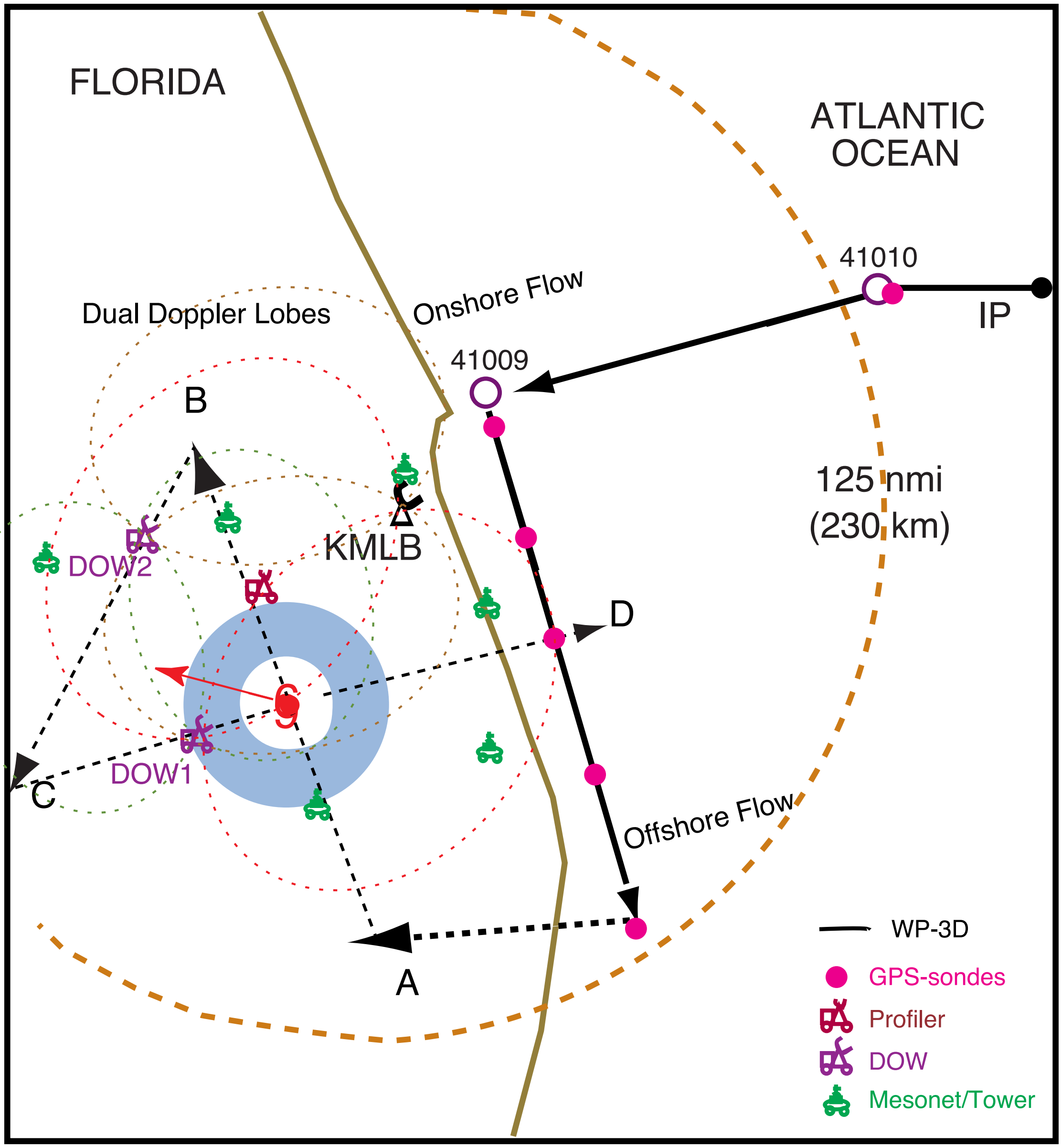


Fig. 19. Post landfall module flight pattern.

• Note 1.	The WP-3D should fly a coastal survey pattern (sold line) at an altitude of ~10,000-15,000 ft (3-4 km) dropping GPS-sondes near buoys of opportunity and within 10-20 km of the shore in both the onshore and offshore flow regimes.
• Note 2.	The WP-3D executes a 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).
• Note 3.	If possible, the WP-3D should fly legs along the WSR-88D radials. Set airborne Doppler radar to F/AST scanning on all legs.
• Note 4.	All aircraft should avoid penetration of intense reflectivity regions (particularly those over land). Wind center penetrations are optional.

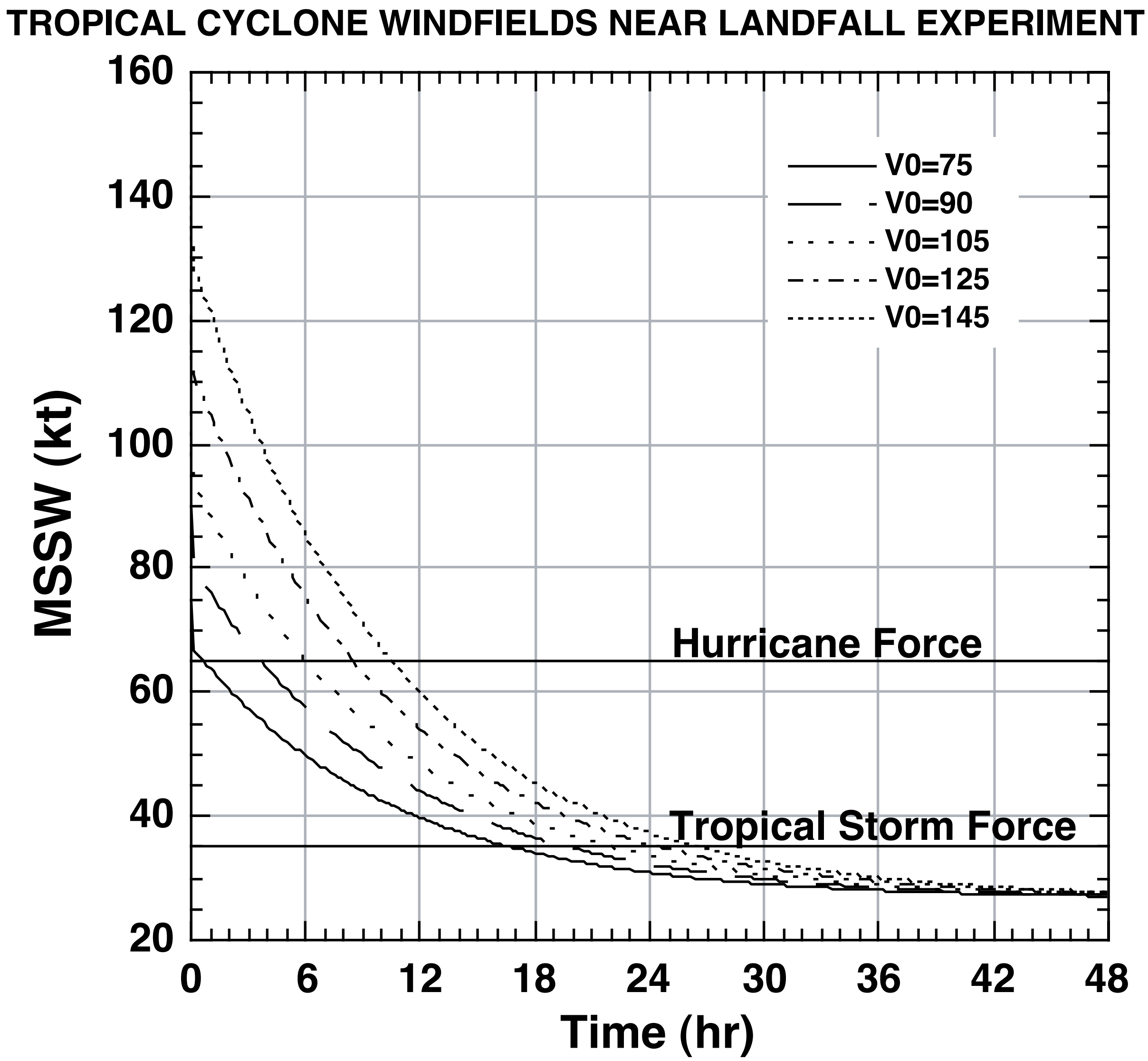


Fig. 20. Maximum sustained surface winds (MSSW) after landfall estimated using the Kaplan/DeMaria inland wind decay model for TCs with landfall intensities (V0) of 75,90,105,120, and 145 kt.

12. 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 WP-3D 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 100 operational "Synoptic Surveillance" missions have been flown with the NOAA G-IV jet in the environments of TCs threatening the United States coastline; almost half of these have been supplemented with dropwindsonde observations from one or two WP-3D aircraft during Hurricane Synoptic Flow Experiments. An improved dropwindsonde based on the Global Positioning System 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 (targeting) have increased in importance. Current efforts include operational use of objective targeting techniques to provide the greatest possible improvement in initial condition specification and subsequent forecasts.

Objectives: The goal of synoptic surveillance is to improve landfall predictions of TCs by releasing dropwindsondes in the environment of the TC center. These data will be used by TPC/NHC and 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 resolution of these intervals is an ongoing area of research.

A number of methods to find targets have been investigated, mainly in the wintertime extratropics. 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. This method is relatively expensive, and full implementation in the Tropics where adiabatic processes dominate has proven difficult, and the linear assumption tends to break down at the 72 h forecast time necessary for the posting of hurricane watches and warnings. Related strategies involve the sensitivity vector, and quasi-inverse linear method. All these methods may depend on the accuracy of the initial conditions determined without the supplemental data.

A fully nonlinear technique uses the breeding method, the operational NCEP perturbation technique in which initially random perturbations are repeatedly evolved and rescaled over a relatively short cycling time. These vectors are related to local Lyapunov vectors and, therefore, define the fastest growing modes of the system. Changes to initial conditions due to dropwindsonde data obtained from operational synoptic surveillance missions during the 1997 and 1998 hurricane seasons grow (decay) in regions of large (small) perturbation in the operational NCEP Ensemble Forecasting System. Therefore, these bred-modes provide a good estimate of the locations in which supplemental observations are likely to have the most impact. However, though the breeding 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 which do not.

A more generalized objective method that can use any dynamical ensemble forecast system is the Ensemble Transform Kalman Filter (ETKF).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. This method has shown promise during previous synoptic surveillance missions.

Mission Description: A sample mission is shown in Fig. 21. If requested due to operational considerations, two WP-3D aircraft and the G-IV will begin their missions at the same time. Subject to safety and operational constraints, each WP-3D will climb to the 500-mb level (about FL 180) or above, 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.*

GPS-sondes are released in one of two modes. Beyond 40 nm (75 km) from the storm center, drops are made at pre-assigned locations, generally every 25 min or 120 nm (222 km). These drop locations are provided with the particular mission flight tracks 2 h before departure. Within 40 nm (75 km) of the TC's center, drop locations are specified relative to the center's position (e.g., 40 nm (75 km) north of the eye). During in-storm portions of the mission, drops will be made with possible spacing <8 min or 40 nm (75 km).

At least one aircraft will fly through the TC center and execute a figure-4 pattern. This aircraft's Doppler radar should be set to scan perpendicular to the aircraft track. *"Hard" center fixes are not desirable*. On the downwind leg of the figure-4, the Doppler should be set to record forward and aft (F/AST) continuously. If both aircraft penetrate the storm, the figure-4 pattern will generally be executed by the *second* aircraft through the storm, and the first aircraft through will collect vertical incidence Doppler data. Coordination with potential USAF reconnaissance is necessary to ensure adequate aircraft separation. The in-storm portion of the missions is shown schematically in Fig. 22, although the actual orientation of these tracks may be rotated.

Of paramount importance is the transmission of the GPS-sonde data to NCEP and TPC/NHC for timely incorporation into operational analyses, models, forecasts, and warnings. Operational constraints dictate an 0600 or 1800 UTC departure time, so that the GPS-sonde 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 and TPC/NHC's analysis and forecasting schedules.

HURRICANE SYNOPTIC SURVEILLANCE

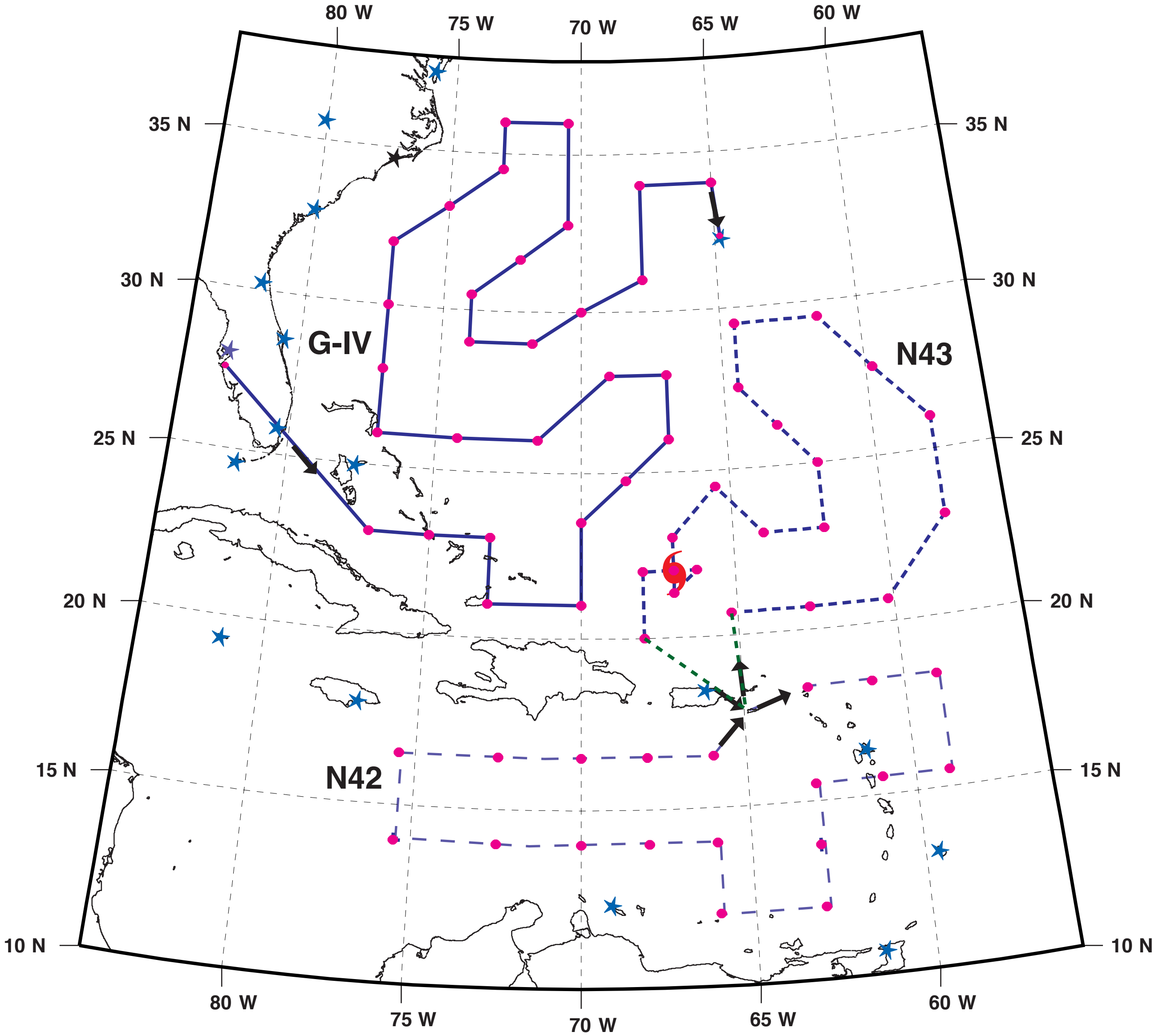


Fig. 21.Sample Environmental Patterns

• Note 1.	During the ferry to the **IP**, the WP-3D aircraft will climb to the 500 mb level (about FL 180). The 400 mb level (about FL 250) 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 41,000 ft (200 mb) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

HURRICANE SYNOPTIC SURVEILLANCE

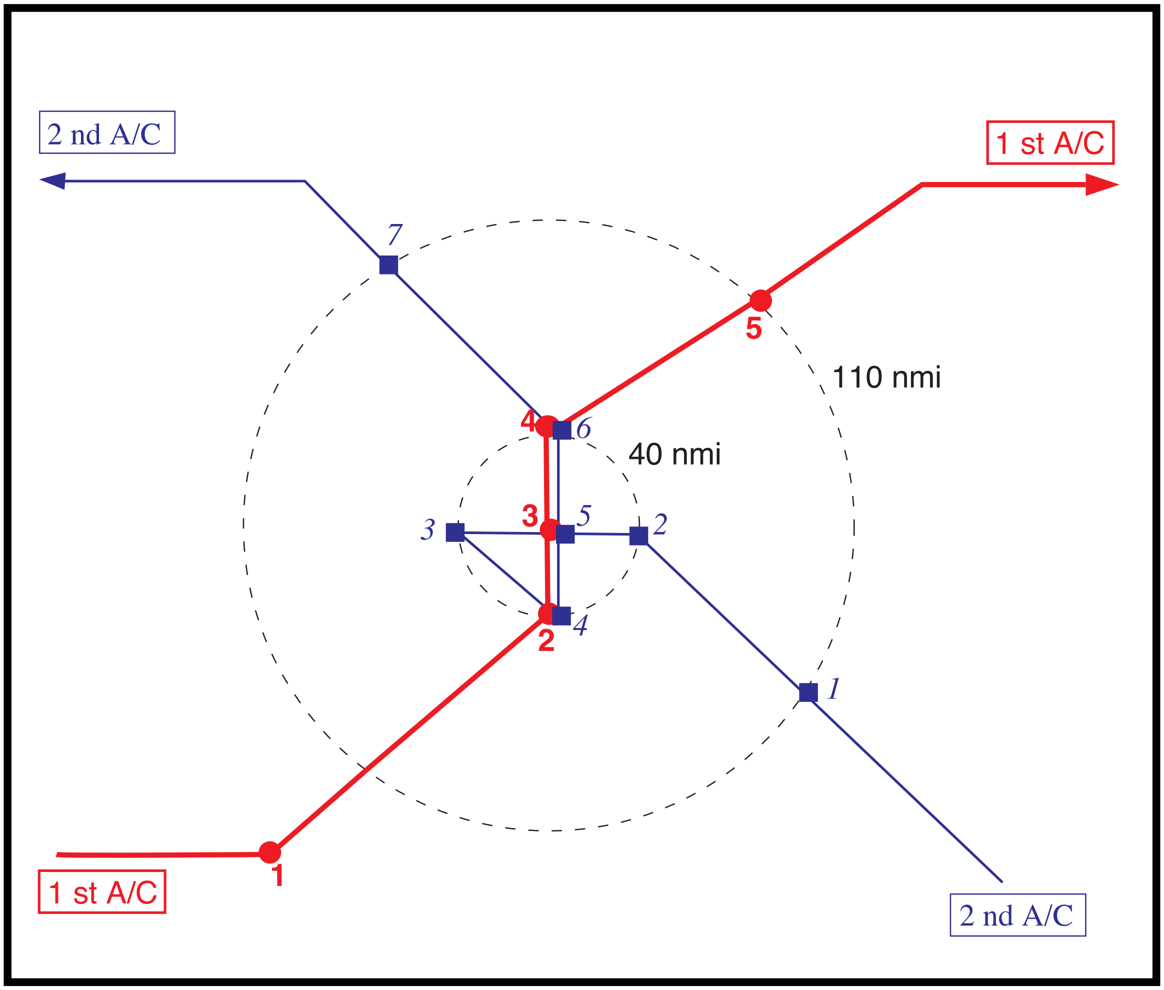
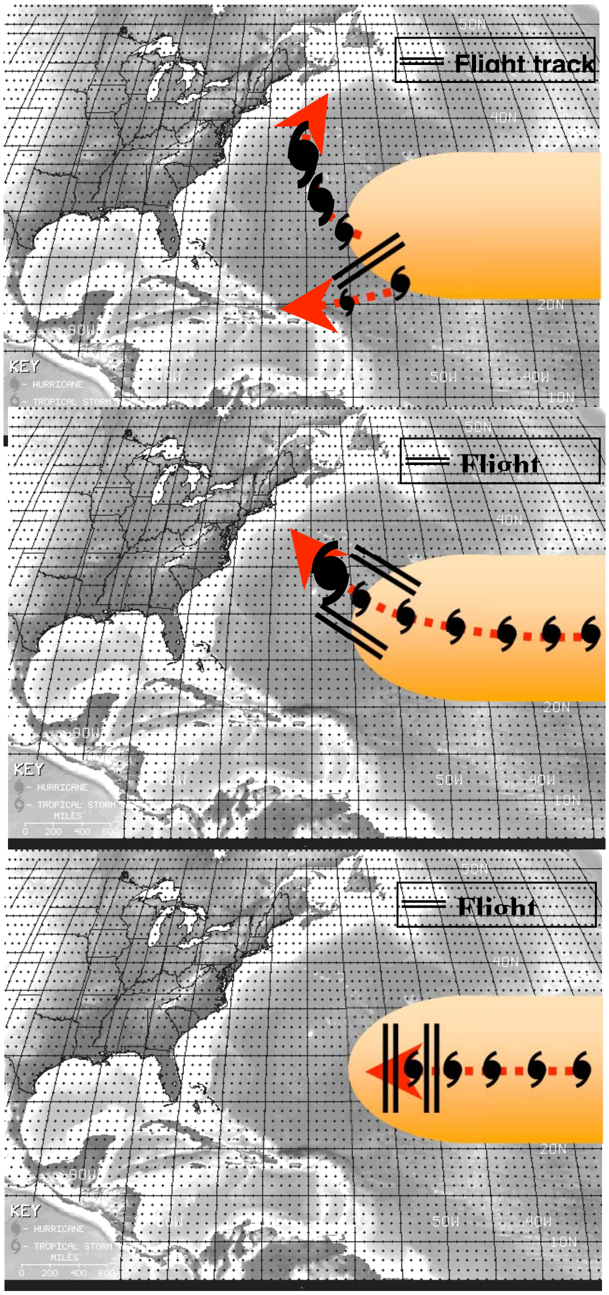


Fig. 22 In-Storm Patterns

- Note 1. Within the 40 nm (75 km) range ring, all legs are on cardinal tracks.
- Note 2. The second aircraft through the storm will execute the Doppler "figure-4" pattern. The Doppler radar should be set to continuously scan perpendicular to the track during radial penetrations and to F/AST on the downwind leg.
- Note 3. Numbered symbols (◆, ■) reflect scheduled drops for each aircraft.
- Note 4. Drop #5 in the "figure-4" pattern occurs on the second pass through the eye.
- Note 5. A/C 1 should collect vertical incidence Doppler data during storm penetration.
- Note 6. If missions are not repeated, then block times may exceed 9 h. In addition to the GPS-sonde data, *3-4 RECCO's* h^{-1} *should be transmitted during each mission.*

Saharan Air Layer - Synoptic Surveillance Follow on

Mission Description: The G-IV (flying at 200 mb) GPS sonde drop points will be based on slight modifications to a synoptic surveillance flight pattern selected using information from the UW-CIMSS/HRD GOES SAL tracking product. Specific effort will be made to gather atmospheric information within the SAL, the transitional environment along its boundaries, and the immediate surrounding tropical environment (as part of the surveillance mission). Several SAL/TC interaction scenarios are candidates for this mission:



1) Classic two-disturbance scenario with connecting "rooster tail" of convection. This convection represents the leading edge of the westward advancing SAL. The northern disturbance typically intensifies as it recurves and leaves the suppressing influences of the SAL behind. The southern disturbance is often overrun by the SAL and dramatically weakened. GPS sonde transects (~20 km spacing) can be made to run perpendicular to the region of the "rooster tail".

2) Single tropical disturbance is embedded within the SAL and intensifies upon emerging. These systems are often candidates for rapid intensification. GPS sonde transects (~20 km spacing) perpendicular to the leading edge of the advancing SAL and near to possible points of the tropical disturbance's emergence from the SAL are desirable.

3) Single tropical disturbance is embedded within the SAL for its entire life cycle. These systems struggle to intensify and are often characterized by their low-level circulation racing out ahead (west) of their mid-level convection. North/south GPS sonde transects (~50 km spacing) on the west and especially east sides of the tropical disturbance are desirable.

Figure 23. Sample SAL / tropical cyclone scenarios

The G-IV/WP-3D aircraft should fly at 41,000/20,000 ft. In order to capture the SAL structure, particular attention should be paid to any dropsonde sequences that cross the leading edges of the SAL.

13. Saharan Air Layer Experiment (SALEX)

Program Significance: The Saharan Air Layer (SAL) has been investigated fairly extensively during the past several decades, buts its role in influencing Atlantic TC activity 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 over the African continent. This air mass is extremely warm and dry, with surface temperatures of 38-42 C and mixing ratios of 3-6 g/kg. The SAL is often associated with a low-level easterly surge centered at about 700 mb and concentrated along its southern boundary.

SAL outbreaks typically move westward off the northwestern African continent 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) **Mineral dust** suspended within the SAL absorbs solar energy and subsequently release longwave infrared energy. These thermal emissions act to warm the low-levels of the SAL and can re-enforce the tropical inversion that already exists in the north Atlantic basin. This warming helps to stabilize the environment as well as limit vertical mixing through the SAL, allowing it to maintain its distinctive structure for extended periods of time.
2) The mineral dust acts as a tracer for **dry, stable air** associated with the SAL. This relatively denser dry air can diminish local convection by promoting convectively driven downdrafts and hence suppressing TC formation.
3) The mineral dust also acts as a tracer for the **low-level wind surge** typically associated with the SAL that can greatly increase the local atmospheric vertical wind shear. The low-level circulations of TCs under the influence of this surge tend to race out ahead of their mid-level convection, decoupling the storm and weakening it.

Objectives: This experiment is designed to study the mechanisms by which the SAL's embedded mineral dust, thermodynamic properties, and low-level wind surge affect Atlantic TC genesis and intensity change.

Mission Description: The WP-3D (flying at ~500 mb) GPS sonde drop points will be based on a flight pattern selected using information from the UW-CIMSS/HRD GOES SAL tracking product. Specific effort will be made to gather atmospheric information within the SAL, the transitional environment along its boundaries, and the immediate surrounding tropical environment. Several SAL/TC interaction scenarios are candidates for this mission:

<u>Option 1</u>: Classic two-disturbance scenario with connecting "rooster tail" of convection (Fig. 23). This convection represents the leading edge of the westward advancing SAL. The northern TC (A) typically intensifies as it recurves and leaves the negative influences of the SAL behind. The southern TC (B) is often overrun by the SAL and dramatically weakened. If both WP-3D's are available, TCs A and B will be investigated. If one WP-3D is available, the TC of interest will be selected on a case by case basis.

a) GPS sonde transects (~20 km spacing) will be made across the region of the "rooster tail" south of TC A and the SAL's NW leading edge NE of TC A. Particular attention will be focused on the transitional environment along the SAL's leading edge. The aircraft will then fly through the TC A's center and execute a figure-4 pattern with legs that extend 100 km beyond the outer rain bands. GPS sondes are released at the end of each leg with a focus on dry SAL air being advected into the NW and SW quadrants of the TC A as well as SAL enhanced vertical wind shear in the eastern quadrants of the TC A.

b) GPS sonde transects (~20 km spacing) will be made across the region of the "rooster tail" NW of TC B. Particular attention will be focused on the transitional environment along the SAL's leading edge. The aircraft will then fly through TC B's center and execute a figure-4 pattern with legs that extend ~100 km beyond the outer rain bands. GPS sondes are released at the end of each leg with a focus on dry SAL air being advected into the NW and SW quadrants of TC B as well as SAL induced vertical wind shear in the eastern quadrants of the TC B.

<u>Option 2</u>: Single tropical disturbance moving W or NW is embedded in the SAL and intensifies upon emerging (Fig. 24). These systems are often candidates for rapid intensification. GPS sonde transects (~20 km spacing) will be made south and NE of the TC across the leading edge of the advancing SAL. The aircraft will then fly through the TC center and execute a figure-4 pattern with legs that extend ~100 km beyond the outer rain bands. GPS sondes are released at the end of each leg with a focus on the SAL's dry air being advected into the NW and SW quadrants of the TC as well as SAL enhanced vertical wind shear in the rear quadrants of the TC. Focus will also be made on the non-SAL environment in the front quadrants of the TC that the storm is moving into

<u>Option 3</u>: Single tropical disturbance is embedded in the SAL for its entire life cycle (Fig. 25). These systems struggle to intensify and are often characterized by their low-level circulation racing out ahead (west) of their mid-level convection. A south to north GPS sonde transect (non-SAL environment) to the west of the TC will be made. The aircraft will then fly through the TC center and execute a figure-4 pattern with legs that extend ~100 km beyond the outer rain bands. GPS sondes are released near the outer rainbands and at the corners of each leg with a focus on the SAL's dry air and enhanced vertical wind shear. The initial NW to SE and final NE to SW legs will contain GPS sonde transects that focus on the transitional environment along the SAL's leading edges. The south to north figure-4 leg to the east of the TC will contain a GPS sonde transect entirely in the SAL environment.

Saharan Air Layer Experiment (SALEX)

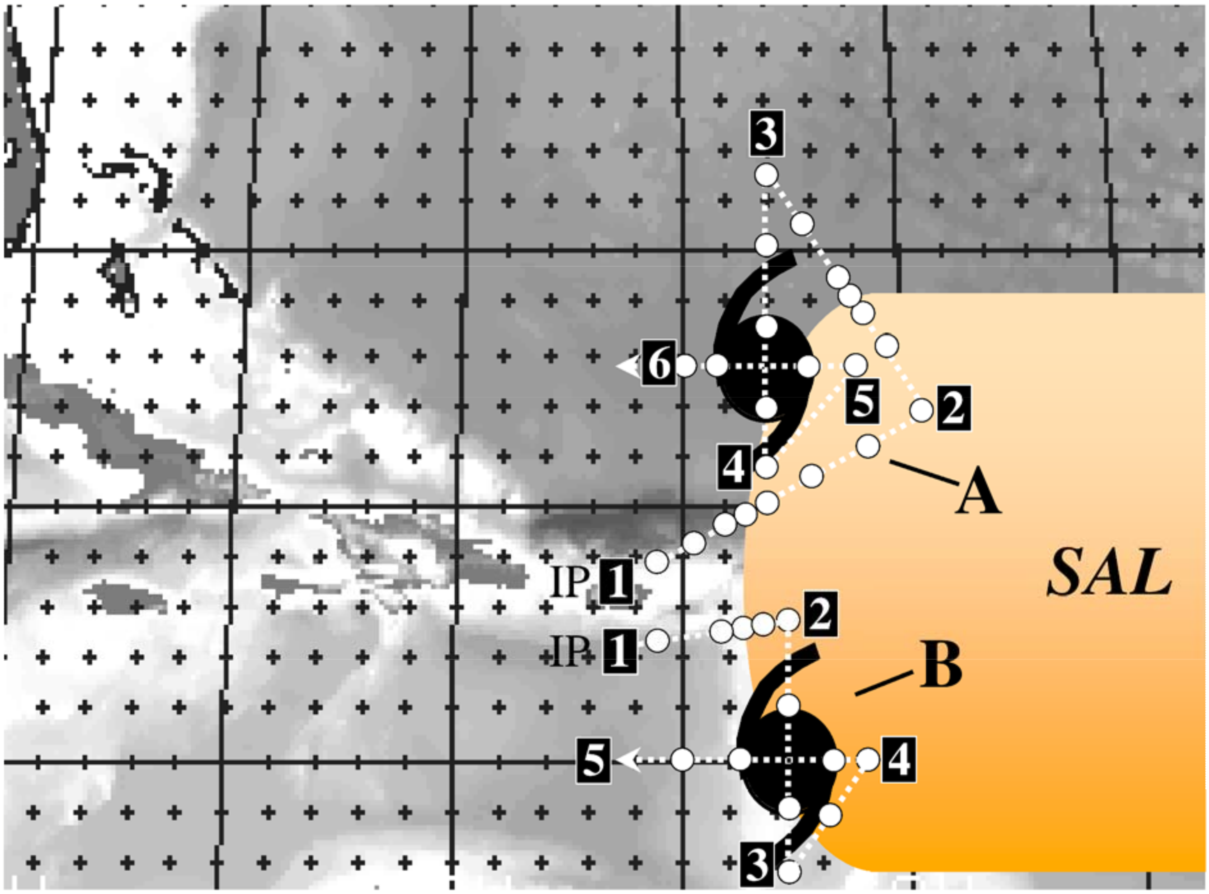


Fig. 23: Two system disturbance at leading SAL edge

- Note 1: Storm "A" WP-3D flies 1-2-3-4-5-6 at ~20,000 ft (6,000 m).
- Note 2: Storm "B" WP-3D flies 1-2-3-4-5 at ~20,000 ft (6,000 m).
- Note 3: In order to capture the SAL structure, particular attention should be paid to the dropsonde sequences that cross the leading edges of the SAL:
  Storm "A": leg 1-2 and leg 2-3
  Storm "B": leg 1-2, leg 3-4, and possibly leg 4-5 (depending on storm position).
- Note 4: Storm "A" will likely separate from the SAL and intensify (rapid intensification is possible).
- Note 5: Storm "B" will likely be overrun by the SAL and weaken. Strengthening may occur if this disturbance reaches the central Caribbean and show signs of separating form the SAL.

Saharan Air Layer Experiment (SALEX)

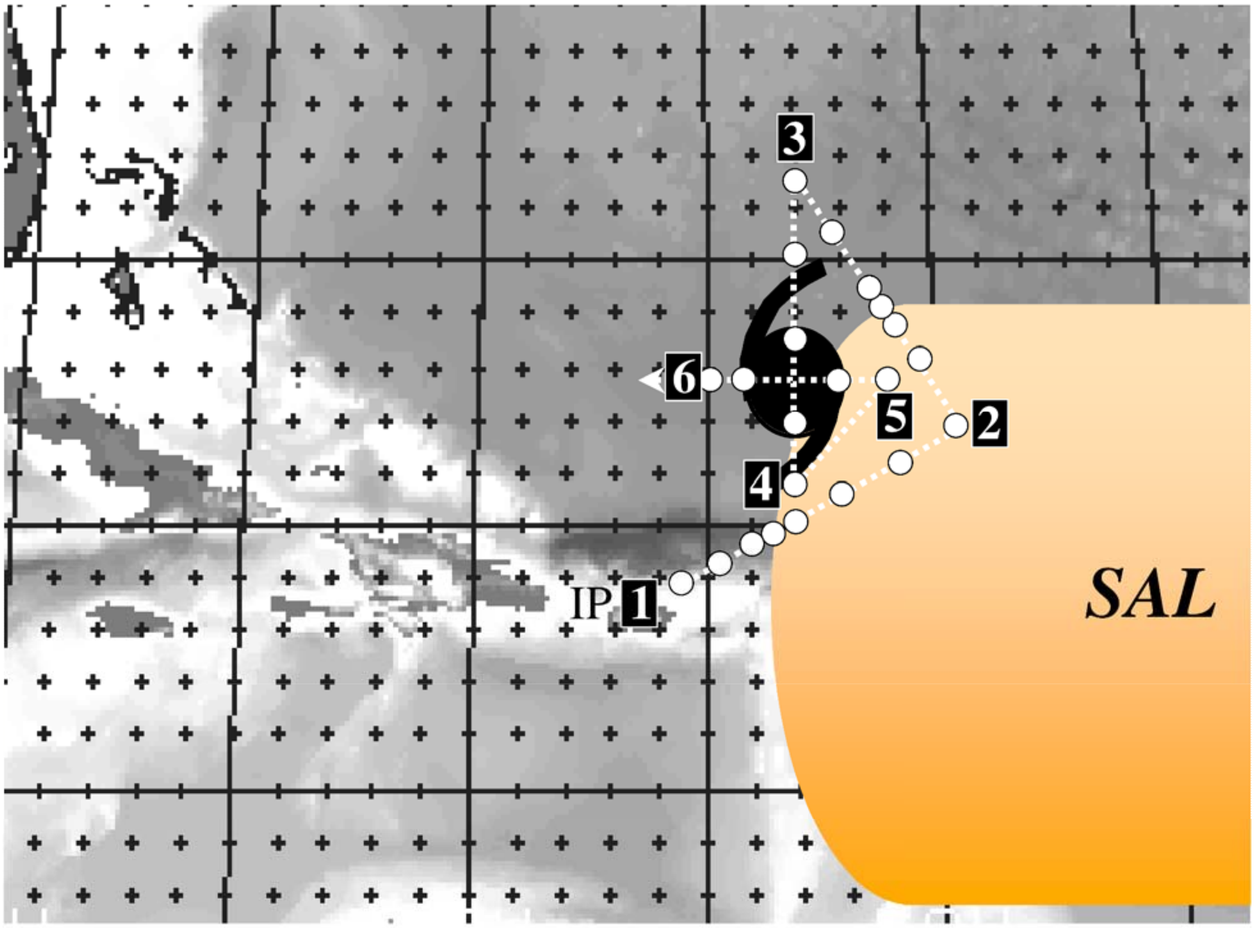


Fig. 24: Single disturbance recurving and separating for the SAL

- Note 1: WP-3D aircraft flies 1-2-3-4-5-6 at ~20,000 ft (~6,000 m).
- Note 2: In order to capture the SAL structure, particular attention should be paid to the dropsonde sequences that cross the leading edges of the SAL (leg 1-2 and leg 2-3).
- Note 3: The disturbance will likely separate from the SAL and intensify (rapid intensification is possible).

Saharan Air Layer Experiment (SALEX)

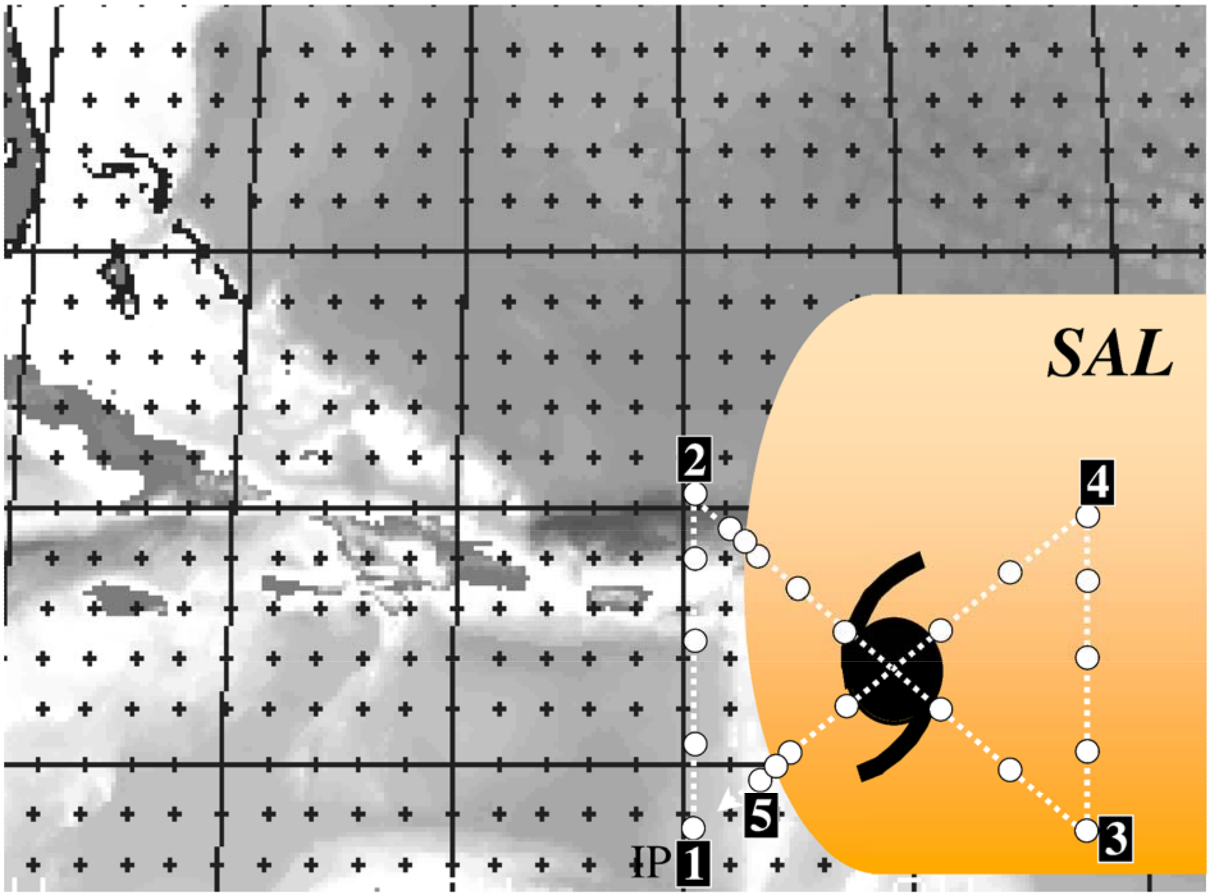


Fig. 25: Single disturbance embedded in the SAL

- Note 1: WP-3D aircraft flies 1-2-3-4-5-6 at ~20,000 ft (~6,000 m).
- Note 2: In order to capture the SAL structure, particular attention should be paid to the dropsonde sequence that crosses the leading edges of the SAL: leg 2-3 and leg 4-5.
- Note 3: The embedded disturbance will likely remain embedded in the SAL unless it is able to recurve to the northwest. Strengthening may also occur if this disturbance reaches the central Caribbean and begins to show signs of separating from the SAL.
- Note 4: The disturbance's low-level circulation may race ahead of the mid-level convection due to the influence of the SAL's low-level wind surge.

14.Tropical Cyclogenesis Experiment

Program Significance: 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. In many of these genesis hypotheses an incipient midlevel (e.g., 850 – 500 mb) cyclonic vortex is required for development of the low-level cyclonic circulation. Where these hypotheses differ is in the role that the midlevel vortex plays in genesis. In one theory, downdrafts driven by evaporational cooling advect the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production. Observations of multiple midlevel vortices prior to genesis have led some 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. Another hypothesis emphasizes the role of the midlevel vortex in axisymmetrizing nearby low-level convectively-generated cyclonic vorticity, leading to spin-up of the surface circulation. Yet another hypothesis emphasizes the role the midlevel vortex plays in providing a favorably-reduced local Rossby radius of deformation to retain the heating from convective bursts and spin up low-level vorticity through low-level stretching caused by the convective heating. The purpose of the proposed experiment is to identify what role, if any, midlevel vortices play in organizing and amplifying low-level cyclonic vorticity.

Since the onset of deep, moist convection is a crucial component in tropical cyclogenesis, the identification of large-scale environments favorable for such convective activity is an important step in identifying likely candidates for genesis. Environments favorable for genesis in the Atlantic Ocean have been revealed by composites of operational analyses and case studies of genesis and lysis events. Western and eastern Atlantic composites have shown the dynamical importance of ascent forced through cyclonic vorticity advection (CVA) in the incipient storm environment. Over the eastern Atlantic, this vorticity advection is generally found equatorward of a 200 mb zonally-oriented ridge axis in association with an upper-level easterly jet, while over the western Atlantic the CVA occurs downstream (upstream) of a 200 mb trough (ridge). In both composites the low-level disturbance is located beneath an area of CVA and near a minimum in vertical wind shear (200 mb-ATOLL level). Developing disturbances in both regions of the Atlantic are found downstream of a 700 mb southeasterly jet along the equatorward side of a ridge axis. The conditions important in the Atlantic basin are similar to those found to be important in other basins, where conditions of weak vertical shear, low-level positive vorticity, and the repeated development of convective bursts are all necessary conditions for tropical cyclogenesis.

Recent observations from airborne Doppler radar have identified important processes on the mesoscale that contribute to tropical cyclogenesis. For example, results obtained from a WP-3D aircraft investigation of Dolly (1996) 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 the midlevel vortex, it is vital that it be sampled in its entirety (which will invariably depend on the distribution of precipitation scatterers) and with a temporal resolution that allows time continuity of the vortex to be established. For a complete picture detailed observations of the mid- and low-level thermal and moisture fields are also necessary.

Since both tropical cyclogenesis and tropical cyclone 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 our 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 ingestion of this data into the NCEP model analysis and initialization schemes will permit an improvement in NCEP model forecast performance based upon a better representation of the mesoscale and synoptic-scale structure in the vicinity of the incipient disturbance. 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. 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.

Objectives: In keeping with the discussions above, the objectives of this experiment are as follows:

- Develop means for identifying likely candidates for tropical cyclogenesis and techniques for finding and tracking midlevel vortices within these candidates.
- Investigate role, if any, that midlevel vortex plays in organizing deep convection.
- Document the development of low-level vorticity in the presence of a midlevel vortex center.
- Study the interactions between low- and mid-level vortices in pre-genesis environments.

Mission Description: This experiment may be executed with aircraft from NOAA alone, or NOAA in cooperation with the USAF flying into pre-genesis and incipient tropical disturbances over the Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and tropical eastern North Pacific Ocean. The primary mission will require two WP-3Ds flying back-to-back with the G-IV aircraft flying a coordinated pattern. The two WP-3Ds will fly mesoscale patterns in close proximity to any suspected mid-level vortices while the G-IV simultaneously flies at upper levels (200-300 mb) and collects observations to a distance of ~1500 km from the center of the disturbance. Crucial to a complete understanding of the genesis process is the collection of observations with high temporal and spatial resolution. Therefore, the staggered WP-3D missions are designed to commence on station at 3am local and again on station at 3 pm local. The G-IV mission would occur coincident with the afternoon flight and consistent with synoptic missions centered on the 00 GMT synoptic time. If available, the USAF WC-130 aircraft can be used to enhance flight-level observations.

The main aircraft for the mesoscale flights will be the two WP-3Ds. Doppler radar observations, GPS-sondes, and flight level observations obtained during these flights will help locate low- and mid-level vortices and help document their structures and life cycles. A primary aspect of this experiment will be to observe the complete life cycle and interaction of low- and mid-level vortices and understand how these vortices are influenced by the diurnal cycle of convection. The location of persistent areas of deep convection and candidate vortices will be determined using high-resolution visible and infrared GOES-winds produced at HRD and rapid-scan and super-rapid-scan visible satellite imagery provided by CIRA/Colorado State University. Additionally, favorable large-scale 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 winds, and QuikScat imagery, all available at HRD.

Staggered missions with the two WP-3D aircraft will begin with the first aircraft flying a low-level diamond pattern at 700-500 mb (10,000-18,000 ft) shown in Fig. 27. Leg lengths will be 325-430 nmi (600-800 km), and the pattern will be centered approximately on the vortex as identified from satellite analyses. The benefit of this pattern is that it covers a relatively broad horizontal area, while the return flight allows for some temporal continuity (on the order of 3 hours) to the data. The primary purpose of these aircraft missions will be to collect F/AST Doppler radar and GPS-sonde 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. Once a mid-level vortex is identified the aircraft will fly a pattern centered on the vortex (Fig. 28). Flight legs will be significantly reduced in length [100-135 nmi (180-250 km)] to allow for the collection of data with high temporal and spatial resolution in the vicinity of the vortex. The length of these flight legs is designed to completely include any low-level vortex within about 50-100 km of the midlevel vortex center. This will be important in documenting any interaction between the midlevel and low-level vortices.

If available, the G-IV will be most beneficial flying a synoptic-scale pattern. It will fly at maximum altitude observing the upper and lower troposphere with GPS-sondes in the pre-genesis and incipient tropical disturbance environment. A potential genesis event occurring in conjunction with primarily an upper tropospheric anticyclone will require a flight pattern similar to that given in Fig. 29a. The aircraft will dispense 20-25 GPS-sondes mostly on the poleward side of the incipient disturbance during the flight to help define wind, temperature and moisture patterns near the ridge axis. Should a potential genesis event occur in association with an upper-tropospheric trough-ridge couplet a flight pattern similar to that shown in Fig. 29b will be required. This flight pattern will collect observations in the vicinity of both the trough and ridge with upwards of 20-25 GPS-sondes. These flight patterns are designed to define those regions where large-scale forcing for ascent exists and persistent deep convection is favored.

An enhancement of the data collected during genesis by the three NOAA aircraft may be accomplished by adding observations from investigative USAF WC-130 aircraft. Should a USAF WC-130 aircraft be available it would be requested to fly at maximum altitude dispensing GPS-sondes in the southern and eastern quadrants of the incipient disturbance. This aircraft would be requested to fly a saw-tooth pattern centered on asymptotes of confluence, convective inflow bands, and/or thermal boundaries within ~300 nmi (500 km) of the incipient disturbance.

In addition to the satellite and airborne data described above, temperature soundings of the mid- and upper-level thermodynamic environment of the system will be obtained using the GOES satellite and the AMSU instrument aboard the polar-orbiting NOAA-15 satellite. These observations will yield important information about the response of the vortex's thermal structure to the convective bursts that will complement well the GPS sondes dropped from the aircraft. SSM/I imagery, available from the World Wide Web, will also be used to infer the intensity of incipient disturbances during times when the aircraft are not flying.

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

- **Option 1 (lesser experiment):**

The two core NOAA WP-3D aircraft alone will fly staggered figure-4 or grid patterns (Figs. 7-8) centered on the area of persistent deep convection and/or any low level vortex over a 2-4 day period.

- **Option 2 (primary experiment):**

Option 1 augmented with large-scale upper- and lower-tropospheric observations obtained by the G-IV aircraft flying patterns similar to those given in Fig. 29.

- Option 3 (optimal experiments):

A) Option 2 with USAF WC-130 flying a standard reconnaissance mission.
B) Option 2 with USAF WC-130 flying a targeted mission to sample asymptotes of confluence, convective inflow bands, and/or thermal boundaries within ~300 nmi (500 km) of the incipient disturbance.
C) Option 2 with the G-IV aircraft to collect quasi-continuous observations in the upper and lower troposphere within ~900 nmi (1500 km) of the disturbance.
D) Option 3B with the G-IV aircraft to collect quasi-continuous observations in the upper and lower troposphere within ~900 nmi (1500 km) of the disturbance.

Tropical Cyclogenesis Experiment

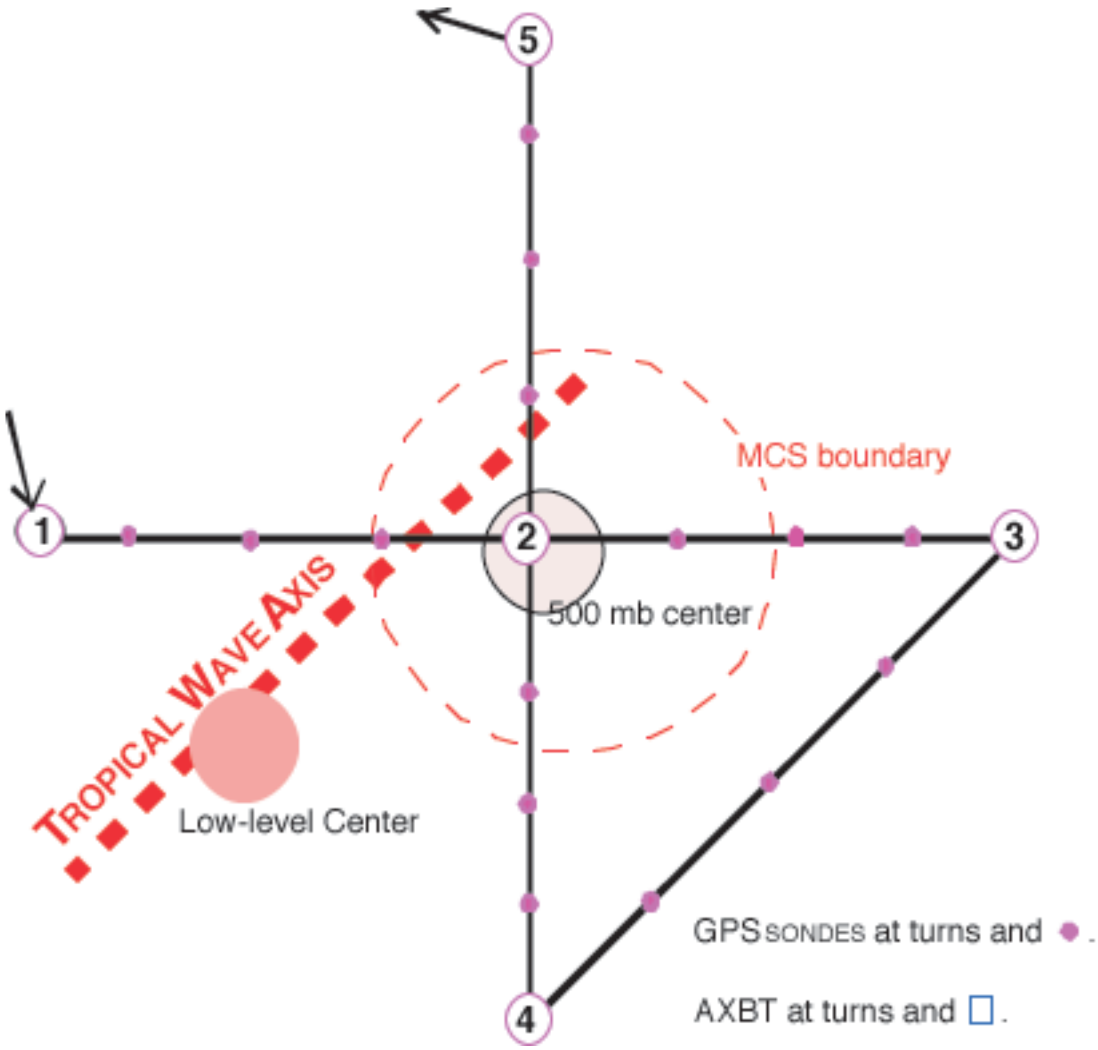


FIGURE 26 Synoptic-scale Aircraft Flight Track

- Note 1: True airspeed calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. Fly 1-2-3-4-2-5 at 18,000 ft (5.5 km or ~500 hPa), 325-430 nmi (600-800 km) leg length, depending on ferry distance.
- Note 4. Point 2 is near the moving apex of the trough axis.
- Note 5 Set airboirne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

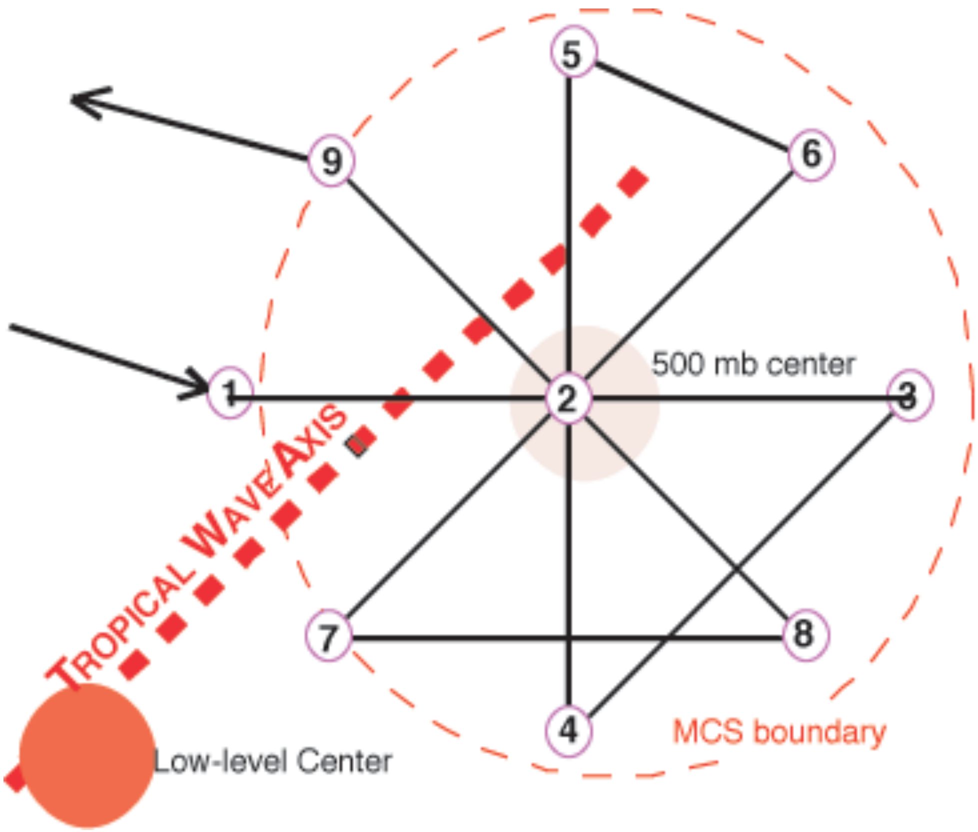


Figure 27 Mesoscale Aircraft Flight Track

- Note 1: True airspeed calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. Fly 1-2-3-4-2-5-6-2-7-8-2-9 at 600 or 700 hPa, 100-135 nmi (185-250 km) leg length.
- Note 4. Point 2 is near the moving apex of the trough axis.
- Note 5 Set airboirne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

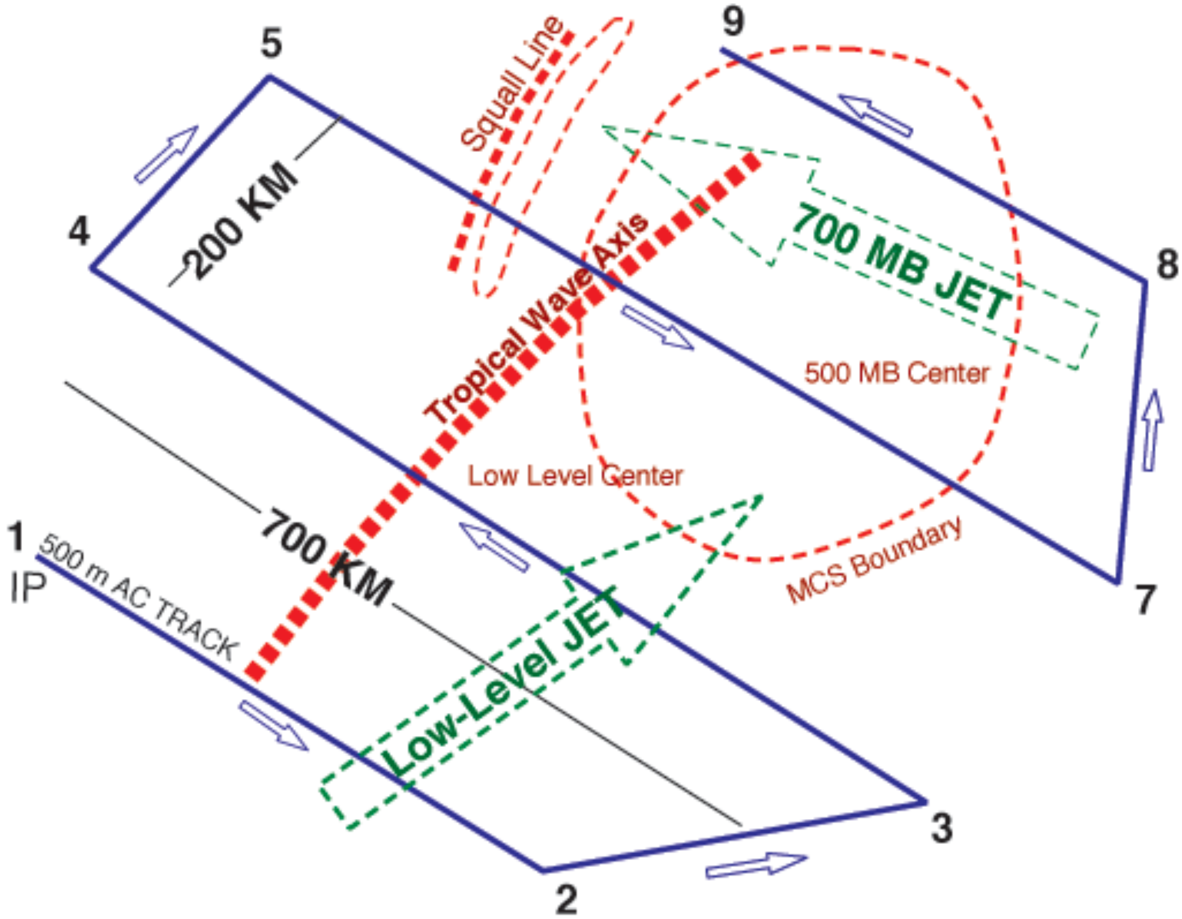


Figure 28 Low-level Grid Flight Track

- Note 1: True airspeed 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. Fly 1-2-3-4-5-6-7-8-9 at 1,000 ft (300 m) or 10,000 ft (3.o km) altitude, passing throught the low-level jet, low-level circulation center, MCS and associated mid-level center, or across mid-level jet.
- Note 4. Set airboirne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

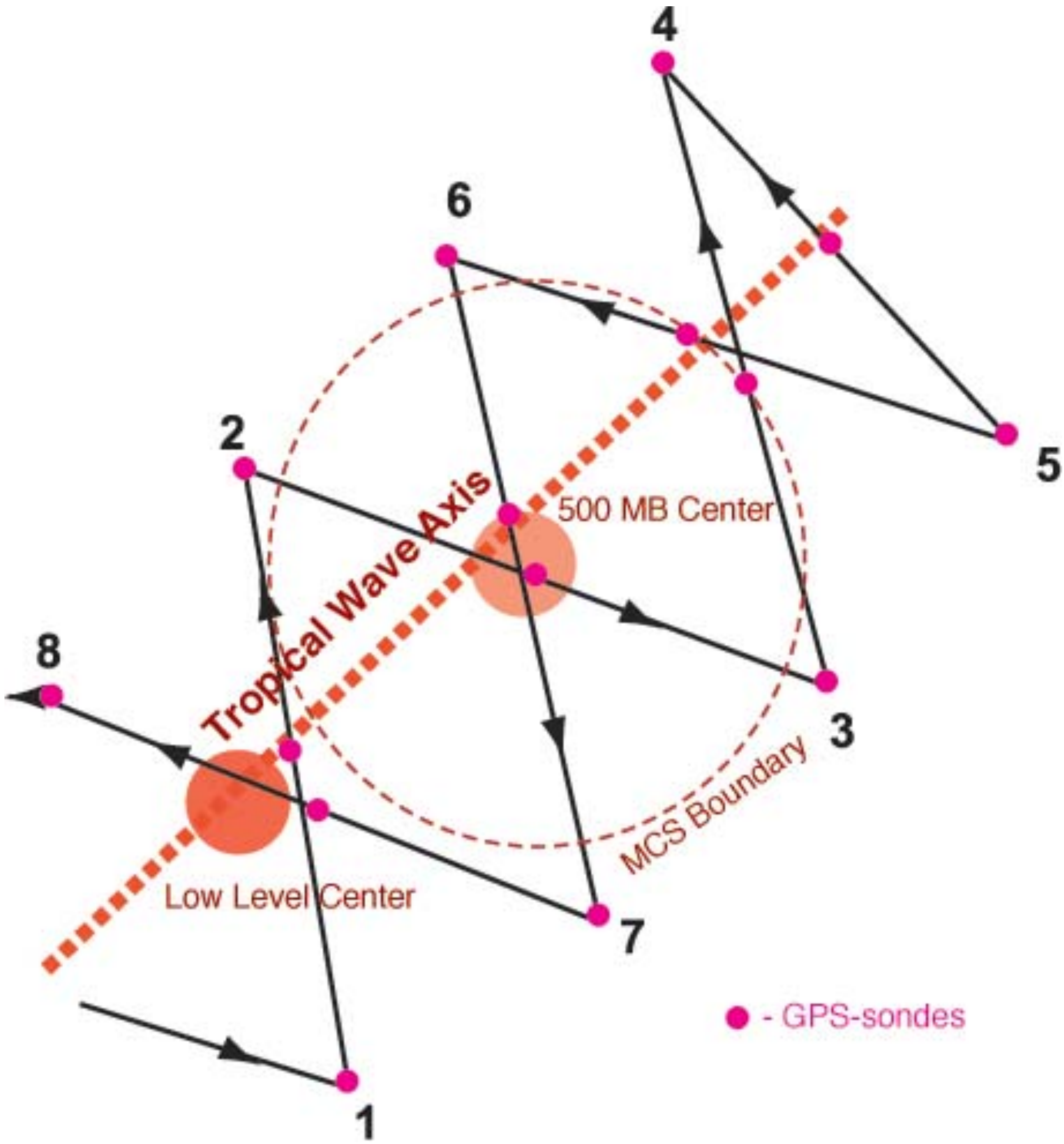


Figure 29 Alternate Grid Pattern

- Note 1: True airspeed 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. Fly 1-2-3-4-5-6-7-8 at 1,000 ft (300 m) or 10,000 ft (3.o km) altitude, passing through the low-level jet, low-level circulation center, MCS and associated mid-level center, or across mid-level jet.
- Note 4. Set airboirne Doppler radar to scan F/AST on all legs.

15. Tropical Cyclone-Midlatitude Interaction Experiment

PROGRAM SIGNIFICANCE: The poleward movement of a tropical cyclone (TC) initiates complex interactions with the midlatitude environment such that the nearly symmetric distributions of winds, clouds, and precipitation concentrated about the mature TC circulation center develop asymmetries that expand greatly in area. 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 extremely large surface wave fields due to the high wind speeds and increased translation speed of the TC that results in a trapped-fetch phenomenon. The relatively 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 specify the exact evolution of winds, waves, and precipitation during the period in question, hereafter referred to as extratropical transition (ET).

During the interaction between a TC and the midlatitude flow, low potential vorticity air in the upper-level TC outflow typically 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. Further 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 interaction between the TC circulation and the midlatitude baroclinic zone may result in enhanced precipitation ahead of the TC that may lead to secondary development on the baroclinic zone and a similar tropopause modification to that caused by the TC outflow.

This interaction between a TC and the midlatitude environment is a source of significant errors in numerical weather prediction models, both with regard to the forecast of the TC track and structure and with regard to the evolution of the downstream midlatitude environment. Because of the lack of observations and the inability of numerical models to adequately resolve the structure of the TC undergoing ET, diagnoses of the changes involved in the interaction are often inconclusive. Furthermore, the downstream modification of the midlatitude flow can lead to significant forecast errors in the 3-14 day forecasts such that errors in the representation of a TC may lead to a degradation of the forecast globally. The observations obtained during this experiment will be used to assess to what extent improvements to analyses of TC structure and the interaction with the midlatitude flow improves numerical forecasts and to develop ensemble and targeting techniques for the forecasting of these interactions.

Targeting data for optimal improvement of forecast of high-impact events has proven to be effective in reducing numerical forecast errors in both the tropics and extratropics. Techniques such as singular vectors, bred vectors, and the ensemble transform Kalman filter have been used in research and operational field programs. However, only bred vectors have proven effective for tropical cyclone targeting. More study is necessary to discern the best technique or combination of target-finding techniques for the ET forecast problem.

The European Composite Observing System (EUCOS) has performed an Atlantic/European THORPEX Observing System Test (TOST) for autumn 2003. The TOST aims to fulfill the following four primary objectives:

1. Test the ability to select appropriate cases for data targeting,
2. Test the predictability of sensitive areas (targets),
3. Assess the ability to target these areas with additional observations,
4. Define the benefit of these additional observations.

EUCOS hopes to gather data from civilian aircraft outfitted with AMDAR, ASAP profiles from ships, enhanced coverage of drifting buoys in the northern Atlantic Ocean, frequent rawinsonde soundings from islands and other remote locations and the European and North American mainlands, driftsonde flights from North America, Meteosat-6 rapid scan winds, and flights from Canadian, German, and UK research aircraft with LIDAR and dropwindsonde capabilities. A number of European operational centers are to perform impact studies with the TOST. The multiple aircraft platforms and suite of sensors available during the combined TOST and the 2004 NOAA Hurricane Field Program, and the overlapping goals of the two, provide a unique and unprecedented opportunity to achieve a detailed observational description of the characteristic changes associated with the interaction of TCs or cyclones undergoing ET with the midlatitude circulation in the western Atlantic from the initial stages of ET, to ultimate impact in Europe. Improved understanding of these changes will contribute to the development of conceptual and numerical models that will lead to improved warnings associated with these potentially dangerous systems. The data gathered during this experiment will be used to develop targeting strategies for improving numerical forecasts of TC/midlatitude interaction.

OBJECTIVE : The objective of this experiment is to gather data to study the impact of extra observations in and around an ET event on the predictability of the cyclone undergoing transition and of the downstream midlatitude flow. 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 and to obtain targeted observations in sensitive regions.

Specific goals are:

- To obtain an over-sampled dataset in order to test targeting and observing strategies and to validate remotely sensed data sets of various parameters during ET.
- To obtain targeted observations in sensitive areas related to the ET event.
- To investigate the viability of the various techniques available for the prediction of sensitive areas associated with ET.
- 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 and validate numerical forecasts of ET with observations.
- To examine whether the TC structure must be observed in order to accurately forecast ET.
- To understand the dynamical and physical processes that contribute to poor numerical weather forecasts of TC/midlatitude interaction.
- To develop ensemble forecasting techniques for ET cases.
- To improve data assimilation into numerical analyses with emphasis on incorporation of special observation types.
- 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 coordinate Canadian and European aircraft with the NOAA WP-3D and Gulfstream-IV (G-IV) aircraft 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 gather microphysical and oceanic measurements of opportunity along the aircraft flight paths.

MISSION DESCRIPTION: The mission is designed to use multiple aircraft to monitor interactions between the TC and the midlatitude circulation and to obtain targeted data in sensitive regions. The ideal storm will be a poleward-moving hurricane that is offshore of the mid-Atlantic coastline of the United States. The optimal mission is designed to examine the tropical core and theTC/midlatitude interface (Fig. 30) and to obtain data in sensitive regions. A list of primary and secondary objectives is provided in Table 1 together with critical observation parameters. Table 1 can be used to determine asset coordination in the event that optional scenarios are required due to limited aircraft availability, storm characteristics, etc. The experiment requires that GPS dropwindsondes should be available on all aircraft. If the opportunity for additional observations is available,

- AXBT instrumentation should be available on the NOAA WP-3Ds.
- The lower fuselage and tail Doppler radars should be operational on both WP-3Ds.
- The C-SCAT and microphysical instruments should be operational on the WP-3D that will fly at upper levels.
- The SRA should be operational on the WP-3D that will fly at low levels.

Flight-level and dropwindsonde data from one NOAA P3 can be used to monitor the cyclone core. Typically, the P3 will be able to be on station for 4-6 h flying “figure 4” “ALPHA” patterns along the cardinal. Nominal leg lengths are 150 n mi at an altitude between 700 mb and 500 mb .

In an optimal setting, three aircraft will participate in staggered missions. The changes in the primary cyclone core characteristics will be examined by N43RF during part of a mission since the SRA will be required to examine surface wave spectra especially in the right front quadrant of the decaying TC. Due to the interaction with the midlatitude baroclinic environment, the structural characteristics of the cyclone change rapidly. Aircraft missions will be staggered to provide continuous coverage of the primary features associated with the decaying TC. Options provide for unavailability of various aircraft. Flight plans for these options are a matter of substituting available aircraft for those unavailable.

CYCLONE REGION: The G-IV will fly a modified figure-4 “ALPHA” pattern at an altitude of 45,000 ft in which three passes over the center of the cyclone undergoing ET will be made (Fig. 31). The pattern will be skewed such that the legs to the north of the center will be longer than those to the south. Also, the pattern will be oriented such that one approach to the center will be from the north to compliment the pattern of the WP-3D that will fly patterns (Fig. 32) rotated to be in the northeast and northwest quadrants of the decaying TC.

If the G-IV and WP-3D depart their base at nearly the same time, the decaying TC center will be observed from 45,000 ft at 1.25, 3.25, and 5 h after takeoff time and from lower levels at 2.25, 4.5, and 6 h after takeoff time. Therefore, the evolution of the warm core and deep convection near the cyclone center will be sampled nearly once an hour during this period of often rapid transformation.

Both the G-IV and WP-3D will deploy GPS 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 that is north of the cyclone center (12 AXBTs).

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

TC/MIDLATITUDE INTERFACE: Immediately ahead of the decaying TC there are important interactions between the midlatitude jet stream and the outflow from the TC. This region will be investigated primarily by the G-IV (Fig. 31), and this portion of any G-IV flight would be available for targeting and predictability studies in coordination with the TOST.

TARGETED OBSERVATIONS: The flight tracks of the second WP-3D and portions of the G-IV flight track will be designed so as to gather data in sensitive areas. A variety of techniques from different forecast models will be considered and a consensus target area defined. The techniques will include bred vectors, singular vectors with a target area along the forecast track of the tropical cyclone, singular vectors with target areas over Europe and the eastern North America, and the ensemble transform Kalman filter.

Potential targets related to ET might be the pre-storm precipitation area, the interface between the upper-level TC outflow and the midlatitude jet, targets upstream of the tropical cyclone, or a trailing anticyclone to the southeast of the tropical cyclone. A possible flight track for the second WP-3D is given in Fig. 33. If no potential target areas are identified for the WP-3D then the pre-storm precipitation area will be investigated (Fig. 34).

If the target areas are close to the storm then both WP-3Ds will do coordinated passes through the storm perpendicular to each other at the beginning and end of each mission. Between these times targeted observations will be made.

Typically, a decaying TC that has entered the transformation stage of ET may translate northward at speeds in excess of 30 kt. If a typical translation speed is observed, the flight plans will be modified to allow recovery in either New England or Nova Scotia. For the second set of missions the cyclone core will be within range of the Canadian aircraft. In this case the Canadian aircraft will observe the cyclone core (http://projects.novaweather.net/work.html) and the WP-3Ds and the G-IV will sample the midlatitude/TC interface and obtain targeted observations. Flight plans will be modified to allow for recovery back to MacDill AFB.

PRE-STORM PRECIPITATION REGION: In the absence of attainable target areas for the WP-3D the pre-storm precipitation region that typically forms ahead of the TC near the primary interface with the midlatitude circulation will be investigated (Fig. 34) by the second WP-3D (preferably N43RF). Initially, the WP-3D will pass through the decaying TC center from the west. If N43RF departs approximately one hour prior to N42RF and the G-IV, it will provide the first center observation about 0.5 h prior to the first Gulfstream-IV observation. Following the pass through the center, N43RF will proceed to the east then turn to the north along a path across the region of warm frontogenesis and potential significant wave heights. Of importance on this leg are observations of surface winds with the C-band scatterometer. Near the pre-storm precipitation area, N42RF will enter a rotated “figure-4” pattern at an altitude near 20,000 ft to examine the lower portion of the TC/midlatitude interface and the microphysical and dynamical characteristics of the pre-storm precipitation area. Two passes along leg 4-5 are planned to observe the lower-levels across the midlatitude jet and TC outflow as the entire system translates northward.

The N42RF aircraft will deploy its first GPS dropwindsonde in the TC center. No dropwindsondes will be required along leg 2-3 since this will be well sampled by the G-IV and N43RF aircraft. Starting at waypoint 3, GPS dropwindsondes will be deployed at approximately 60 n mi intervals (20-25 dropwindsondes) through the second pass along leg 4-5. The ocean thermal profile will be observed ahead of the decaying TC via AXBTs that will deployed starting at waypoint 3 then at 150 nmi intervals (approximately 9 AXBTs). Recovery will be at Boston, MA, Providence, RI, or Greenwood, NS.

Limited Aircraft Availability Option: In the case when one or more aircraft are unavailable, altitude and distance considerations will determine the mission priority. Using Table 1, scenarios may be devised to eliminate or concentrate on specific regions or characteristics.

i) G-IV Unavailable Option: If the G-IV is unavailable, 0ne WP-3D will observe the TC/midlatitude interface and obtain targeted observations (Fig. 33), and the other WP-3D will fly the inner core (Fig.32).

ii) only one WP-3D available: The available WP-3D will fly the TC core pattern (Fig. 32) due to the importance of observing the structural changes of the tropical cyclone during the interaction with the midlatitude flow.

Table 1. Primary and secondary objectives plus optimal aircraft flight level, instrumentation, and aircraft.

Primary Objectives			
Purpose	**Vertical Level**	**Instrumentation**	**Aircraft**
Examine the changes in the structure of the TC core associated with the icreased vertical wind shear of the midlatitude environment, and interactions between the TC core and upper-level synoptic-scale features	Middle troposphere (20,000-30,000 ft) and below	GPS dropwindsondes	WP-3D
Examine the interactions between the TC outflow and the midlatitude environment into which the decaying TC is moving	Upper troposphere (45,000 ft) and below	GPS dropwindsondes	G-IV
Obtain targeted observations in sensitive areas	Upper troposphere (45,000 ft) and below	GPS dropwindsondes	G-IV, WP-3D
Secondary Objectives			
Examine the thermodynamic structure of the pre-storm environment to assess the presence of potential instability and conversion to slantwise, or gravitational instability. Important for organization of heavy precipitation in the pre-storm precipitation area.	Middle troposphere (20,000-30,000 ft) and below	GPS dropwindsondes Microwave radiometer (SFMR)- rain rate Doppler radar	WP-3D N42RF (high-level aircraft)
Examine the microphysical characteristics of the pre-storm precipitation area	Middle troposphere (20,000-30,000 ft) and below	Cloud physics package GPS dropwindsondes	WP-3D N42RF (high-level aircraft)
Examine the oceanic temperature profiles	Ocean	AXBTs	WP-3D (either aircraft)
Examine the surface wind field	Surface	C-band scatterometer (C-SCAT)	WP-3D N42RF (high-level aircraft)
Examine the surface wave spectra ahead of the decaying TC	Ocean surface	Radar altimeter (SRA)	WP-3D N43RF (low-level aircraft)
Examine the evolution of deep convection in response to increased vertical wind shear in the midlatitude environment	Upper troposphere (45,000 ft) and below	GPS dropwindsondes	G-IV
		GPS dropwindsondes Doppler radar Cloud physics package	WP-3D N43RF, low-level aircraft but can be used at Midlevels until SRA is needed in TC/midlatitude interface region
Examine the evolution of extratropical cyclone characteristics such as frontogenesis, asymmetric wind distribution, and warm and cold temperature advection	Middle troposphere and below	GPS dropwindsondes Doppler radar	WP-3D N43RF, low-level aircraft but can be used at mid levels until SRA is needed in TC/midlatitude interface region

Tropical Cyclone-Midlatitude Interaction Experiment

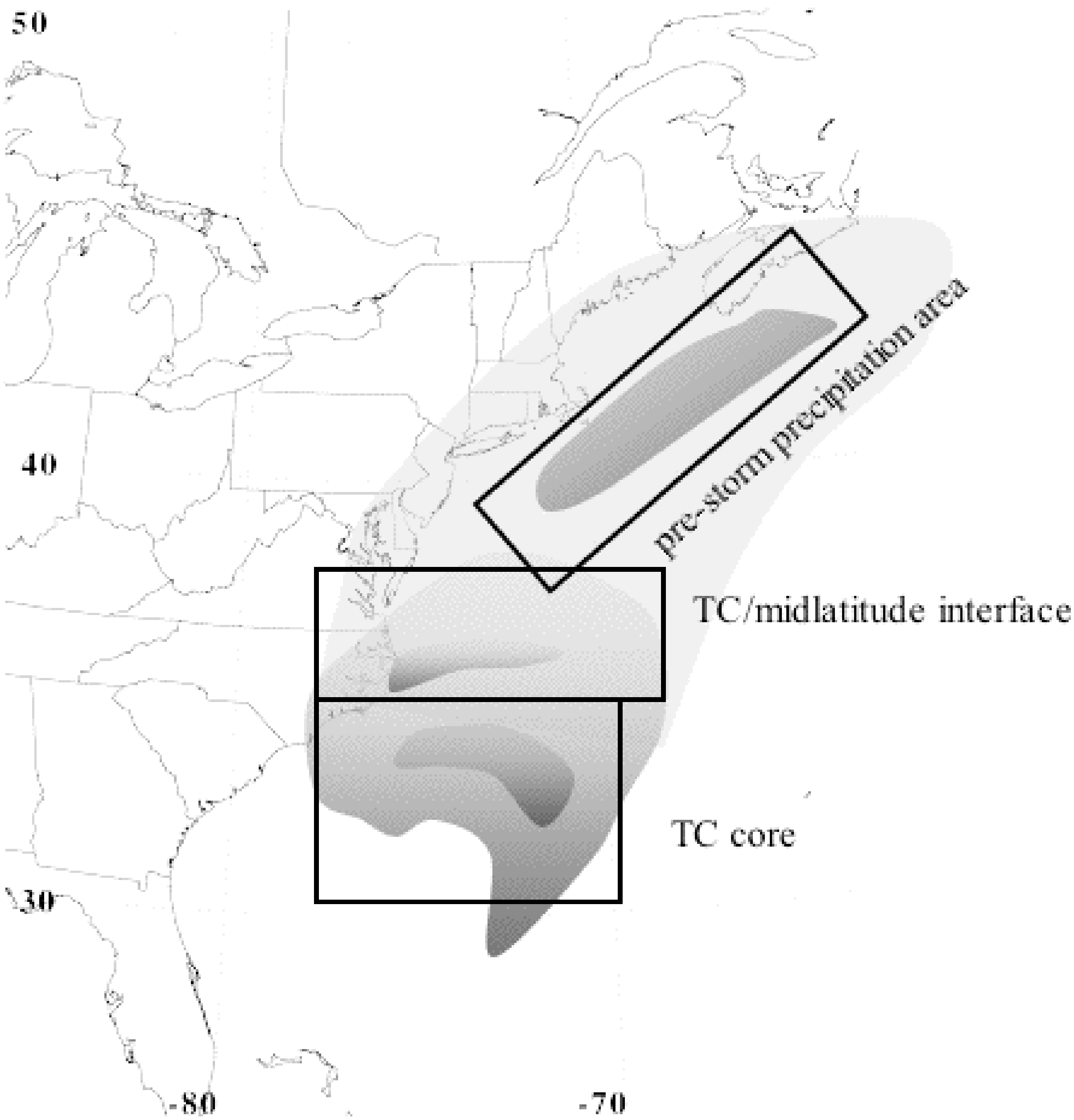
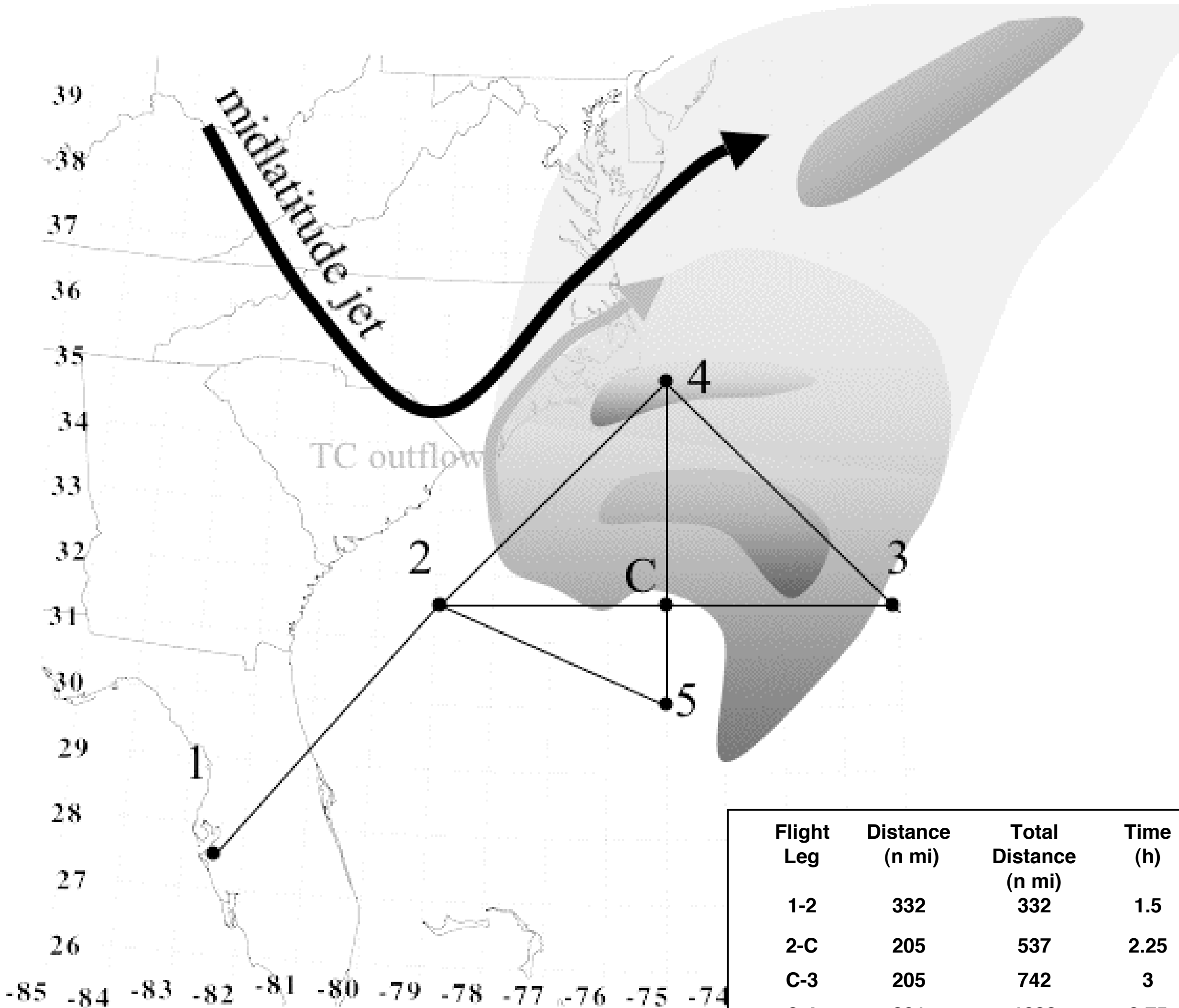


Figure 30. Schematic of Tropical Cyclone undergoing extra-tropical transition.

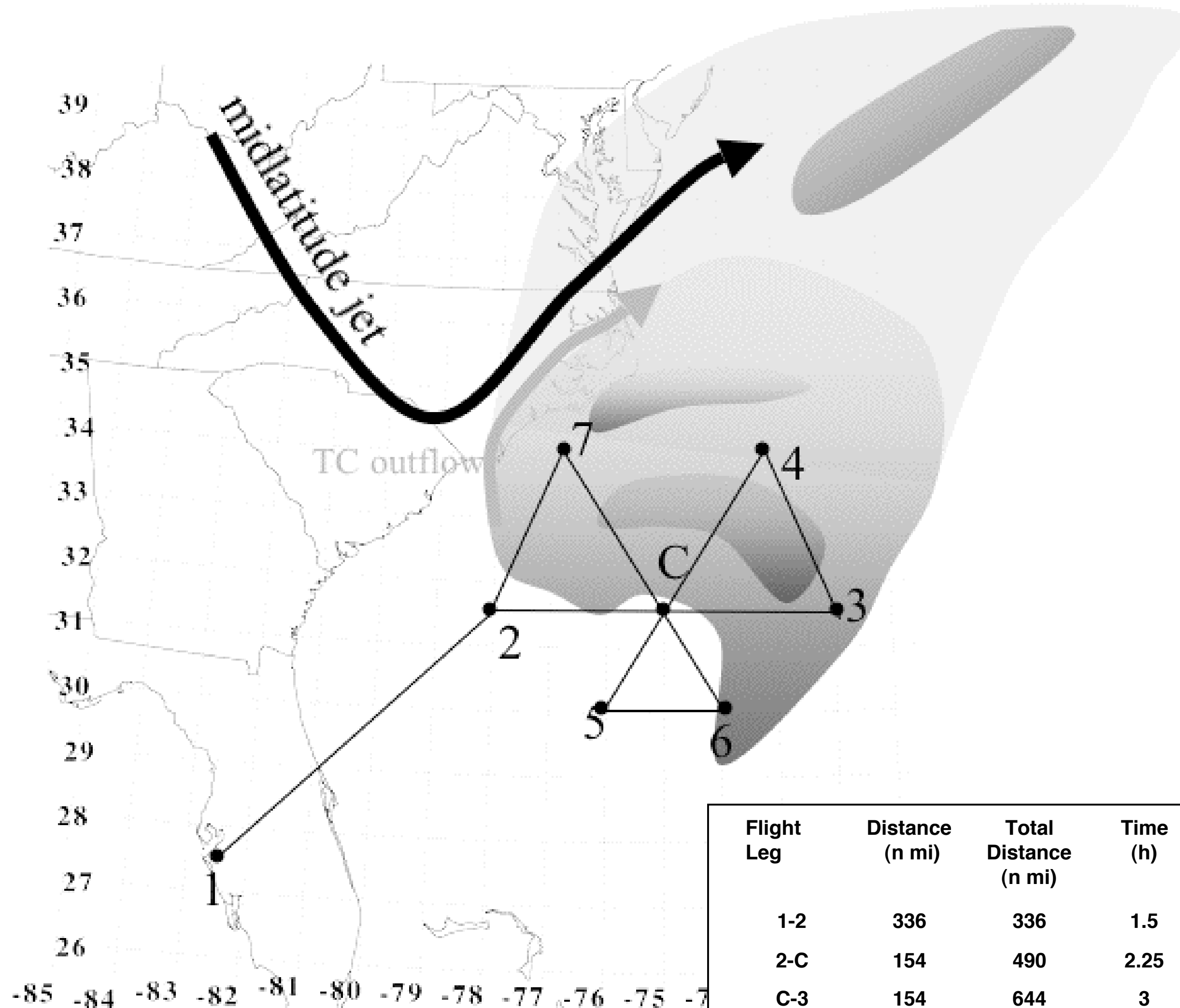
Tropical Cyclone-Midlatitude Interaction Experiment



Flight Leg	Distance (n mi)	Total Distance (n mi)	Time (h)
1-2	332	332	1.5
2-C	205	537	2.25
C-3	205	742	3
3-4	291	1033	3.75
4-C	210	1243	4.25
C-5	90	1333	4.5
5-2	225	1558	5.25
2-C	205	1763	6
C-3	205	1968	6.5
3-4	291	2259	7.25
4-2	291	2550	7
2-1	142	2692	9.5

Figure 31 NOAA G-IV Flight Plan

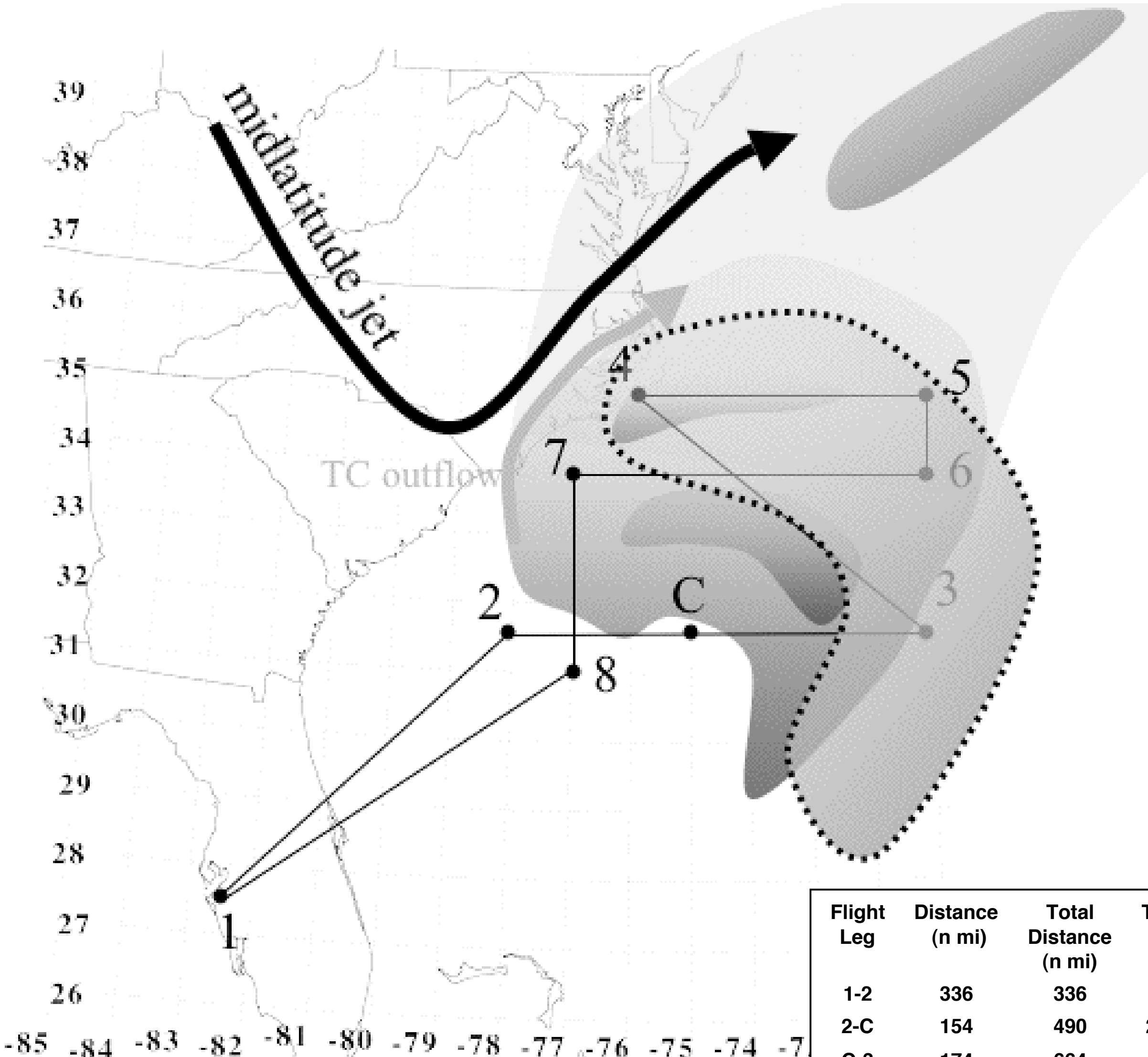
Tropical Cyclone-Midlatitude Interaction Experiment



Flight Leg	Distance (n mi)	Total Distance (n mi)	Time (h)
1-2	336	336	1.5
2-C	154	490	2.25
C-3	154	644	3
3-4	158	802	3.75
4-C	181	983	4.5
C-5	104	1087	5
5-6	104	1191	5.5
6-C	104	1295	6
C-7	181	1476	6.75
7-2	158	1634	7.5
2-1	336	2070	8.75

Figure 32 NOAA WP3-D inner core pattern.

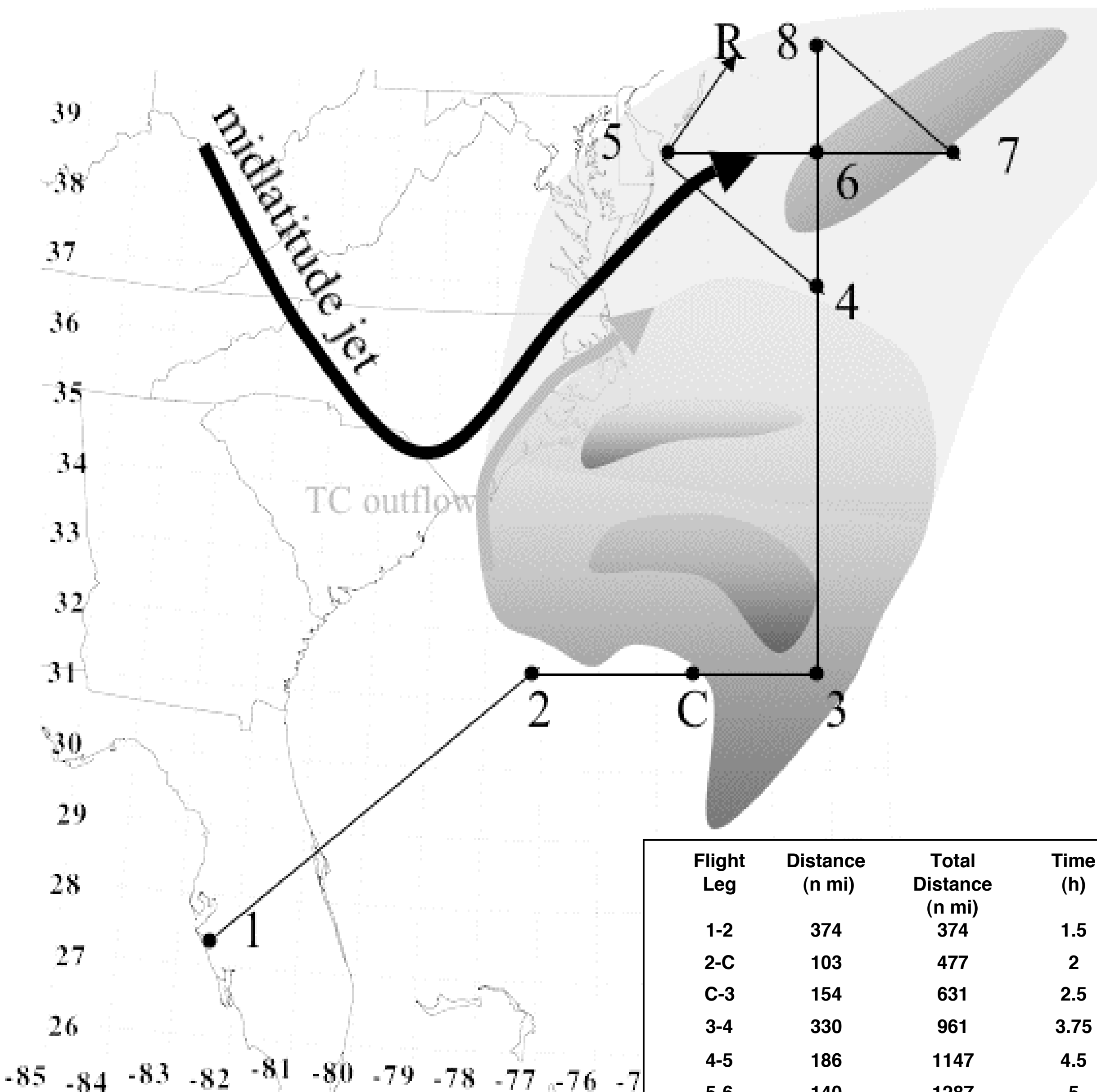
Tropical Cyclone-Midlatitude Interaction Experiment



Flight Leg	Distance (n mi)	Total Distance (n mi)	Time (h)
1-2	336	336	1.5
2-C	154	490	2.25
C-3	174	664	3
3-4	318	982	4.5
4-5	217	1199	5.5
5-6	60	1259	5/75
7-7	290	1549	7
7-8	180	1729	8
8-1	357	2086	9.5

Figure 33. NOAA WP3-D pattern to investigate a typical region of initial condition sensitivity (defined by the area enclosed by the dashed line) associated with a case of extratropical transition in the Western North Atlantic.

Tropical Cyclone-Midlatitude Interaction Experiment



Flight Leg	Distance (n mi)	Total Distance (n mi)	Time (h)
1-2	374	374	1.5
2-C	103	477	2
C-3	154	631	2.5
3-4	330	961	3.75
4-5	186	1147	4.5
5-6	140	1287	5
6-7	140	1427	5.5
7-8	183	1610	6.25
8-6	120	1730	6.75
6-4	120	1850	7.25
4-5	186	2036	8
5-R	237	2273	9

Figure 34 NOAA WP3-D flight pattern to investigate pre-storm precipitation region.

APPENDIX A: AIRCRAFT SCIENTIFIC INSTRUMENTATION

Table A.1. NOAA/AOC WP-3D (N42RF, N43RF) instrumentation

Instrument	Parameter	PI	Group	Electronics Location	Instrument Location	42RF	43RF
Navigational							
INE1/2	LAT, LON		AOC			X	X
GPS1/2	LAT, LON		AOC			X	X
APN-159 altimeter (C-band)	Radar altitude		AOC			X	X
Standard Meteorological							
dew point	Td		AOC			X	X
Rosemount temp	T, T'		AOC			X	X
Static pressure	P		AOC			X	X
Dynamic pressure	P'		AOC			X	X
Horizontal wind	U, V		AOC			X	X
Vertical wind	W		AOC			X	X
Infrared Radiation							
Side CO2 radiometer	T		AOC			X	X
AOC down radiometer	SST		AOC	Under floor,	Down radiometer port	X	X
FRD down radiometer [2]	SST	French	ARL/FRD	Station C3X	LIPA		X
Weather Radar							
LF radar	RR	Marks	HRD	Station 3	Lower fuselage	X	X
TA Doppler radar	U, V, W vs Z, RR	Marks	HRD	Station 3	Fuselage tail	X	X
Passive Microwave							
HRD SFMR/horn ant. [1]	U10, RR	P. Black, Uhlhorn	HRD	Laser hole	LIPF		X
AOC SFMR/pod[2]	U10, RR	Goldstein	AOC	pod	Inner right pylon		X
USFMR (UMASS) [1]	U10, RR	Zhang/ Chang	UMASS/ MIRSL	Station 7	Laser hole	X	
Active Microwave							
IWRAP (CSCAT, KSCAT) [1]	U10, V10; RR; U, V, W vs Z	Zhang/ Chang	UMASS/ MIRSL, NESDIS	Station 7	Fore & aft pressure domes	X	
SRA[1]	$HS_{1/3}$, WPS, WDS, RR	Walsh	NASA/ GSFC,ETL	Station 7	Fore Press Dome		X
Laser Systems							
Laser Altimeter[1]	$H_{1/3}$, WP	Terrill	SIO	Station 7	Vert. Camera port		X
Particle Dynamics Analyzer[2]	Sea spray	Asher	UW/APL	Station C3X	Station3-window blank		
Airborne Ocean Profiler							
AXBT receiver AOC DAT recorder[1]	TS vs Z	Cione	HRD	Station 2	Free-fall chute (aft station 5)		X
AXBT DAT recorder	TS vs Z	Cione	HRD			X	
AOC AXBT receivers	TS vs Z	Smith	AOC	Station 5		X	X
AXBT/SFMR laptop[1]	processor	Uhlhorn	HRD	Station 2	------------------	X	X
Sonobuoy receiver[1]	U10, RR	Terrill	SIO	Station 2		X	
Dropsonde Systems							
GPS AVAPS Dropsonde-4CH	U, TA, RH vs Z	Smith	AOC	Station 5	Aft station 5		X
GPS AVAPS Dropsonde-8CH[1]	U, TA, RH vs Z	Smith	AOC	Station 5	Aft station 5	X	
GPS Dropsonde- 'full up system'	U, TA, RH vs Z	Smith	AOC	Station 5	Aft station 5	X	

Video Systems							
AOC video down	F(%), WD		AOC		Vert. Camera port	X	
Side, nose video	LCL		AOC		Side, nose camera port	X	X
MASS (video down) [1]	WC(%), F(%), WD	Terrill, Melville	SIO	Station 7	Vert. Camera port		X
Down IR camera [2]	Wave breaking	Melville	SIO	Station 7	Aft pressure Dome		X
Cloud Microphysics/ Sea Spray							
2D-P PMS mono probe	Precip size spectra, RR	R. Black	HRD/AOC	Station 4	Outer left pylon		X
FSSP-100 probe	Aerosol, small cloud size spectra	R. Black	HRD/AOC	Station 4	Outer left pylon	X	X
DMT CIP probe[1]	Spray spectra	Fairall	ETL	Station 2	Outer left pylon		X
DMT CIP probe[2]	Cloud LWC	Fairall	ETL	Station 2	Outer left pylon		X
DMT DAS[2]	processor	Fairall	ETL	Station 2	------------		X
2D-C PMS mono probe	Cloud size spectra	R. Black	HRD/AOC	Station C3X	Outer left pylon	X	
2D-P PMS grey probe	Precip size spectra, RR	R. Black	HRD/AOC	Station C3X	Outer left pylon	X	
HVPS (replaces 2DP grey probe)	Precip size spectra, RR	R. Black	HRD/AOC /NASA	Station C3X		X	
SEA M200 DAS	processor		AOC	Station 4	------------	X	X
Johnson-Williams hot wire	Cloud liquid water	R. Black	HRD		Station x	X	
King probe	Total liquid water	R. Black	HRD			X	
Electric field mills (5)	3-axis electric field	R. Black	HRD			X	
Particle Dynamics Analyzer [2]	Sea spray	Asher	UW/APL	Station C3X	Station 3-window blank		X
Water salinity isotope analyzer [3]	Sea spray	Lawrence, Geller	UHOU		Station 3-window blank	X	
TECO Ozone sampler [3]	ozone	Carsey	AOML			X	X
Turbulence Systems							
Friehe radome gust probe system	U',V',W',T'	Drennan	UM/ RSMAS	Nose radome bulkhead	Nose radome	X	X
BAT probe	U',V',W',T'	French	ARL/FRD	C3X	Nose boom		X
IRGA	q'	French	ARL/FRD	C3X	Radome window compartment		X
FAST Hygrometer [1]	RH, q'	Drennan, Hubler	UM/RSMAS ,AL		fuselage		X
LICOR-750 water vapor analyzer[2]	q'	Drennan	RSMAS/ AOC	Nose radome bulkhead	Nose Radome bulkhead	X	X
On board processing							
HRD Workstation	GPS sonde, LF radar processing	Griffin	HRD	Station 3		X	X

[1] Re-installation, user supplied
[2] 2003 installation
[3] Lower priority
[4] 2004 installation
* STD- data on standard DAT tape and CD- one each per aircraft

APPENDIX B: NOAA EXPENDABLES AND RECORDING MEDIA

Table B-1.1. Required expendables for 2004 experiments per flight day for 42RF, 43RF and G-IV

Experiment	GPS sondes			AXBTs		CADs		Sonobuoys
			43RF	42RF	43RF	42RF	43RF	43RF
Saharan Air Layer	15	20	15	20	15	20	15	
Tropical Cyclogenesis	15	30	10	18	18	--	--	
Extratropical Transition	15	30	30	18	18	--	--	
TC Wind fields at Landfall		--	25	--	20	--	20	
Hurricane Synoptic-Flow	40	35	35	--	--	--	--	
Hurricane Air-								
Sea Interaction		--		--		--		--
Pre-Storm		--	24	--	24	--	20	--
(Ahead)		42	32	46	--	20	--	--
Pre-Storm (Eddy)		--	30	--	20	--	20	--
In Storm								
CBLAST								
Day 1		68	24	23	17	20	17	10
Day 2		64	24	18	24	18	14	10
Rainband Test		30	30	--	--	--		

Table B-1.2. Required recording media for 2004 experiments per flight day for 42RF, 43RF and G-IV

	DATs[1]	CDs[2]	ZIPs	D-Audio	S-VHS
Experiment			**BAT Probe**	**AXBTs**	**Nose/Side/Down**
Saharan Air Layer (SALEX) 42RF or 43RF	1/1/4 = 6	1/2/2/-/1/1=5	--	6	1/2/1=4
Tropical Cyclogenesis 42RF or 43RF	1/2/4 = 7	1/2/2/-/1/1=5	--	6	1/2/1=4
Extratropical Transition	1/2/4 = 7	1/2/2/-/1/1=5	--	6	1/2/1=4
TC Wind fields at Landfall 43RF	1/2/4 = 7	1/2/2/2/1/1=7	6	6	1/2/-=3
Hurricane Synoptic-Flow					
42RF	1/-/4 = 5	1/2/2/-/1/1=5	--	6	1/2/1=4
43RF	1/2/4 = 7	1/2/2/2/1/1=7	6	6	1/2/-=3
Air-Sea Interaction					
42RF	1/2/4 = 7	1/2/2/-/1/1=5	--	6	1/2/1=4
43RF	1/2/4 = 7	1/2/2/2/1/1=7	6	6	1/2/-=3
CBLAST					
42RF	1/2/4 = 7	1/2/2/-/1/1=5	6	6	1/2/1=4
43RF	1/2/4 = 7	1/2/2/2/1/1=7	6	6	1/2/-=3

[1]DATs required for Slow / Fast flight-level / Radar data
[2]CDs required for Slow / Fast flight-level / Cloud Physics / BAT / AVAPS / HRD workstation data
NOTE: *1 DAT and 1 CD are required for G-IV missions*

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