13. TC-Ocean Interaction Experiment

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

Significance and Goals:

This component of the experiment broadly addresses improving understanding of the ocean's role in air-sea interaction and controlling TC intensity by making detailed measurements of these processes in storms. Specific science goals are in two categories:

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

1. Quantify the influence of the underlying ocean on atmospheric boundary layer thermodynamics and ultimately storm intensity.

2. Quantify the capabilities of the operational coupled model forecast system to accurately capture and represent these processes

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

Rationale:

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

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

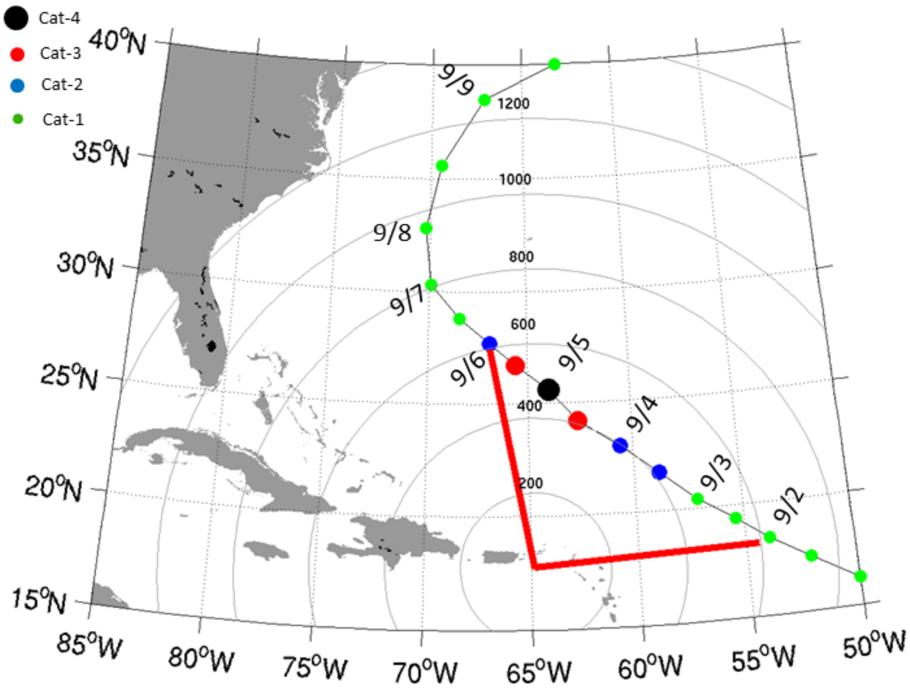


Figure 13-1: *Storm track with locations plotted every 12 hours. of Range rings are 200 nmi relative to forward operating base at St. Croix, USVI (STX/TISX), and red line delineates storm locations within 600 nmi of STX. In this example, the storm center remains within 600 nmi for 4 days.*

This multi-aircraft experiment is ideally conducted in geographical locales that avoid conflict with other operational requirements, for example, at a forward/eastward-deployed base targeting a storm not imminently threating the U.S. coastline. As an example, an optimal situation is shown in Fig. 13-1, with missions operating from St. Croix, USVI. A TC of at least minimal hurricane intensity is desired. In this example, the hypothetical storm remains within 600 nmi (a reasonable maximum distance) for four days, and at no time is forecasted to be a threat to land, including the U.S. coast.

a) Expendable profiler surveys from P-3 aircraft

Flight sequence:

Pre-storm: To establish the pre-storm upper ocean thermal and mass structure prior to a storm's arrival, a pre-storm expendable survey will be conducted. This mission will consist of deploying a large grid of AXCTDs/AXBTs to measure the three-dimensional temperature and salinity fields (Fig. 13-2). This flight would occur **48 hours prior to storm arrival**, based primarily on the forecasted track, and optimally covers the forecast cone-of-error. A total of **50-60 probes** would be deployed, depending on mission duration, and spaced approximate 0.5 deg. apart. The experiment is optimally conducted where horizontal gradients are relatively small, but AXCP probes may be included if significant gradients (and thus currents) are expected to be observed. Either P-3 aircraft may be used as long as it is equipped with ocean expendable data acquisition hardware.

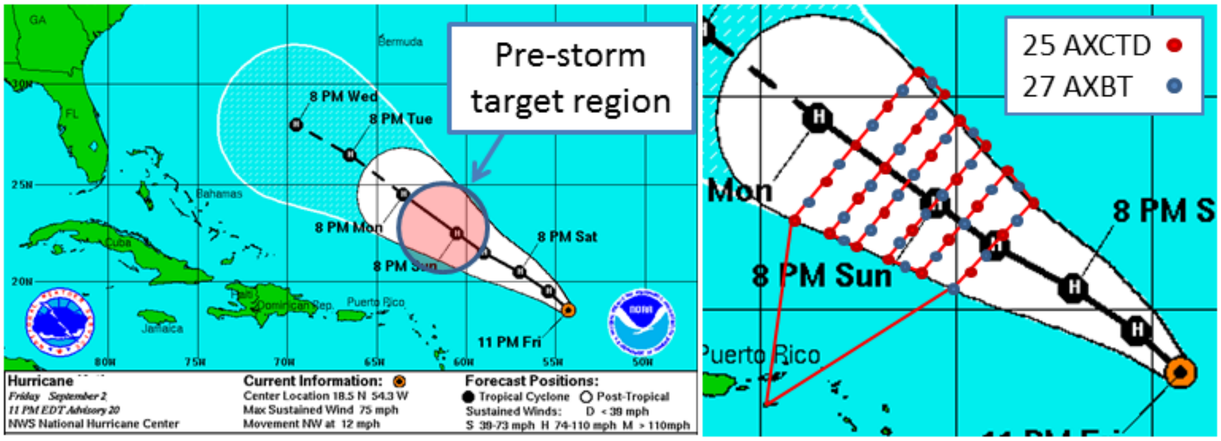


Figure 13-2: *Left: NHC official forecast track, which pre-storm ocean sampling region highlighted. Target region is centered ~48 hours prior to forecast arrival of storm. Right: P-3 flight track (red line) and ocean sampling pattern consisting of a grid of AXCTD/AXBT probes Probes are deployed at ~0.5 deg. intervals. Total time for this pattern is estimated to be ~9 hours.*

In-storm: Next, a mission is executed within the storm over the ocean location previously sampled (Fig. 13-3). This flight shall by conducted by the **P-3 carrying the Wide-swath Radar Altimeter (WSRA)** for purposes of mapping the two-dimensional wave field. The flight pattern should be a **rotated Figure-4**, and up to **20 AXBTs** should be deployed in combination with GPS dropwindsondes. Note that other experimental goals can and should be addressed during this mission, and a multi-plane mission coordinated with the other P-3, as well as G-IV, is desirable.

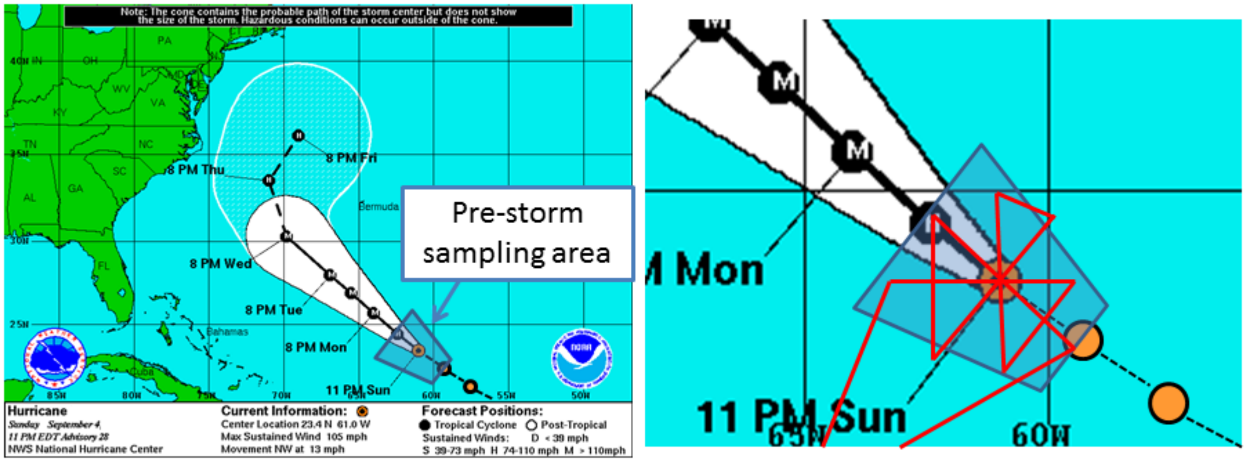


Figure 13-3: *Left: NHC official forecast track at time of in-storm mission, with pre-storm sampled region highlighted. Right: P-3 in-storm flight pattern centered on storm and over previously-sampled ocean area. Typical pattern is expected to be a rotated Fig-4. Total flight time ~8 hrs.*

Post-storm: Finally, a post-storm expendable survey shall be conducted over the same geographical location to assess ocean response, with slight pattern adjustments made based on the known storm track (Fig. 13-4). Approximately **60-70 probes** would be deployed (depending on duration limits), consisting mainly of **AXBTs/AXCPs** to map the three-dimensional temperature and currents, ideally 1-2 days after storm passage. In the Fig. 3-8 example, the pattern extends 470 km along the storm track, which in this example is ~0.75Λ, where

$\Lambda = 2\pi V/f$ is the inertial wavelength. Ideally, the pattern should extend up to 1Λ to resolve a full ocean response cycle. The storm speed V and flight duration limits will dictate whether this is possible. As for the pre-storm survey, either P-3 may be used.

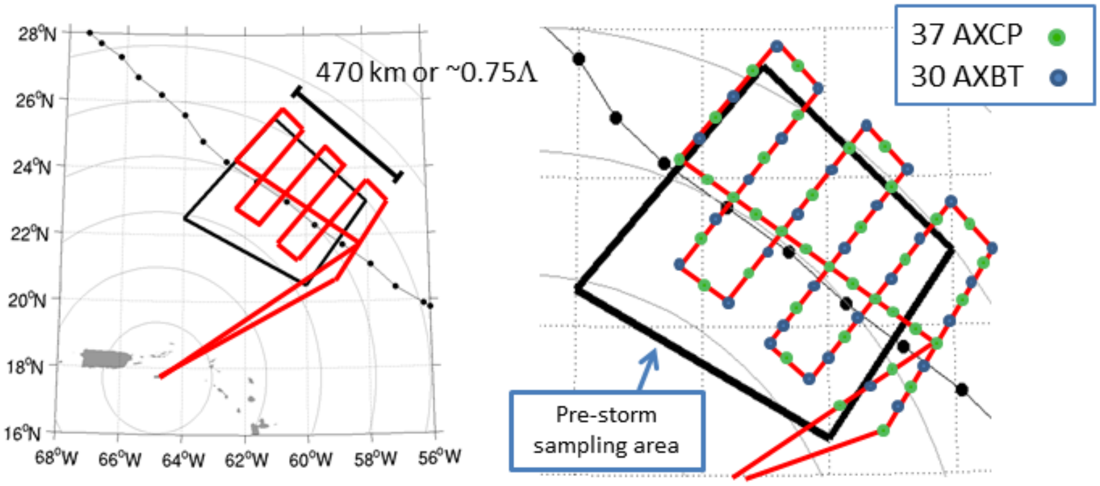


Figure 13-4: *Left: Post-storm ocean sampling flight pattern (red line), over previously-sampled area (black box). In this example, the pattern extends around 470 km in the along-track dimension, or around 0.75 of a near-inertial wavelength. Right: Flight pattern with expendable drop locations, consisting of a combination of AXCP and AXBT probes.*

b) Coordinated float/driftedeployment by AF C-130

Measurements will be made using arrays of drifters deployed by AFRC WC-130J aircraft in a manner similar to that used in the 2003 and 2004 CBLAST program. Additional deployments have since refined the instruments and the deployment strategies. This work will be coordinated with P-3 deployments of AXBTs, AXCTDs and AXCPs to obtain a more complete picture of the ocean response to storms.

MiniMet drifters measure SST, sea level air pressure and wind velocity. Thermistor chain Autonomous Drifting Ocean Station (ADOS) drifters add ocean temperature measurements to 150m. All drifter data are reported in real time through the Global Telecommunications System (GTS) of the World Weather Watch. An additional stream of real-time, quality controlled data is also provided by a server located at the Scripps Institution of Oceanography. A number of E-M APEX Lagrangian floats will measure temperature, salinity and velocity profiles to 200m. Float profile data will be reported in real time on GTS.

Coordination and Communications

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

Flights:

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

Day 1- WC-130J Float and drifter array deployment- Figure 13-5 shows a possible nominal deployment pattern for the float and drifter array. It consists of two lines, A and B, set across the storm path with 8 and 4 elements respectively. The line length is chosen to be long enough to span the storm and anticipate the errors in forecast track, and the lines are approximately in the same location as the pre-storm P-3 expendable probe survey. Instrumentation should be deployed 24-48 hours prior to storm arrival. The element spacing is chosen to be approximately the RMW. In case of large uncertainties of the forecast track a single 10 node line is deployed instead. The thermistor chain drifters (ADOS) are deployed near the center of the array to maximize their likelihood of seeing the maximum wind speeds and ocean response. The Minimet drifters are deployed in the outer regions of the storm to obtain a full section of storm pressure and wind speeds. The drifter array is skewed one element to the right of the track in order to sample the stronger ocean response on the right side (cold wake).

Day 2. P-3 In-storm mission- The in-storm mission will be conducted by the P-3 as previously described. Efforts will be made to deploy AXBTs during the mission near the locations of drifters/floats as reported in real time. It is highly desirable that this survey be combined with an SRA surface wave survey because high quality surface wave measurements are essential to properly interpret and parameterize the air-sea fluxes and boundary layer dynamics, and so that intercomparisons between the float wave measurements and the SRA wave measurements can be made.

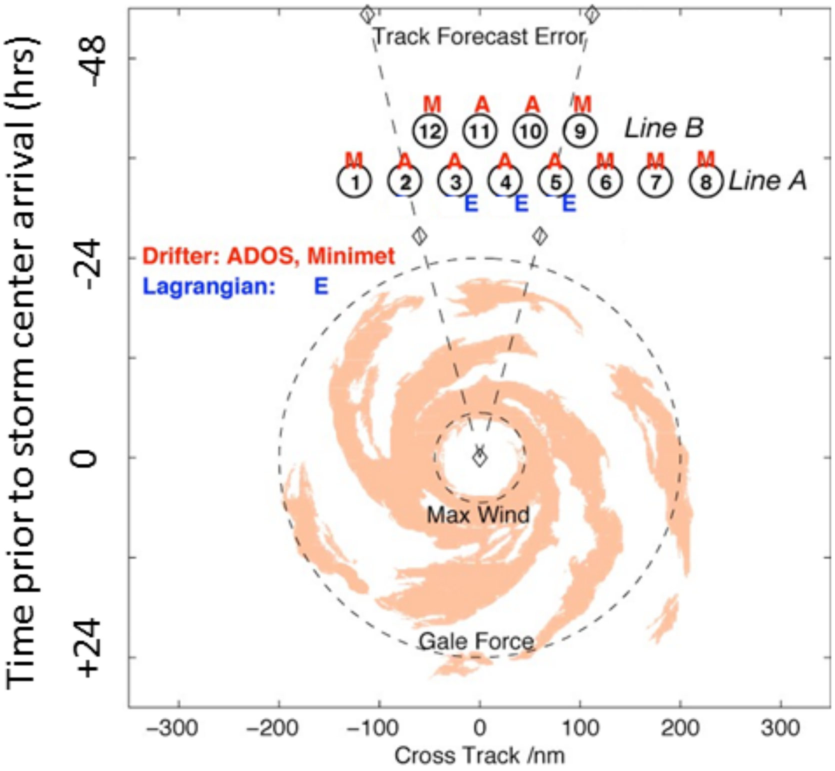


Figure 13-5: *Drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of ADOS thermistor chain (A) and minimet (M) drifters, and EM-APEX Lagrangian floats (E). Two items are deployed at locations 3, 4 and 5, and one item elsewhere.*

c) Underwater glider operations

To complement the aircraft-based experiments, underwater glider operations that started during the 2014 hurricane season will continue. Underwater gliders are cost-effective observational platforms used for targeted and sustained upper-ocean T, S observations, they operate easily in open waters, even under hurricane strength winds, and can be navigated across moderately strong currents. The main objectives of the proposed work are to maintain upper ocean observations from underwater gliders, to evaluate their impact on and to improve understanding of ocean response to hurricane wind forcing and to help improve hurricane intensity forecasts. Of critical importance will be the joint analysis of the data collected through this project with those obtained through other targeted observations, WP-3D and WC-130J flights that deploy a suite of atmospheric sensors, and sustained ocean observations, such as surface drifters, Argo floats, eXpandable BathyThermographs (XBTs), etc.

3.1. Ocean Observations

The first two hurricane underwater glider missions were carried during the 2014 and 2015 Atlantic hurricane seasons (Fig. 13-6). In each mission, two gliders, one in the Caribbean Sea and one in the tropical North Atlantic Ocean, off Puerto Rico, were used and collected approximately 14,000 temperature, salinity, and oxygen profiles in regions that are severely undersampled. Gliders can navigate approximately 4,000 km during one mission and collect and transmit thousands of profiles during a 5-month deployment. While surfaced, they can also download any new instructions for altering the navigation route. Data are transmitted in real-time into the GTS and submitted to data centers for assimilation in forecast models.

During the previous hurricane missions, gliders were piloted to obtain repeated upper ocean sections of temperature and salinity before, during, and after the passage of a hurricane. These data allows to analyze the response of the ocean to the passage of a hurricane and to assess the recovery of the ocean.

Starting in the 2016 Atlantic hurricane season, the network will be expanded to four gliders, with two deployed in the Caribbean Sea and two in the tropical North Atlantic Ocean. These gliders will also include additional sensors, such as CDOM, chlorophyll-a, and backscatter.

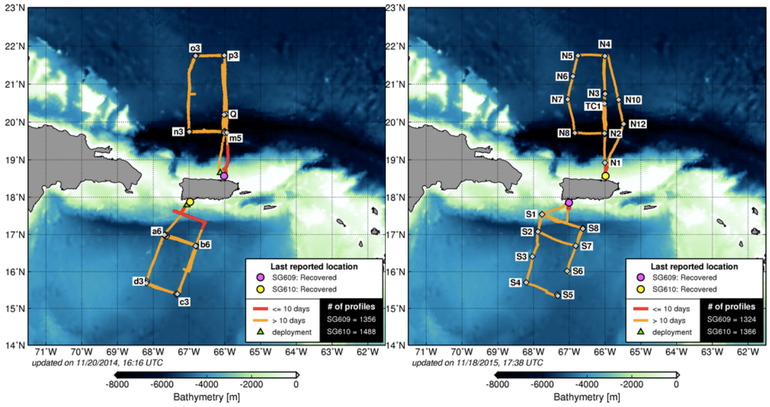


Figure 13-6. *Location of underwater glider observations during the 2014 (left) and 2015 (right) Atlantic hurricane seasons.*

d) AXBT deployments by TROPIC on AF C-130

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

e) Loop current experiment

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

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

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

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

The variability of the Gulf of Mexico Loop Current system and associated eddies have been shown to exert an influence on TC intensity. This has particular relevance for forecasting landfalling hurricanes, as many TCs in the Gulf of Mexico make landfall on the U.S. coastline. To help better understand the LC variability and improve predictions for coupled model forecasts, upper-ocean temperature and salinity fields in the vicinity of the LC will be sampled using expendable ocean profilers (see Fig. 13-7).

Pre- and post-storm expendable profiler surveys

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

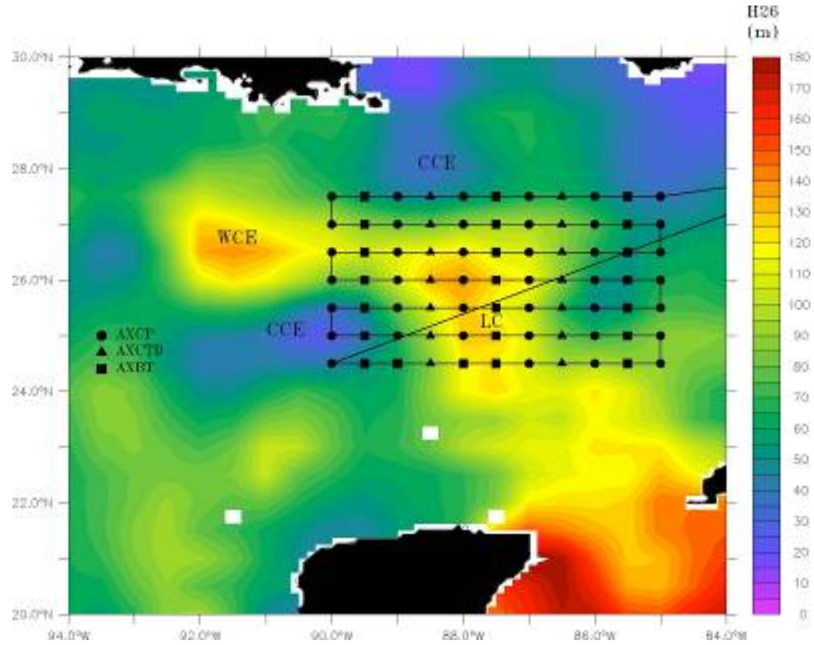


Figure 13-7: *Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at KMCF.*

Track-dependent survey. For situations that arise in which a TC is forecast to travel outside of the immediate Loop Current region, a pre- and post-storm ocean survey focused on the official track forecast is necessary. The pre-storm mission consists of deploying AXBTs/AXCTDs on a regularly spaced grid, considering the uncertainty associated with the track forecast. A follow-on post-storm mission would then be executed in the same general area as the pre-storm grid, possibly adjusting for the actual storm motion. Figure 13-8 shows a scenario for a pre-storm survey, centered on the 48 hour forecast position. This sampling strategy covers the historical “cone of uncertainty” for this forecast period.

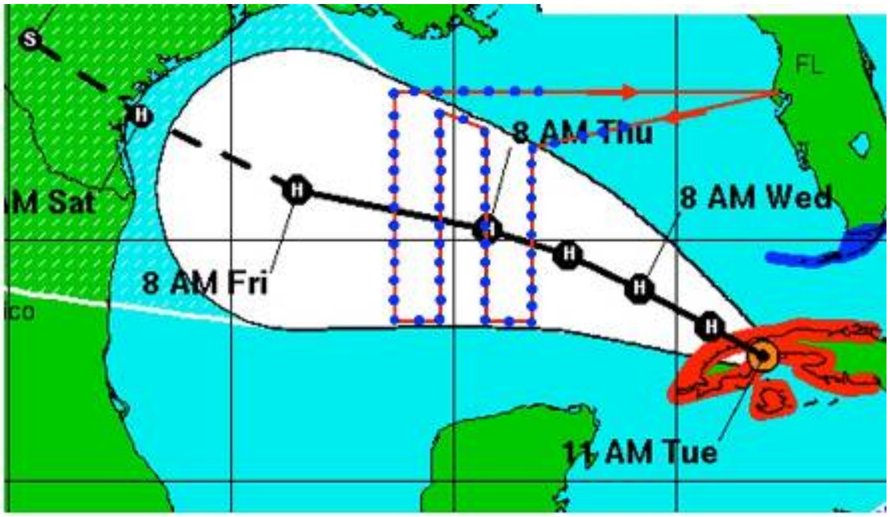


Figure 13-8: *Track-dependent AXBT/AXCTD ocean survey. As for the Loop Current survey, a total of 60-80 probes would be deployed on a grid (blue dots).*

Coordinated float/drifter deployment overflights:

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

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

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

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

Flights:

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

Day 1- WC-130J Float and drifter array deployment- Figure 13-9 shows a possible nominal deployment pattern for the float and drifter array. It consists of two lines, A and B, set across the storm path with 8 and 4 elements respectively. The line length is chosen to be long enough to span the storm and anticipate the errors in forecast track. The element spacing is chosen to be approximately the RMW. In case of large uncertainties of the forecast track a single 10 node line is deployed instead. The thermistor chain drifters (ADOS) are deployed near the center of the array to maximize their likelihood of seeing the maximum wind speeds and ocean response. The Minimet drifters are deployed in the outer regions of the storm to obtain a full section of storm pressure and wind speeds. The drifter array is skewed one element to the right of the track in order to sample the stronger ocean response on the right side (cold wake).

Day 2. P-3 In-storm mission- Figure 13-10 shows the nominal P-3 flight path and dropwindsonde locations during the storm passage over the float and drifter array. The survey should ideally be timed so that it occurs as the storm is passing over the drifter array.

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

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

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

Extended Mission Description:

If the storm remains strong and its track remains over water, a second or possibly third oceanographic array may be deployed, particularly if the predicted track lies over a warm ocean feature predicted to cause storm intensification (Fig. 13-11). The extended arrays will consist entirely of thermistor chain and minimet drifters, with 7-10 elements in a single line. As with the main mission, the spacing and length of the line will be set by the size of the storm and the uncertainty in the forecast track.

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

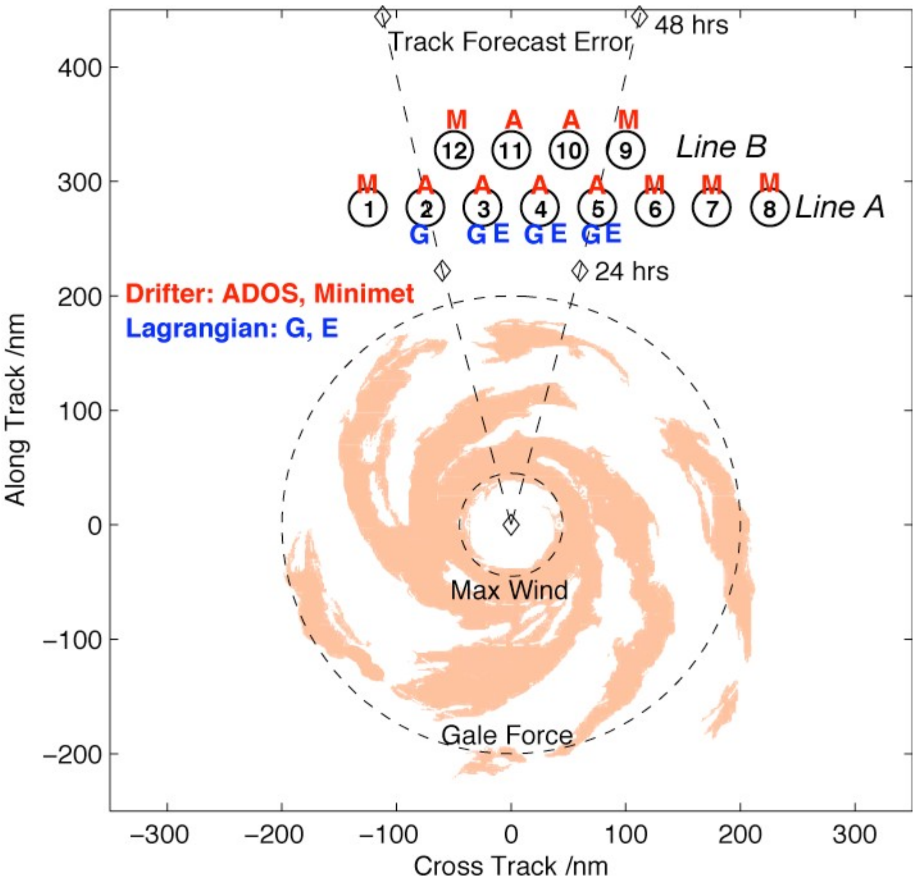
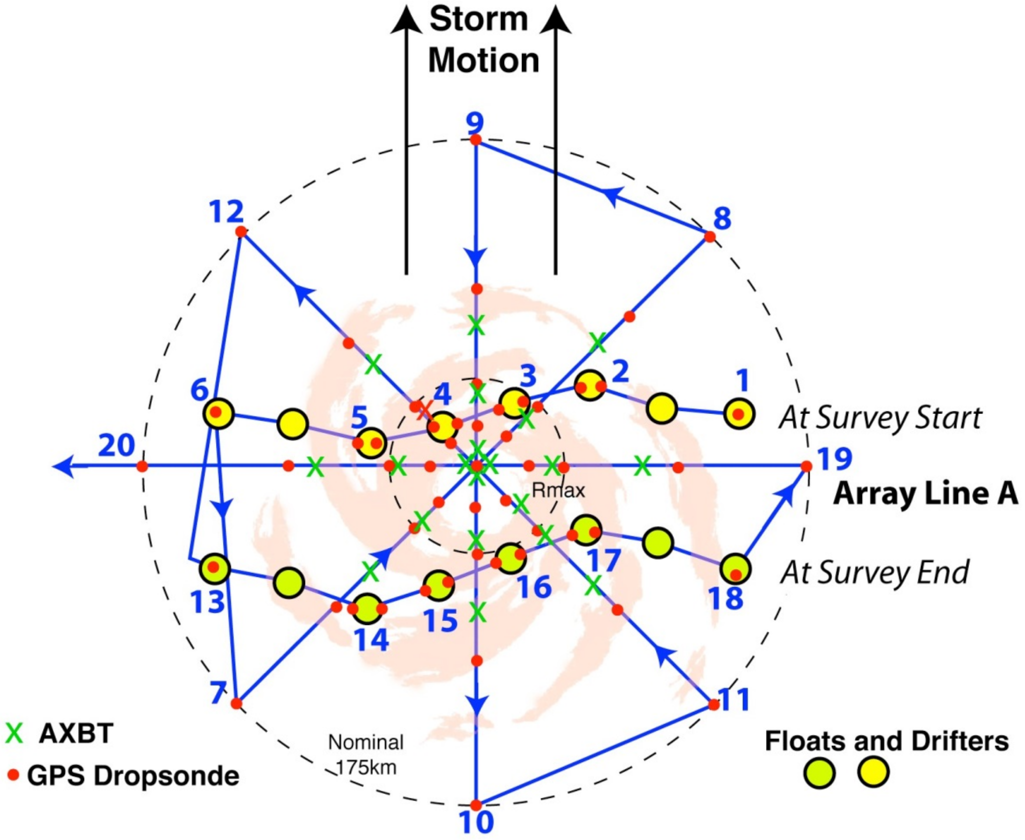


Figure 13-9: *Drifter array deployed by AFRC WC-130J aircraft. The array is deployed ahead of the storm with the exact array location and spacing determined by the storm speed, size and the uncertainty in the storm track. The array consists of ADOS thermistor chain (A) and minimet (M) drifters. Gas (G) and EM (E) Lagrangian floats could be added if available. Three items are deployed at locations 3, 4 and 5, two items at location 3 and one item elsewhere.*



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

Figure 13-10: *P-3 pattern over float and drifter array. The array has been distorted since its deployment on the previous day and moves relative to the storm during the survey. The pattern includes two legs along the array (waypoints 1-6 and 13-18) and an 8 radial line survey. Dropwindsondes are deployed along all legs, with double deployments at the floats. AXBTs are deployed in the storm core.*

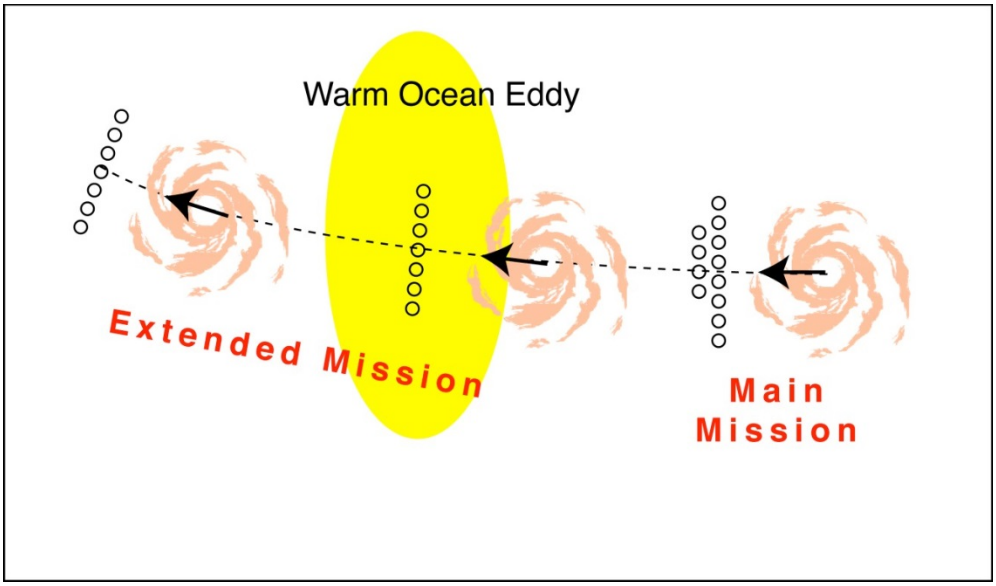


Figure 13-11: *Extended Mission. Two additional drifter arrays will be deployed along the storm track.*