OCEAN OBSERVING EXPERIMENT
Science Description

Experiment/Module: Ocean Survey Experiment

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Requirements: Categories 1–5

Plain Language Description: Physical representation of how the atmosphere and ocean interact in tropical cyclone (TC) forecast models has not been evaluated in great detail. Near simultaneous measurements of the ocean and the atmosphere just above the ocean surface, the energy exchanges that occur between them, and how they change over time will provide a unique opportunity to evaluate how well models represent these lowest regions of storms. The observations that are collected should help improve how forecast models represent interactions between the ocean and atmosphere in hurricanes.

Ocean Observing Science Objective(s) Addressed:

1. Collect datasets that can be used to improve the understanding of intensity change processes, as well as the initialization and evaluation of 3-D numerical models, particularly for TCs experiencing moderate vertical wind shear [*APHEX Goals 1, 3*].
2. Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in early stage TCs. These measurements include improved three-dimensional representation of the TC wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*APHEX Goal 2*].
3. Collect temporal and spatially coincident ocean, wave, and atmosphere observations during the pre-, during, and post-storm phases in order to better address hypotheses related to the ocean and wave boundary layer's role in energy exchange and intensification, evaluate the efficacy of new observing platforms such as wave drifters and Alamo profiling floats, and support data assimilation [*APHEX Goals 1, 3*].

Motivation: Understanding physical processes associated with hurricane intensity and structure change is important for improving hurricane forecast through advanced numerical weather prediction models. Recent improvement in flux parameterizations has led to significant advancement in the accuracy of hurricane simulations and forecasts. These parameterizations, however, were 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. In addition to flux observations, this Ocean Survey Experiment aims to measure the two-dimensional sea surface temperature 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 structure and intensity change. To deduce the mechanisms and entrainment rates (shear-induced) of ocean cooling, the three-dimensional temperature, salinity and velocity structure of the ocean beneath the storm and thereby will also be measured. These observations will be used to assess the accuracy of the oceanic component of the coupled hurricane modeling system. The role of ocean waves in creating spray and spume is thought to be a critical component to both the heat and momentum change and these physics are roughly parameterized in a drag coefficient and drag relationship. The coincident wave observations will begin to build a dataset for evaluating the representativeness of the wave field and drag relationship.

Background: Upper ocean properties and dynamics play a key role in determining hurricane intensity. However, how air-sea interaction influences TC intensity and structure change remains to be explored. Previous 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 and ocean interaction with enough detail to rigorously test coupled TC models. This Ocean Survey Experiment broadly addresses improving understanding of the ocean's role in air-sea interaction and controlling hurricane intensity by making detailed measurements of these processes in storms.

Goal(s): Collect observations targeted at better understanding the response of hurricanes to changes in underlying ocean conditions. Evaluate and improve TC model physics related to air-sea interaction.

Hypotheses: The following hypotheses will guide the sampling strategies for understand the ocean response to TCs and ocean impact of TC intensification:

1. TC intensity is highly sensitive to air-sea fluxes and ocean heat content.
2. Upper ocean properties and dynamics play a key role in determining TC structure and intensity.

Objectives:

1. Collect observations targeted at better understanding the response of hurricanes to changes in underlying ocean conditions.
2. Collect temporal and spatially coincident ocean, wave, and atmosphere observations during the pre-, during, and post-storm phases in order to better address hypotheses related to the ocean and wave boundary layer's role in energy exchange and intensification.
3. Use observational data collected in this experiment to evaluate and improve hurricane model physics related to air-sea interaction and support data assimilation.

Aircraft Pattern/Module Descriptions Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): This multi-aircraft experiment is ideally conducted in geographical locales that avoid conflict with other operational requirements, for example, at a forward/eastward-deployed base targeting a storm not imminently threatening the U.S. coastline. As an example, an optimal situation is shown in Fig. OC-1 for 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 n mi (a reasonable maximum distance) for four days, and at no time is forecasted to be a threat to land, including the U.S. coast.

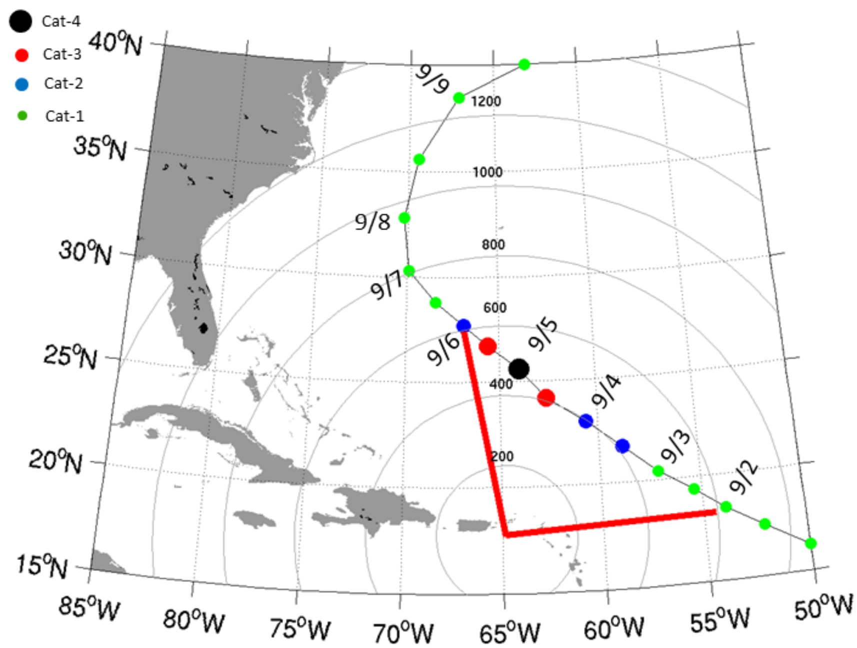

Figure OC-1: *Storm track with locations plotted every 12 hours. Range rings are 200 n mi relative to the forward operating base at St. Croix, USVI (STX/TISX), and the red line delineates storm locations within 600 n mi of STX. In this example, the storm center remains within 600 n mi for 4 days.*

P-3 Pattern #1: Ocean Survey (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. A-sized DWSTM wave drifters (pending AOC approval for deployment from the NOAA P3) will be deployed in a transect crossing the projected path of the TC. Up to 5-6 A-sized DWSTM wave drifters will be made available for each transect. This flight would occur 24-48 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 (when both available) may be used as long as it is equipped with ocean expendable data acquisition hardware.

P-3 Pattern #2: Ocean Survey (In-storm)

This mission is executed within the storm over the ocean location previously sampled. This flight shall be conducted by the P-3 carrying the Wide-swath Radar Altimeter (WSRA) for purposes of mapping the two-dimensional wave field. The flight pattern should be a rotated Figure-4, and up to 20 AXBTs should be deployed in combination with GPS dropwindsonde. A-sized DWSTM wave drifters (pending AOC approval) will be deployed, at least one in each quadrant of the storm, to compare with the WSRA and to provide a measure of wave spectral changes. 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.

P-3 Pattern #3: Ocean Survey (Post-storm)
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. 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, over the same area as the pre-storm survey. A transect of 5-6 A-sized wave buoys would be deployed to measure the corresponding changes in the wave field.

P-3 Pattern #4: Ocean Survey (Loop Current, Pre- and Post-storm)
For missions targeting Loop Current effect on hurricane intensity and structure, each feature-dependent survey consists of deploying 60–80 expendable probes, with takeoff and recovery at AOC. Pre-storm missions are to be flown one to three days prior to the TC's passage in the Loop Current. Post-storm missions are to be flown one to three days after storm passage, over the same area as the pre-storm survey. Wave-current interactions will be measured using a transect crossing the Loop Current boundary. The A-sized wave buoys would be deployed together with the Alamo float deployments and can also use the free-fall chute (pending approval by AOC). 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 (6–8 kft).

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.

P-3 Pattern #5: Ocean Survey (Loop Current, In-storm)
In-storm missions, when the storm 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 20–40 aircraft expendables deployed for measuring sea surface temperatures, salinity and currents underneath the storm. In-storm missions will coordinate with float/drifter deployment by AFRC WC-130J aircraft. In addition to the traditional hurricane drifter deployments, the A-sized DWSTM wave drifter will be deployed. 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), also assisted by Lance Braasch, Terri Paluzkiewicz, and Rick Lumpkin will be the primary points of contact for coordination with the

53rd WRS and CARCAH. One deployment opportunity will be sought, on a non-interference basis with the atmospheric data collection missions.

P-3 Pattern # 6: Ocean Survey (Float and Drifter)
Coordinated float and 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. Luca Centurioni, Lancelot Braasch and Terri Paluszkiewicz will be the primary POC for the ADWS^{TM} drifter missions.

P-3 Pattern # 7: Ocean Survey (Glider coordination)
Coordinated glider deployments would nominally consist of one P3 flight. The flight pattern should be a Figure-4 or rotated Figure-4, and up to 8 AXBTs should be deployed in combination with GPS dropsondes. The goal is to sample the area where the gliders are deployed in storms.

Operations and Logistics:

During Day 1, WC-130J will deploy floats and drifters ***ahead of the storm***. 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 DWSTM wave drifters are deployed closest to the MiniMet drifter to create a database of observations that will be useful in evaluating the ocean wave forecast models; the nearly coincident measurement of waves and winds allows for better determination of appropriate data assimilation and comparison of wind-wave forecasts. 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). Three quasi-Lagrangian floats (APEX-EM) will be deployed along the track, 1–2 Radius of the maximum wind speed (RMW) and 3–4 RMW to measure the rapidly evolving velocity shear and extent of the vertical mixing and cooling of the surface mixed layer.

During Day 2, the P3 ocean survey should ideally be timed, so that it occurs as the storm is passing over the drifter ***and float array***. The survey includes legs that follow the elements of float/drifter line 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 will therefore be determined from the real-time positions of the array elements. Each line uses 10 dropsondes, 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 10 m data. The rest of the survey consists of 8 radial lines from the storm center. Dropsondes are deployed at the eye, at half RMW, at RMW, at twice RMW and at the end of the line, for a total of 36 releases. Aircraft expendables are deployed from the sonobuoy launch tubes at the eye, at RMW and at 2 RMW. This array is focused on the storm core where the strongest air-sea fluxes occur; the buoy and float array will fill in the SST field in the outer parts of the storm. If conditions indicate, reserved A-sized DWSTM wave drifters can be deployed in the storm core to support the comparisons described below.

It is highly desirable that this survey be combined with an *WSRA (Wide Swath Scanning Radar Altimeter)* 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 and drifter wave measurements* and the WSRA wave measurements can be made. In addition, the directional wave measurements from the WSRA, and the DWSTM wave drifters, when combined with current measurements from AXCPs or APEX-EM floats, provide structural observations of the effect of surface waves on the oceanic planetary boundary layer processes.

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. 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.

Links to Other Experiments/Modules: The pre- and post-storm versions of this experiment can be flown in conjunction with the ADM-Aeolus Satellite Validation Module. The in-storm P-3 pattern can be flown in conjunction with most Early, Mature, and End Stage experiments. In particular, planning will be done in conjunction with the hurricane boundary layer module, RICO SUAVE and Ocean Observing Module so that both ocean and atmospheric boundary layer kinematics and thermodynamics are sampled concurrently to understand air-sea feedback to TCs.

Analysis Strategy: Upper-ocean three-dimensional thermal, salinity, and current structures will be measured from P-3 aircraft with airborne expendable bathythermographs (AXBT), conductivity–temperature–depth sensors (AXCTD), and current profilers (AXCP). Specifically, AXBT data will be acquired to ~400-m depth, compared to 1000m and 1500m for AXTCD and AXCP data, respectively. Additionally, measurements will be made using arrays of profiling and Lagrangian floats (APEX-EM) and wave and other drifters deployed by AFRC WC-130J aircraft in a manner similar to that used in the 2003 and 2004 CBLAST program (Black et al. 2007), and the ITOP experiment (D'Asaro et al., 2011; Mrvaljevic et al., 2010). Additional deployments have since refined the instruments and the deployment strategies. MiniMet drifters will measure SST, surface pressure and wind speed and direction. Thermistor chain Autonomous Drifting Ocean Station (ADOS) drifters add ocean temperature measurements to 150m. The Directional Wave Spectral Drifters will measure wave spectra and provide wave height, direction, dominant period and energy spectra. The A-sized DWSD provides the same information but it "A-sized" so is deployable from a sonoabuoy chute. All drifter data is reported in real time through the Global Telecommunications System (GTS). Flux Lagrangian floats will measure temperature, salinity, oxygen and nitrogen profiles to 200m, boundary layer evolution and covariance fluxes of most of these quantities, wind speed and scalar surface wave spectra. E-M Lagrangian floats will measure temperature, salinity and velocity profiles to 200m. Profile data will be reported in real time on GTS.

The basic analysis follows that presented in recent observational studies of TC-ocean interaction (Shay et al. 1992; 1994; 2000; Shay and Uhlhorn 2008; Halliwell et al. 2011; Zhang et al. 2011, 2013, 2015; Sanabia et al. 2013; Jaimes et al. 2015; 2016; 2021 Lumpkin 2016; Rudzin et al., 2020; Wadler et al. 2021). These analyses include: estimate of sea surface cooling after the storm; estimate of change in the ocean mixed layer depth and ocean heat content (relative to the 26^{o}C isotherm depth) during and after the storm; computation of surface fluxes using the bulk method; estimate of ocean current change during and after the storm, with emphasis in upwelling processes and vertical shear development; evaluate how the surface fluxes are related to storm structure and intensity change; and evaluation of the surface-layer and boundary-layer structure in operational hurricane models using the observational data collected in this experiment.

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