OCEAN OBSERVING EXPERIMENT
Science Description

Experiment/Module: *CHAOS*: Coordinated Hurricane Atmosphere-Ocean Sampling

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Requirements: No requirements: flown at any stage of the TC lifecycle

Plain Language Description:
CHAOS presents a coordinated multi-platform, multi-institutional approach utilizing a diverse suite of innovative observing platforms (i.e., autonomous, uncrewed, expendable) and conventional ones (e.g., aircraft) focused on:

- Targeted coordinated observations of the air-sea transition zone, including the open ocean and coastal regions, to improve the understanding of air-sea interactions before, during, and after tropical cyclone (TC) passage for improved prediction and modeling
- Coordinated atmospheric and oceanic observations with sustained monitoring of key ocean features – e.g., major ocean currents, oceanic eddies and rings, and freshwater barrier layers

Ocean Observing Science Objective(s) Addressed:

1. Collect observations targeted at better understanding air-sea interaction processes contributing to hurricane structure and intensity change [*APHEX Goals 1, 3*]

2. Collect observations targeted at better understanding the response of hurricanes to changes in underlying ocean conditions, including changes in sea surface temperature, ocean mixed layer depth, turbulent mixing and ocean heat content [*APHEX Goals 1, 3*]

3. Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne and surface measurements in TCs. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds and underlying ocean conditions [*APHEX Goal 2*]

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Motivation:
This effort seeks to improve our understanding and characterization of the air-sea transition zone before, during, and after TC passage by coordinating a diverse suite of innovative and conventional observing systems. We present a coordinated multi-platform, multi-institutional approach to better capture and understand ocean and atmosphere features that affect TC changes.

Background:
Air-sea interactions under high-wind conditions are one of the processes critical to TC intensification changes. Recent progress and developments in understanding air-sea interactions and coupled data assimilation for hurricane forecast models point to the importance of observing the air-sea transition zone (the upper ocean, air-sea interface, and atmospheric marine boundary layer as an integrated identity). While the ocean provides the energy needed for storms to intensify, until recently, collocated measurements across the air-sea interface remain limited. Most instances of collocated measurements prior to this experiment were from singular profilers that were sparsely distributed in space and time. Since the introduction and subsequent successes of CHAOS, these collocated observations have started to become more frequent. However, scientific advancements have only further demonstrated the need for these critical collocated observations. The goal of this experiment is to continue observing key features in the air-sea transition zone by coordinating observations across multiple platforms in order to elucidate the physics which guides the evolution of both the ocean and atmosphere.

Goal(s): Facilitate the coordination of a diverse suite of oceanic and atmospheric observing platforms to increase collocated observations of the air-sea transition zone before, during, and after TCs to:

1. Improve understanding of processes in the upper ocean and atmospheric boundary layer that impact TC changes and observe their coupling
2. Improve representation of the ocean in coupled models with sustained monitoring of key ocean features – e.g., major ocean currents, oceanic eddies and rings, and freshwater barrier layers
3. Improve the understanding of how in situ and remote sensing platforms perform, especially during tropical cyclone conditions, with the objective to improve the products provided by these platforms

Hypotheses:

1. Collocated observations in space and time of the air-sea transition zone before, during, and after TC passage will lead to improved understanding of TC track and intensity changes and the ocean's response to TC forcing
2. Dense spatio-temporal coverage of collocated observations of the ocean and atmosphere are necessary for future improvements in coupled modeling
3. Collecting collocated in situ and remote sensing observations in the air-sea transition zone will allow for co-validation and improvement of these platforms.

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Objectives:

1. Coordinated sampling of the upper ocean and atmosphere before, during, and after TC passage using a diverse suite of observing platforms (Fig. 1 below):
    a. Sustained, in situ observations from underwater gliders, saildrones, profiling floats, drifters, moorings, etc.
    b. Targeted observations deployed from aircraft – small uncrewed aircraft systems (sUAS), wave drifters (i.e., A-DWSDs, microSWIFT buoys), atmospheric expendables (i.e., dropwindsondes, IRsondes, StreamSondes), and oceanic expendables (i.e., EM-APEX floats, ALAMO floats, AXBTs).
2. Coordinated sampling of the atmosphere and ocean in varying conditions with remote sensing instruments coincident with in situ platforms and expendables described in Objective 1 to:
    a. Improve understanding of the response of in situ and remote sensing instrument measurements at the air-sea interface in extreme conditions
    b. Improve understanding of the turbulent structure of 3-D near-surface winds in TCs, how they relate to the momentum flux (wind stress) and drag coefficient, and how this relationship varies with the ocean state (wave height, period, age, wind-wave angle).
3. Progress towards a denser suite of coordinated and collocated observations, and demonstrate the improved understanding of atmospheric and oceanic characteristics that influence TCs and the subsequent forecasts.

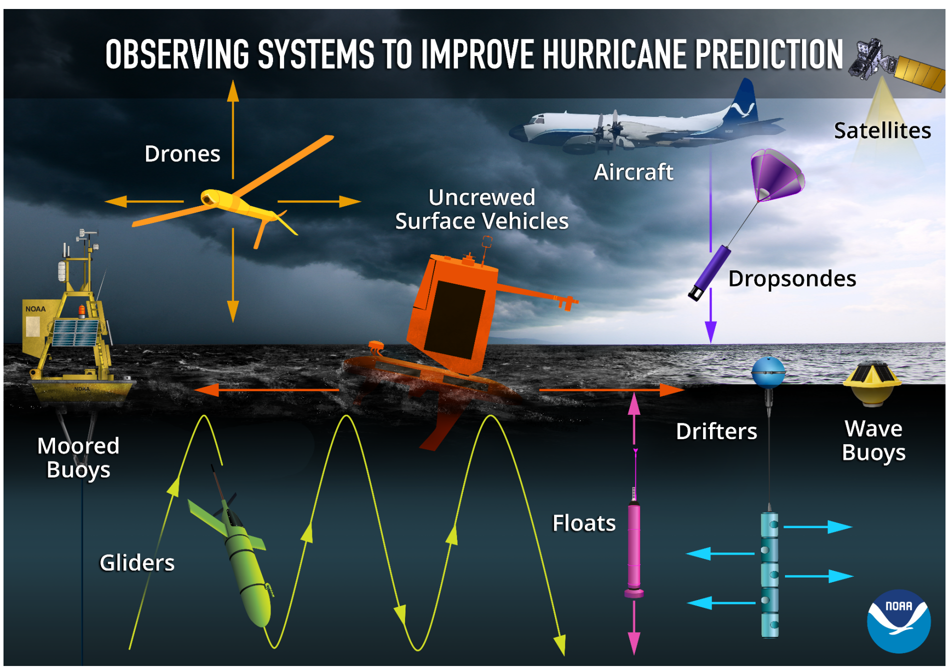

Figure 1: A representation of select platforms used in this experiment to coordinate observations hypothesized to improve the understanding of the evolution of the atmosphere and ocean before. during, and after TCs. *Credit: NOAA PMEL.*

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information):

- **P-3 Pattern #1: Ocean Observing Platform Overflight**
  - The goal for this pattern is to target a pre-existing ocean observing platform (e.g., saildrone, glider, mooring, drifter, profiling float). There is no specific pattern required. Ideally, the pre-existing flight pattern would be adjusted to get as close as possible to the ocean platform. The only constraint is to be within 10 NM of the platform for a successful module. It is a priority to get as close as possible to the platform, with an overfly being preferred. Further, there is a preference for at least one atmospheric and one oceanic expendable (as available) nearest the in situ platform. If multiple ocean platforms are present, conduct Pattern #1 multiple times (if possible) to best fit all platforms present.
- **P-3 Pattern #2: Wave Drifter Deployment and Fly Over**
  - The goal of this pattern is to deploy wave drifters (A-DWSDs and microSWIFTs) in targeted areas within the TC, ahead of the center. For A-DWSD deployments in operationally-based flights, the deployment areas are preferred to be NE (storm-relative) of the TC's center, nearer to the eye wall, with 15-20 NM separation between deployments. For A-DWSD deployments in research-based flights, the deployment area is preferred to be in the eye wall with one being to the NE (storm-relative) of the TC's center and the other being directly to the N (storm-relative) of the TC's center. In both research and operational flights, preference would be to return back to overfly the drifters and deploy atmospheric expendables. However, if overflight is not possible, atmospheric expendables would be co-deployed with the initial drifter deployment. For microSWIFT deployments, preference to be 50 - 100 NM ahead of the TC's center, along the or just to the NE (storm-relative) of the forecasted track. There is an increased desire for both microSWIFTs and A-DWSDs to be deployed during the same mission as complementary to each other. Further, if a pre-existing ocean observing platform is present, there is increased desire to target some of the wave drifters deployments to the ocean observing platform, as requested by the PIs.

- **P-3 Pattern #3: small Uncrewed Aircraft Systems (sUAS)/P-3 Saildrone Overflight**
  - The sUAS is released similarly to either an inflow module or an eyewall module. The drop location for the sUAS is a semicircle away (i.e., directly upwind) from the saildrone, with a preferred distance that gives the sUAS time to establish stable communications with the P-3 and descent to a low altitude. The sUAS will attempt to directly overfly the saildrone at a low altitude. Additionally, the P-3 will overfly the saildrone, preferably as close in time as possible as the sUAS. At this time, the P-3 will deploy as many expendables as possible (especially a possible mass streamsonde deployment). After the overflight, this P-3 module can be conducted using any pattern that maximizes inner core coverage and will collect flight level, TDR, dropsonde, streamSonde, AXBT, and SFMR observations for sUAS comparison and validation. Dropsondes, SST-capable dropsondes, and AXBTs

(10-15 total) will be deployed in locations that are collocated with sUAS under flights. Further, if it is estimated that the sUAS battery and conditions permit a circumnavigation of the TC with a second saildrone overflight, the saildrone/sUAS/P-3 overflight would be conducted again.

- **P-3 Pattern #4: Tropical Cyclone Boundary Layer**
    - The goal of this pattern is to observe the characteristics of the TC boundary layer. This pattern utilizes the standard P-3 patterns (Rotated Figure-4, Butterfly, and Circumnavigation) by deploying dropsondes (18-34 depending on the pattern) and AXBTs (12-16 depending on the pattern) at select locations (e.g., at the RMW, 105 NM radius). All AXBT deployments would be accompanied with a dropsonde. However, not all dropsonde deployments will be accompanied by an AXBT. For all patterns, center drops are requested. The direction the pattern is flown is not relevant. Further, the number of AXBTs can be reduced if IRsondes are used. Optimally, this pattern would be flown in conjunction with sUAS and other UxS (e.g., saildrones, gliders) to augment the boundary layer measurements from AXBTs and dropsondes.

- **P-3 Pattern #5: Surface Wind Temporal Sampling**
    - The goal of this pattern is to collect SFMR, flight-level, dropsonde, and TDR data over a buoy or ocean platform with a reliable anemometer. The aircraft will fly 10-minute legs parallel to the flight-level wind direction in a region of homogenous wind and rain conditions upwind and downwind centered on the buoy or ocean platform's location for approximately 30 minutes, releasing a dropsonde during each pass over the buoy or ocean platform's location. Performing this module in various storm-relative regions of a TC and at different wind speeds would provide insight into the variability of the relationships, allowing us to determine the spatial and/or temporal averaging of aircraft and dropsonde data needed to average and adjust the various observations to be statistically consistent with 1-minute mean winds from buoys. This module would preferably be performed in a region of stratiform precipitation to obtain wind speeds from the TDR.

Links to Other Experiments/Modules:
- SASCWATCH – led by Michael Bell and David Richter
- Ocean Survey Experiment – led by Jun Zhang
- Strategic use of Emerging Technologies To Advance Hurricane Prediction - led by Joseph Cione
- Ocean Winds – led by Paul Chang
- Multi-Lidar Observations of Tropical Cyclone Inflow - led by Guo Lin

Analysis Strategy:
Collocated atmospheric and oceanic observations will be used to understand processes within the air-sea transition zone and investigate the impacts of observations on operational and experimental forecast models. We will focus on better understanding how the evolution of atmospheric and oceanic characteristics and processes before, during, and after TCs influence these dynamic and complex relationships. Further, the collocation of these measurements will permit for a more

robust analysis on the ocean's response to and feedback on these extreme conditions. For example, targeted wave drifter deployments collocated with atmospheric observations allows for the analyses of the evolution of wave-state characteristics with varying atmospheric conditions. Intercomparisons of collocated observations will be performed to calibrate and co-validate the various sensors to provide consistent and improved observations of the air-sea transition zone.

Most data obtained from the observing platforms described above are transmitted in real-time and used in the analyses and improvements of experimental and operational models. Further, these collocated observations provide a broader temporal context throughout the passage of a storm that complements the more discrete overflight observations. Observations collected from these platforms incorporate key air-sea interaction parameters (waves, heat and moisture fluxes), as well as subsurface hydrographic observations (temperature, salinity, currents) that inform operational and experimental coupled models aiming to improve hurricane forecasts. This is accomplished, in part, by providing more realistic initial conditions through data assimilation methods to historically data sparse areas (e.g., upper ocean).

Examples of data assimilative models are the operational Real Time Ocean Forecasting System (RTOFS-DA, coupled to HYCOM) and the experimental Marine JEDI-DA (coupled to MOM6). The value of the various data collected will be analyzed through Observing System Experiments (OSEs). Their impact on hurricane forecasts will provide insights on improvements of the initialization of the Hurricane Analysis and Forecast System (HAFS-MOM6), which is NOAA's current operational tropical cyclone modeling system.

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