**OCEAN OBSERVING EXPERIMENT**
***Science Description***

---

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

**Investigator(s):** Jun Zhang (CIMAS/HRD), Joshua Wadler (Embry Riddle Aeronautical University), Johna Rudzin (Mississippi State), Joe Cione (NOAA AOML/HRD), Nick Shay (UMiami), Chidong Zhang (NOAA PMEL), Gregory Foltz (NOAA AOML), Stephan Howden (USM), Kevin Martin (USM), Travis Miles (Rutgers), Gustavo Goni (NOAA AOML), Kathy Bailey (U.S. IOOS), Steven Jayne (WHOI), Alex Gonzalez (WHOI), Pelle Robbins (WHOI), Paul Chang (NOAA NESDIS), Zorana Jelenak (NOAA NESDIS), Joe Sapp (NOAA NESDIS), Luca Centurioni (Scripps), Martha Schonau (Scripps), Hyun-Sook Kim (NOAA AOML), Matthieu Le Henaff (CIMAS/PhOD), HeeSook Kang (CIMAS/PhOD), Lew Gramer (CIMAS/HRD), Cheyenne Stienbarger (NOAA GOMO)

*Collaborators*: Dave Jones, StormCenter Communications | GeoCollaborate

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

**Plain Language Description:** CHAOS focuses on the coordination of diverse new observing platforms (i.e., autonomous, uncrewed, expendable) and conventional ones (e.g., aircraft) to support:

- Sustained monitoring of key ocean features of the Gulf of Mexico, tropical Atlantic, and/or the Caribbean Sea – e.g., Loop Current, Gulf Stream, eddies and rings, and freshwater barrier layers from the Mississippi & Amazon-Orinoco River Plumes
- Targeted observing of the air-sea transition zone to improve the understanding of air-sea interactions for improved prediction of TC intensification, and/or
- A combination of sustained and targeted observing approaches.

**Ocean Observing Science Objective(s) Addressed:**

1. Collect ocean and atmospheric 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 to underlying upper ocean conditions and their changes, 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 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*]

## OCEAN OBSERVING EXPERIMENT
*Science Description*

**Motivation:**
This effort seeks to improve our understanding and characterization of the air-sea transition zone in the extreme environmental conditions found within a TC by coordinating in-situ and remote observing systems measurements within these conditions. We present a coordinated, multi-institutional, and multi-platform approach to fully capture many of the ocean and atmosphere features that affect TC intensity change.

**Background:**
Air-sea interaction under high wind conditions is one of the processes critical to tropical cyclone (TC) intensification. Recent progress in research of understanding air-sea interaction and developing strongly coupled data assimilation for hurricane forecast models points to the importance of observing the air-sea transition zone (the upper ocean, air-sea interface, and atmospheric marine boundary layer as a single integrated identity). While the ocean provides the energy needed for storms to intensify, to date, co-located measurements of both fluids at the air-sea interface remain rare. Most instances of co-located measurements are from singular profilers that are sparsely distributed. The goal of this module is to observe key features of the air-sea transition zone from multiple platforms in order to elucidate physics of temperature, humidity, and momentum transfer which guides the evolution of both fluids.

**Goal(s):** Deploy and operate a coordinated suite of ocean-atmosphere observing instruments and facilitate colocated observations of the air-sea transition zone before, during, after TCs.

1. Improve representation of the ocean in ocean-atmosphere coupled models through sustained monitoring of key ocean features of the Gulf of Mexico, tropical Atlantic, and/or the Caribbean Sea – e.g., Loop Current, Gulf Stream, eddies and rings, and freshwater barrier layers from the Mississippi & Amazon-Orinoco River Plumes
2. Improve understanding of processes in the upper ocean and lower atmosphere that impact TC intensity through new and established observing systems.
3. Improve understanding of what microwave remote sensing instruments are responding to in the extreme conditions found in TCs, which will in turn improve products provided by these sensors.

**Hypotheses:**

1. Elucidating the role of air-sea interaction and boundary layer recovery will improve understanding of hurricane intensity change.
2. Coordinating ocean and atmosphere observing assets at critical times of rapid intensification will increase opportunities for colocated measurements and improve understanding of the air-sea transition zone during high wind events.
3. Focused observations of essential ocean features before a TC will improve understanding of the ocean's role in TC intensification or weakening.

**OCEAN OBSERVING EXPERIMENT**
***Science Description***

**Objectives:**

1. Sample the upper ocean and atmosphere before, during, and after hurricane events with observations gathered through a diverse suite of platforms:
    a. Sustained, in situ observations from underwater gliders, saildrones, rapid cycling Argo profiling floats, drifters
    b. Targeted observations deployed from aircraft – small uncrewed aircraft systems (sUAS), A-sized Directional Wave Spectra Barometer (A-DWSB) drifters, EM-APEX floats, IRsondes, dropsondes).

2. Sample the atmosphere and ocean surface in hurricane-force wind conditions with varying degrees of rain with IWRAP, KaIA, SFMR(s), and GPS dropsondes coincident with the in situ platforms and expendables described in Objective 1 to:
    a. Improve understanding of the response of microwave remote sensing instrument measurements in the air-sea interface in extreme storm conditions by characterizing this with the proper instrumentation (in-situ and remote sensing instruments) and data collection methodologies.
    b. Improve understanding of the turbulent structure of 3-D near-surface winds in hurricanes, how it relates to the momentum flux (wind stress) and drag coefficient, and how those vary with the ocean state (wave height, period, age, wind-wave angle).

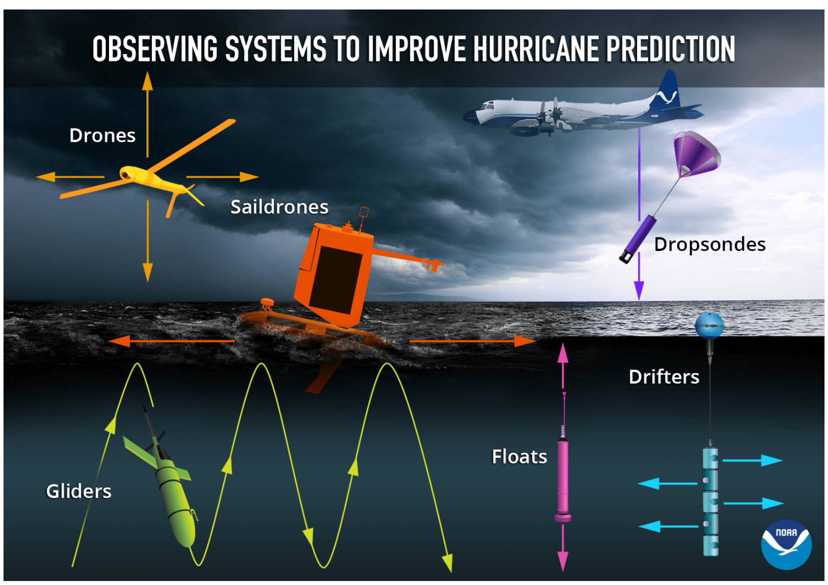


Figure 1: A visual representation of the diverse observing platforms the CHAOS experiment will work to coordinate to observe key features of the air-sea transition zone to better understand TC intensification. *Credit: NOAA PMEL.*

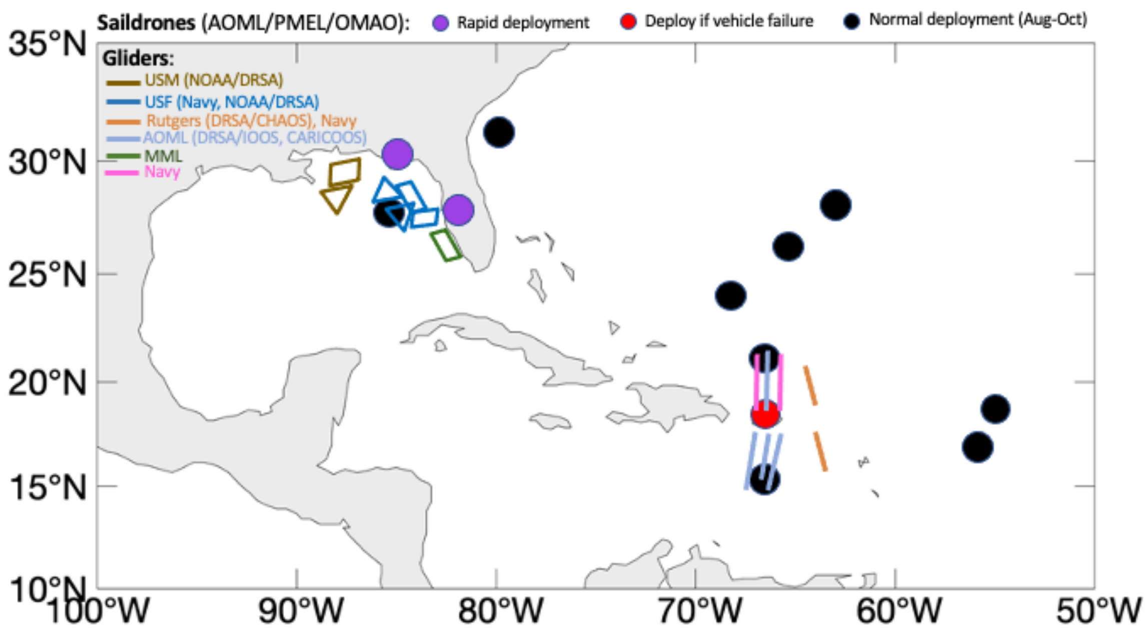


Figure 2: Planned operating areas for saildrones (black circles) and gliders (colored lines/shapes) during the 2023 hurricane season. The glider tracks displayed here represent a subset of the broader Hurricane Glider Program deployments. Purple circles indicate land-stationed saildrones for possible rapid deployment ahead of a storm. Red circle shows location of land-stationed saildrone for replacement of damaged/malfunctioning saildrone, if needed. *Credit: G. Foltz.*

**Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information):** CHAOS_2023HFP_OceanObserving_Flight_Patterns.docx

- **Aircraft Pattern/Module #1 (P-3 Pattern #1):** This is a dynamic, weather-targeting pattern. The interest is in targeting hurricane force winds in both rain and rain-free environments coincident with saildrone, A-DWSB drifters, and EM-APEX floats to obtain insitu wind and wave data in these extreme conditions. Ideally this would involve repeated fly overs of a saildrone, A-DWSB drifters, and EM-APEX floats in the eyewall region. The sensitivity of the IWRAP system defines the preferred flight altitude to be below 10,000 ft radar altitude to enable the system to still measure the ocean surface in the presence of rain conditions typical of tropical systems. With the Air Force Reserve typically flying at 10,000 ft pressure altitude, we prefer an operating altitude of 7,000 ft radar altitude. Operating at a constant radar altitude is desired to minimize changes in range and thus measurement footprint on the ground, but pressure altitude is acceptable. Higher altitudes would limit the ability of IWRAP to consistently see the surface during intense precipitation, but these altitudes would still provide useful data, such as measurements through the melting layer, to study some of the broader scientific questions.
- **Aircraft Pattern/Module #2 (G-IV Pattern #1):** This pattern follows standard G-IV patterns in coordination with the CHAOS and Ocean Survey experiment teams to collect

collocated dropsonde data with ocean platforms. Of note, while coordination with the G-IV is a plus, it is not a requirement for the module to be successful.

**Links to Other Experiments/Modules:**
- Ocean Survey Experiment – led by Jun Zhang
- Hurricane Boundary Layer Module – led by Jun Zhang
- Research In Coordination with Operations Small Uncrewed Air Vehicle Experiment (RICO SUAVE) – led by Joe Cione
- Ocean Winds – led by Paul Chang

**Analysis Strategy:**

Co-located atmospheric and oceanic measurements will be used to understand the transfer of heat, moisture, and momentum. We will focus on how both fluids impact the thermodynamic and kinematic evolution of the hurricane boundary layer with a goal of understanding boundary layer recovery and its relationship to hurricane intensity change.

Most data obtained from the observing platforms described above are distributed in real-time and used in analysis and experimental or operational modeling efforts. In addition, other observations conducted from these platforms incorporate new key parameters, such as waves, sea spray, heat and moisture fluxes, which also serve to advance operational coupled models to improve hurricane intensity forecasts. The impact of the various ocean data collected on the ocean state estimates will be analyzed through ocean Observing System Experiments (OSEs) performed with the RTOFS-DA system, and their impact on hurricane forecasts will be analyzed by initializing coupled hurricane-ocean HAFS-HYCOM prediction with outputs from the ocean OSEs.

**References:**

Domingues, R., M. Le Henaff, G. Halliwell, J.A. Zhang, F. Bringas, P. Chardon, H.-S. Kim, J. Morell, and G. Goni. (2021) Ocean conditions and the intensification of three major Atlantic hurricanes of 2017. Monthly Weather Review, 149(5):1265-1286, https://doi.org/10.1175/MWR-D-20-0100.1.

Le Hénaff, M., R. Domingues, G. Halliwell, J.A. Zhang, H.-S. Kim, M. Aristizabal, T. Miles, S. Glenn, and G. Goni. (2021). The role of the Gulf of Mexico ocean conditions in the intensification of Hurricane Michael (2018). Journal of Geophysical Research–Oceans, 126(5):e2020JC016969, https://doi.org/10.1029/2020JC016969.

Miles, T.N., D. Zhang, G.R. Foltz, J. Zhang, C. Meinig, F. Bringas, J. Triñanes, M. Le Hénaff, M.F. Aristizabal Vargas, S. Coakley, C.R. Edwards, D. Gong, R.E. Todd, M.J. Oliver, W.D. Wilson, K. Whilden, B. Kirkpatrick, P. Chardon-Maldonado, J.M. Morell, D. Hernandez, G. Kuska, C.D. Stienbarger, K. Bailey, C. Zhang, S.M. Glenn, and G.J. Goni. 2021. Uncrewed ocean gliders and saildrones support hurricane forecasting and research. Pp. 78–81 in Frontiers in Ocean Observing: Documenting Ecosystems, Understanding Environmental Changes, Forecasting Hazards. A Supplement to Oceanography 34(4), https://doi.org/10.5670/oceanog.2021.supplement.02-28.

Sanabia, E.R., and S.R. Jayne (2020). Ocean observations under two major hurricanes: Evolution of the response across the storm wakes. AGU Advances, 1:e2019AV000161, https://doi.org/10.1029/2019AV000161.

Wadler, J. B., J. A. Zhang, R. F. Rogers, B. Jaimes, and L. K. Shay, 2021: The Rapid Intensification of Hurricane Michael (2018): Storm Structure and the Relationship to Environmental and Air–Sea Interactions. Mon. Wea. Rev., 149, 245–267, https://doi.org/10.1175/MWR-D-20-0145.1.

Zhang, J.A., J. J. Cione, E. A. Kalina, E.W. Uhlhorn, T. Hock, and J.A. Smith, 2017: Observations of infrared sea surface temperature and air-sea interaction in Hurricane Edouard (2014) using GPS dropsondes. J. Atmos. Oceanic Technol., 0, doi: 10.1175/JTECH-D-16-0211.1.