OCEAN OBSERVING EXPERIMENT
Science Description

Experiment/Module: Sustained and Targeted Ocean Observations

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Requirements: No requirements: work completed at any stage of the TC lifecycle

Plain Language Description: The goal of this module is to provide ocean observations that will serve for analysis to improve the ocean representation in hurricane forecast coupled models, improve our understanding of the air-sea transition zone (the upper ocean, air-sea interface, and marine atmospheric boundary layer), and to increase situational awareness about the types of ocean observations available. Sustained and targeted ocean observations will be directed to monitor essential ocean features (e.g., ocean currents, eddies, warm pools, freshwater barrier layers, and subsurface cool pools) known to be linked to TC changes for use in analysis and to improve the ocean representation in coupled models to forecast TC intensity. Sustained (year-round) and seasonal observations will be mainly conducted from underwater gliders, saildrones, Argo floats, drifters, and XBTs, while targeted observations may also come from these observing platforms plus from air-deployed assets (ALAMO floats, drifters, AXBTs) and airborne remote sensing instruments, some of which are described in other modules, and from specifically designed operations to help better assess the ocean impact on TCs (e.g., co-located saildrones-glider pairs).

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 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*].

Motivation:
Ocean observations have been increasingly acknowledged by the scientific and operational forecast communities as a critical piece to improve Earth system prediction and their importance will continue to increase as extreme weather events increase with our changing climate. Closing gaps in NOAA's ocean observing system from sustained and targeted ocean observations, and coordinated collocated ocean-atmosphere observations, is key to correctly represent the ocean component in ocean-atmosphere coupled intensity models and improving forecasts across all timescales.

The design, implementation, and maintenance of observing systems to generate sustained and targeted, regionally-tailored ocean observations across the complex and rapidly changing ocean environments is a complex task which requires coordinated efforts that result in high-quality, timely, accurate, and authoritative observations and products. The error in the intensity forecast using atmospheric-ocean forecast models has shown to be reduced when the upper ocean water mass and dynamic features are correctly represented. This module presents a coordinated, multi-institutional, regional and international, multi-platform approach to fully capture many of the ocean features that affect the intensity changes of hurricanes.

Background:
Ocean observing efforts in support of hurricane intensity forecasts have been in place for several years. This module coordinates the implementation and operation between the different ocean observing platforms, including underwater gliders, surface and special drifters, ALAMO floats, saildrones, UAS, IR sondes, expendable bathythermographs (XBTs), airborne remote sensing instruments, and other relevant observations and projects. This work derives from coordination efforts being led by the NOAA Global Ocean Observing and Monitoring Program with contributions and engagement from NOAA labs and programs, Cooperative Institutes, and university partners.

Goal(s):
1. Deploy and operate a suite of ocean-atmosphere observing instruments and platforms to collect observations of Essential Ocean Features and the air-sea transitional zone to be assimilated into operational and experimental forecast models, to validate models, and to use to advance scientific research to improve tropical cyclone (TC) intensity forecasts.
2. Provide tools for monitoring in real and near-real time the location of ocean observational assets, ocean conditions and products, and the air-sea transition zone from in situ and satellite observations.
3. Compare, verify and validate measurements from in-situ sensors and airborne remote sensing instruments.

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Hypotheses:

1. Realtime, in situ atmospheric and oceanic data ingested into numerical forecast models and used in data analysis have the potential to improve hurricane intensity forecasts.
2. Coordinating ocean and atmosphere observing assets will provide greater opportunities for collocated measurements and to improve understanding of air-sea interactions during high wind events.

Objectives:

We list here a suite of targeted and sustained ocean observational assets that will be in place during the 2022 Atlantic hurricane season. These assets are primarily geared towards monitoring changes in the upper ocean density field (temperature and salinity) and dynamics to help identify ocean processes and features linked to the intensification or weakening of TCs and of ocean-atmospheric surface parameters key to understanding air-sea fluxes.

The main objectives of the 2022 planned work are:

1. Coordinate the deployment of ocean assets, such as underwater gliders, regular and special drifters, saildrones, ALAMO floats, sUAS, and XBTs in the tropical Atlantic Ocean, Caribbean Sea, and Gulf of Mexico during the 2022 Atlantic Hurricane Season;
2. Transmit all data in real-time into the GTS and ensure the data are available for operational models and forecasts; and
3. Continue to build partnerships between NOAA and academic field and modeling scientists to assess ocean models and to evaluate the impact of ocean observations in operational hurricane forecast models.

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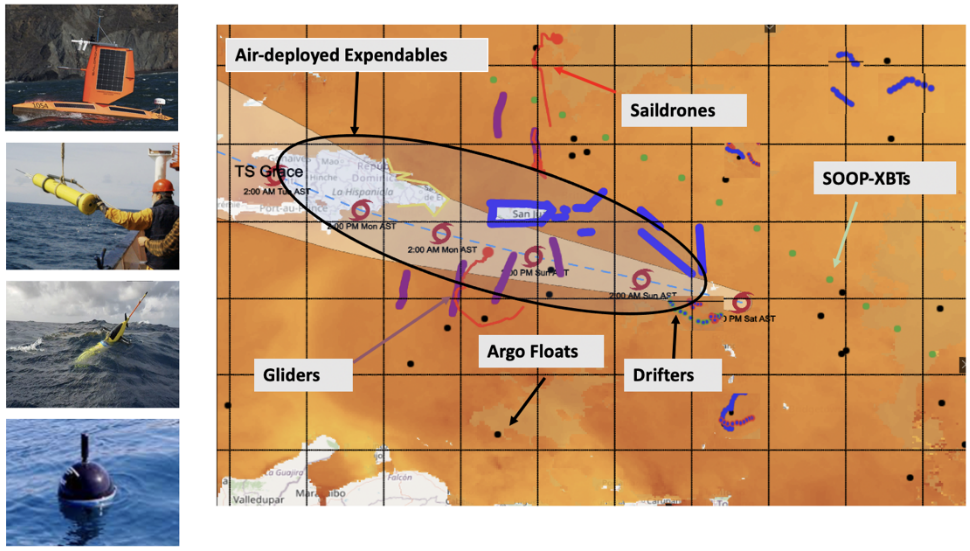

Figure 1. *Typical ocean observations sampling prior Hurricane Grace (2021). The in situ ocean observations include Saildrones, Expendable BathyThermographs (XBTs), gliders, Argo floats, drifters - that complement the observations provided by aircraft measurements, air-deployed expendables, and satellite products.*

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

This experiment seeks any opportunity for collocated deployments and collocated observations with the following platforms:

Underwater Gliders: Gliders are autonomous underwater vehicles that provide targeted observations that profile the water column in both nearshore (as shallow as 10 meters) and deep ocean (up to 1000 meters) environments. Gliders typically transit horizontally while diving with average speeds of 20 km/day, collect data with vertical resolutions of 0.25-10 meters, and transmit data to shore every 2 to 6 hours depending on programmed sampling characteristics. Typical glider observations capture detailed temperature, salinity, and density structure within features of interest or ahead of, during, and after the passage of tropical cyclones. Some gliders may include additional relevant sensing capabilities (e.g., current profiles and turbulent microstructure, oxygen, etc.). Between 15-30 glider missions along 10-20 predetermined lines/transects are planned to be implemented in the tropical Atlantic, Caribbean Sea, Gulf of Mexico, and off east of the US coast during the 2022 Atlantic Hurricane season using a combination of AOML, IOOS Regional Associations, and academic institution assets, logistics, and funding. An additional 12 U.S. Navy deep gliders (1000 m) have been requested to contribute to this effort and are pending Navy approval. This data, and additional leveraged glider data beyond hurricane projects, will be published in real-time via the IOOS Glider Data Assembly Center (DAC), accessed by the NWS and made available to the Global Telecommunication System (GTS) for assimilation into operational ocean models such as RTOFS.

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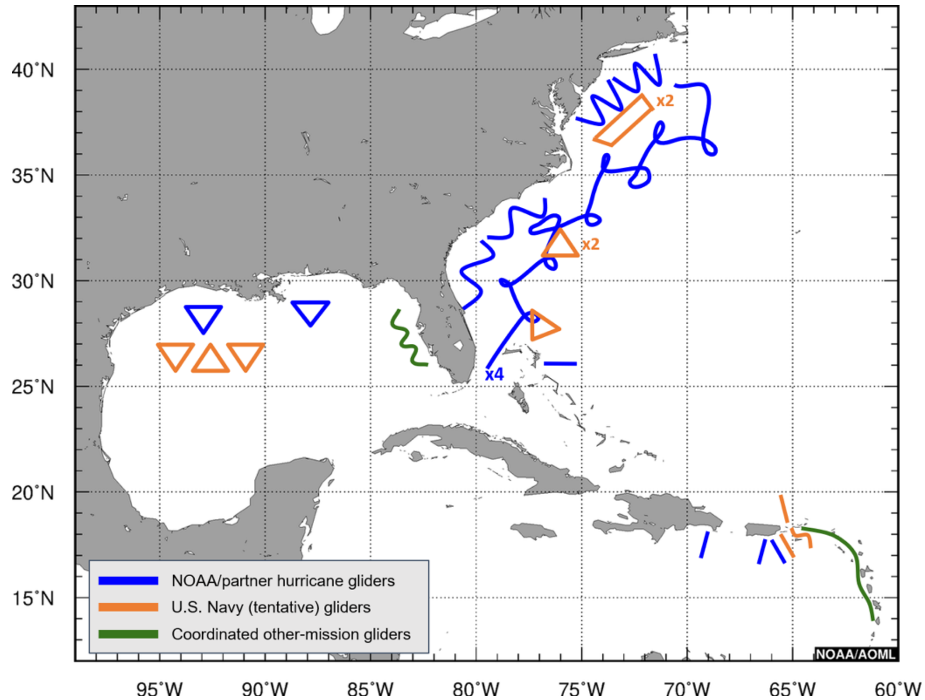

Figure 2. NOAA/partners gliders (blue) are hurricane glider missions with confirmed funding in FY22. U.S. Navy gliders (orange) are tentative, pending Navy approval and pending NOAA funding to support logistics. Coordinated other-mission gliders (green) are deployed by NOAA partners and are funded for non-hurricane missions but PIs/Operators are actively coordinating their deployments with the hurricane glider missions. The "x2" or "x4" indicates 2 or 4 glider missions covering a track, though the deployments are not necessarily concurrent. In the South Atlantic, NOAA/partner Gulf Stream deployments from FL are spaced out temporally and make 1 trip northward along the Gulf Stream.

Saildrones: These uncrewed surface vehicles are powered by solar, wind, and hydro energy, and can stay at sea for up to 12 months (albeit biofouling). Standard measurements include sea surface (-1.5 m) temperature and salinity, upper ocean (6-100 m) currents with 2 m resolution, surface air temperature/humidity (2 m), pressure (0.5 m), and wind direction/speed (3.2m), wave height and period. Long- and short radiation can also be measured but are not part of the standard package. Data (1-min averaged at the top of every 15 min) are transmitted in real time to GTS, bundled once per hour. The current plan is to operate 4 saildrones in the western tropical Atlantic Ocean, Caribbean Sea, and off the US East Coast for 1- 3 months each during August-October 2022.

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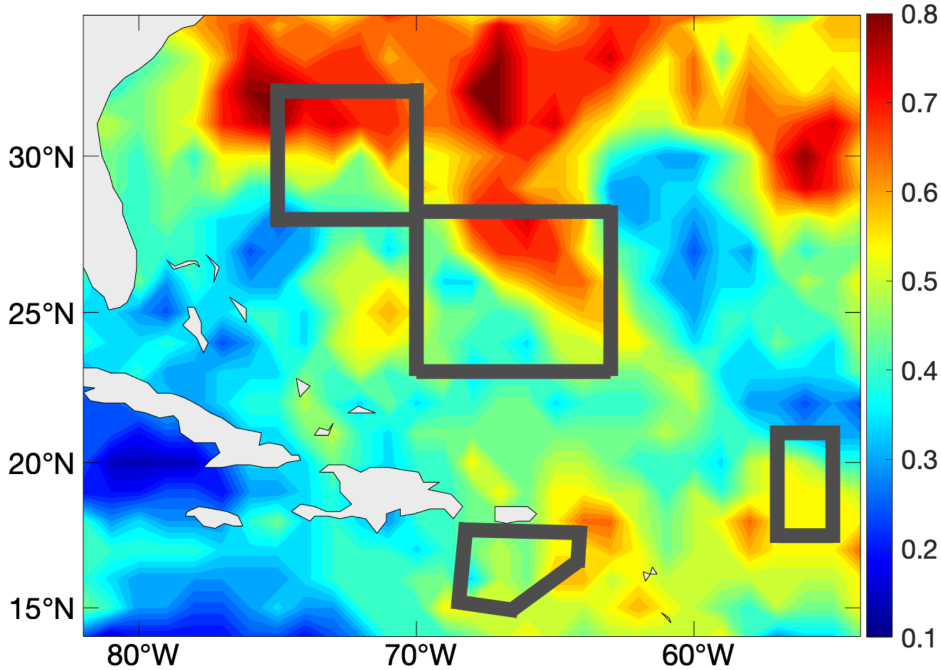

Figure 3. Potential saildrone mission domains, subject to change. Colored shading represents the probability of sustained TS-force winds within 200 km of each location during August-October 2000-2019.

Drifters: Deploy Drifters Coordinated with Flights using radars to measure waves: Sustained drifter observations include:

- SVPB (https://gdp.ucsd.edu/ldl/svpb/) and DWSB drifters (https://gdp.ucsd.edu/ldl/dwsbd/);
- SVP-B includes launching of drifters along an Eastern Caribbean Tropical Shipping trackline, with timing and locations optimized to maintain drifter distribution within the Caribbean Sea during hurricane season. These could be upgraded to Salinity drifters to track fresh water barrier layers.
- In the Minimet drifters that will operate throughout season after targeted deployment (https://gdp.ucsd.edu/ldl/minimet/);
- Autonomous Drifting Ocean Station (ADOS) that will operate throughout season after targeted deployments (https://gdp.ucsd.edu/ldl/ados/); and
- A-sized DWSB drifters that can be deployed via P3 and C-130/WC-130J aircraft (estimated 60 total distributed over 6-10 missions).

In general, the hurricane packages consisting of Minimets (SVPB+wind speed, direction), ADOS (thermistor chains to 150m depth replacing drogue on Minimet), Directional Wave Spectrum Drifters (DWSB), and SVPB drifters are deployed in a line transecting the projected path of the

TC. Air-deployment practices require this to be in advance of the storm outside the extent of gale force winds. Sustained observations with surface drifters will be distributed in the Caribbean, in the Gulf of Mexico and the north Atlantic approximately west of 70°W. Drifter data will include calculation of air-sea transfers of heat salt, and momentum depending on measuring or estimating the terms in the COARE 4 algorithm. The estimation of the Charnock coefficient depends on measures of the wave spectrum coincident with the wind profile. The Drifter/ Aircraft radar module will provide some of this needed data.

Other Sustained Observations and Observing Projects: Several components of the networks of the global ocean observing system encompass in situ networks and satellite observations, including:

- *Argo floats* that provide temperature and salinity profiles to about 2000m with approximate spatial and temporal resolutions of 3x3 degrees and 10 days; some Argo floats will be able to change their temporal sampling when their locations coincide with the forecasted hurricane track). These data are key to correct basin wide temperature and salinity biases;
- *EXpendable BathyThermographs (XBTs)* that are deployed from opportunistic vessels to measure temperature profiles up to 800m deep and along several predetermined transects across the Gulf stream and on the shelf waters off the east US coast. These observations provide unique observations across the Gulf Stream and also where otherwise there would not be shelf observations;
- Satellite observations and products of basin wide sea surface temperature, sea height anomalies, sea surface salinity, and surface and vector winds.

The integration of observations from these sustained observations and products with those that are geared towards hurricane studies and forecasts have demonstrated to be critical, particularly to reduce temperature and density biases in numerical ocean models, to correctly identify the location of mesoscale features, and for ocean forecast model validation.

Links to Other Experiments/Modules:

- Ocean Winds, lead: Paul Chang, NOAA NESDIS
  - These are unique remote sensing instruments that are not installed on both P-3 aircraft.
    - KaIA (Ka-band Interferometric Altimeter (Ka- and Ku-band): will be installed on one P-3
    - IWRAP (Imaging Wind and Rain Airborne Profiler (C- and Ku-band scanning Doppler radar): will be installed on one P-3 with KaIA
  - Additionally, WSRA (Wind Swath Radar Altimeter (Ku-band) will be installed on one P-3. WSRA and KaIA will both provide significant wave height and sea surface height and WSRA will also provide wave spectra data. IWRAP will provide ocean surface wind vector data (scatterometry) and Doppler wind and reflectivity (rain rate) profiles. Overflight with drifters, gliders and saildrones will provide

opportunities to compare, verify and validate observations.

- Research In Coordination with Operations Small Uncrewed Air Vehicle Experiment (RICO SUAVE), lead: Joe Cione, NOAA AOML
  - Plans include deploying up to three (3) small Uncrewed Aircraft Systems (sUAS) within the high-wind air-sea transition zone of Tropical Cyclones (TCs). Planned activities will occur between August - November 2022 within the western tropical Atlantic Ocean, Caribbean Sea and the Gulf of Mexico. Operations will require deployments from NOAA's P-3 aircraft. If feasible, there might be opportunities to deploy over saildrone and gliders to achieve a comprehensive view of the air-sea transition zone.
- Ocean Survey Experiment, lead: Jun Zhang, NOAA AOML
  - This experiment aims to collect air-deployed ocean observations targeted at better understanding the response of hurricane intensity to changes in underlying ocean conditions. Plans include collecting coincident ocean, wave, and atmosphere observations during the pre-, during, and post-storm phases. Flight patterns also include coordination with saildrone and glider deployments.
- Hurricane Boundary Layer Module, lead: Jun Zhang, NOAA AOML
  - This HBL module aims to collect aircraft observations in the atmospheric boundary layer before and during TC intensification to identify key boundary-layer structure and dynamics that are tied to TC intensity change. Plans include deploying combo dropsondes and AXBTs at the storm center, radius of the maximum wind speed, mid- and turn- points. The number of AXBTs will be reduced when IRsondes are used in this module. Collocated saildrone and glider observations with P3 missions will provide additional information of SST and upper ocean structure besides AXBT data.
- Analysis of Intensity Change Processes Experiment (AIPEX), lead: Jon Zawislak, NOAA AOML
  - Predicting the timing and rate of tropical cyclone (TC) strengthening events remains one of the most challenging aspects of hurricane forecasting. In their early stages, the structure of developing storms is often disorganized such that their circulations are tilted in the vertical, have prominent dry air masses that can be transported into the inner circulation, and lack rainfall coverage all around the center. These are all conditions that would otherwise be considered unfavorable for further strengthening and are often a consequence of the storm experiencing unfavorable winds in its environment. Storms with these characteristics can, however, strengthen and the goal of this experiment is to understand the physical

processes and structures that govern whether storms will intensify in this type of environment.

Analysis Strategy: Data Distribution, Use, and Impact

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. Modeling efforts include the NOAA next-generation coupled hurricane model system (HAFS), data assimilation framework (marineJEDI) through the NOAA Unified Forecast System (UFS), and RTOFS Data Assimilation efforts. Data from these observations, mainly from gliders, Argo floats, XBTs, and satellite altimetry, are also used to evaluate models and to conduct data impact studies.

In addition, several data visualization tools will be employed throughout the hurricane season to assist with the coordination of deployments and monitoring of opportunities for collocated observations. Several of these tools provide a web-based platform for monitoring GTS ocean observations with hurricane forecast tracks overlaid. Examples include:

- GeoCollaborate
- NOAA OceanObservations Viewer
- NOAA AOML Hurricane Gliders
- ArgoVis
- Earth Null School
- MARACOOS OceansMap
- Lagrangian Drifter Lab GDP Array Viewer
- Lagrangian Drifter Lab Hurricane Viewer
- IOOS Glider DAC
- IOOS EDS Model Viewer
- WSRA Level 4 Data

Relevant Publications:

Cione J.J., G.H. Bryan, R. Dobosy, J.A. Zhang, G. de Boer, A. Aksoy, J.B. Wadler, E.A. Kalina, B.A. Dahl, K. Ryan, J. Neuhaus, E. Dumas, F.D. Marks, A.M. Farber, T. Hock, and X. Chen, 2020: Eye of the Storm: Observing Hurricanes with a small Unmanned Aircraft System. *Bull. Amer. Meteor. Soc.,* **101**, E186–E205, https://doi.org/10.1175/BAMS-D-19-0169.1

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.

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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

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