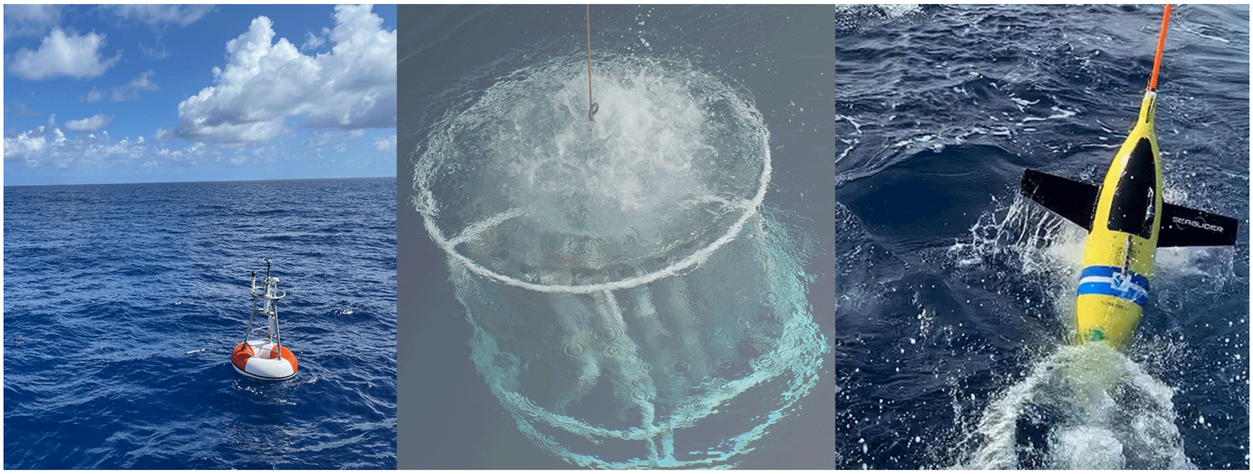
NOAA/AOML's Physical Oceanography Division



The Physical Oceanography Division (PhOD) of NOAA's Atlantic Oceanographic and Meteorological Laboratory carries out interdisciplinary scientific investigations of the physics of ocean currents and water properties to assess and monitor the state and variability of the oceans. The goal of PhOD is to strengthen our scientific understanding of the state of the ocean and its links to global climate, weather events, and fisheries and ecosystems, by enhancing our observational work, research, technological development, and science communications. The tools used to carry out these studies range from sensors on open ocean moorings to floating platforms to satellite-based instruments to measurements made on research and commercial shipping vessels and autonomous vehicles, and include data analyses and numerical modeling as well as theoretical approaches.

Priority Activities:

- Design, implement, and maintain key components of the global ocean observing system
- Carry out process and modeling studies to understand the state of the ocean and its variability
- Assess the physical links between ocean variability and weather events at time scales from hours to multi decades.
- Partner with NOAA Laboratories and Programs to develop applications and transitions to operations to improve forecasts, outlooks and assessments of weather, ecosystems, and fisheries.

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The Argo Program

Argo Mission: Argo is an international program that aims to understand the ocean's role in the Earth System to improve short-term and long-term ocean and weather forecasts.

Argo Key Impacts: Argo collects real-time observations that are used to detect long-term changes in sea level, ocean heat, ocean biogeochemistry, ice volume, and long-term weather signals. Argo is critical for improved global ocean and weather forecasts, including extreme weather events such as hurricanes, and are used within short-range ocean forecast applications for search and rescue operations, fisheries, shipping, oil and gas, and the military.

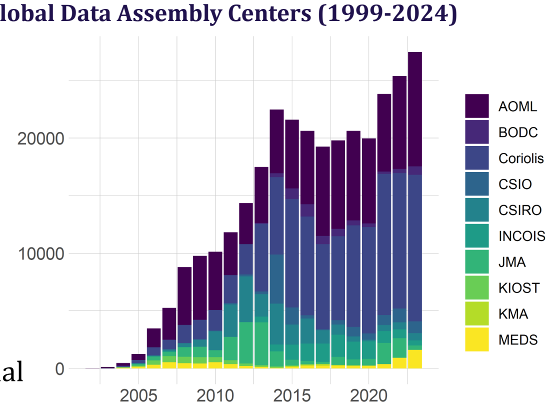
In 2024, Argo, the 'crown jewel' of ocean observing systems, turns 25!! (NOAA News, Dec. 11,2024)

Argo Achievement: Argo is the dominant source of subsurface ocean data. This global array of robotic profiling floats measure from the ocean surface down to 2000 – 6000 meters (float type dependent). Argo data play a pivotal role in the global ocean observing system and are used in nearly 600 NOAA products that contribute significantly to all three of NOAA's strategic goals.

Argo Collaborations: Six U.S. NOAA Agencies, eight U.S. Universities & 30 countries deploy Argo floats.

Argo Data Availability: Argo data and user-friendly tools are freely available from the U.S. Global Ocean Data Assimilation Experiment (USGODAE) Global Data Assembly Center (GDAC) and the Coriolis Argo GDAC.

AOML U.S. DAC Core Profile contributions to the Global Data Assembly Centers (1999-2024)



AOML plays several roles in the Argo project:

- AOML houses the US Argo Data Assembly Center (U.S. DAC), which collects and processes all real-time US Argo data for Core, Deep, Biogeochemical (BGC) and Polar Argo floats. With a median time of 2.8 hours from receipt, these Argo data are transferred to the Global Telecommunication System (GTS) and the two Argo GDACs for use by national and international operational centers and scientists.
- AOML's BGC-Argo Program contributes to the global Argo effort by maintaining the first US marginal sea array in the Gulf of America, which is home to ecologically and economically important ecosystems and natural resources.
- The AOML U.S. DAC participates in the International Argo Data Management Team, which develops standards for ensuring a high quality of the data. The AOML Argo PI participates in the International Argo Steering Team, supporting both U.S. Argo efforts and the U.S. DAC.

AOML U.S. DAC Metrics (1999-2024): For monthly metric reports, visit www.aoml.noaa.gov/argo/

- **1,734,196** total U.S. DAC profile files from **8,972** floats.
- The U.S. DAC assembles **52%** and **35%** of the global Core Profiles and BGC Profiles, respectively.

For more on the AOML U.S. Argo DAC, including monthly metric reports, please visit www.aoml.noaa.gov/argo/

For more on the AOML BGC-Argo Program, please visit www.aoml.noaa.gov/biogeochemical-argo-program/

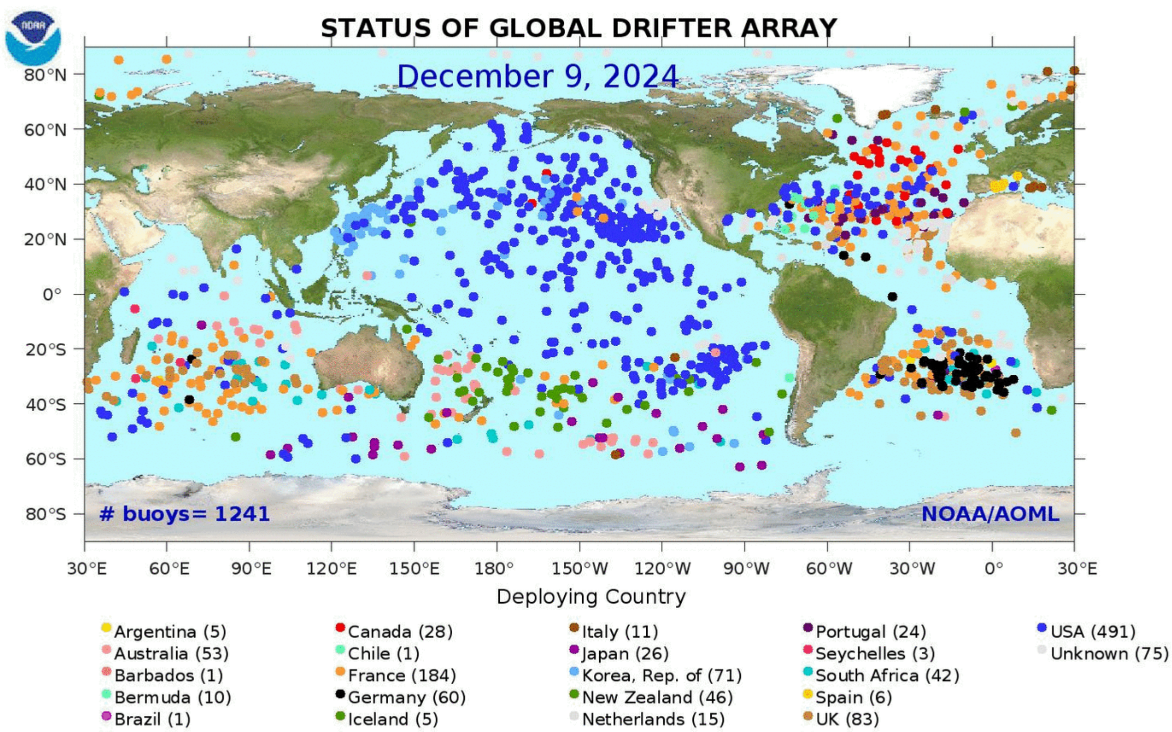
The Global Drifter Program

NOAA's Global Drifter Program aims to:

1. Maintain a global 5°x5° array of ~1,300 satellite-tracked surface drifting buoys to provide an accurate and globally dense set of *in-situ* observations of mixed-layer currents, sea surface temperature, atmospheric pressure, winds, salinity, and waves.

2. Provide a data processing system for the scientific use of these data.

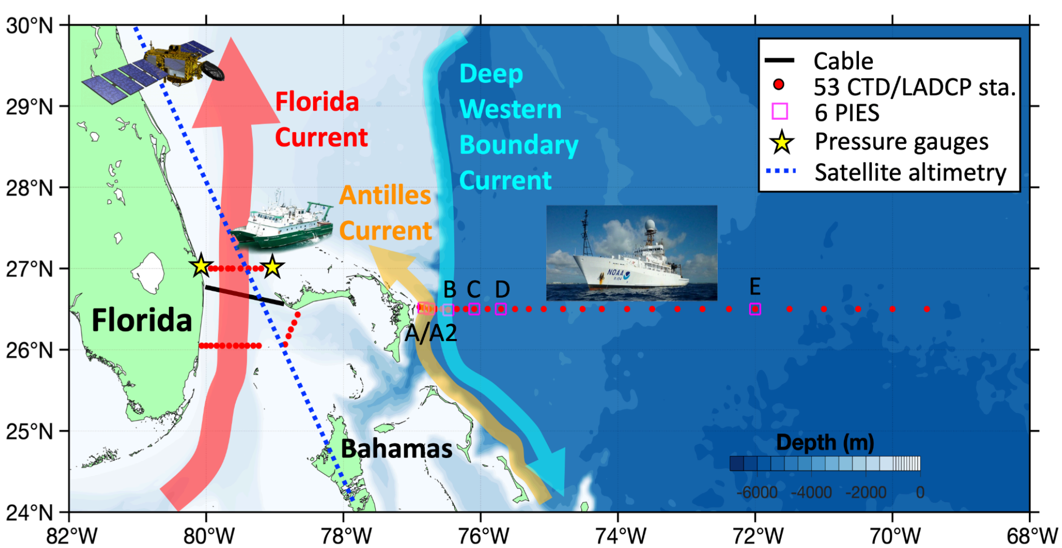
These data support seasonal to interannual predictions, model validation efforts, and calibration and validation of satellite measurements of sea surface temperature and surface currents. Most of the drifters also collect barometric pressure for improved weather forecasting. AOML houses two vital components of the Global Drifter Program: the drifter Data Assembly Center and the Drifter Operations Center**.** These components coordinate worldwide deployments with [many national and international partners](), process, quality-control, archive, and serve the data via [an ERDDAP server](), maintain metadata files describing each drifter deployed, develop and distribute data-based products, and maintain [AOML's Global Drifter Program website]().



Western Boundary Time Series

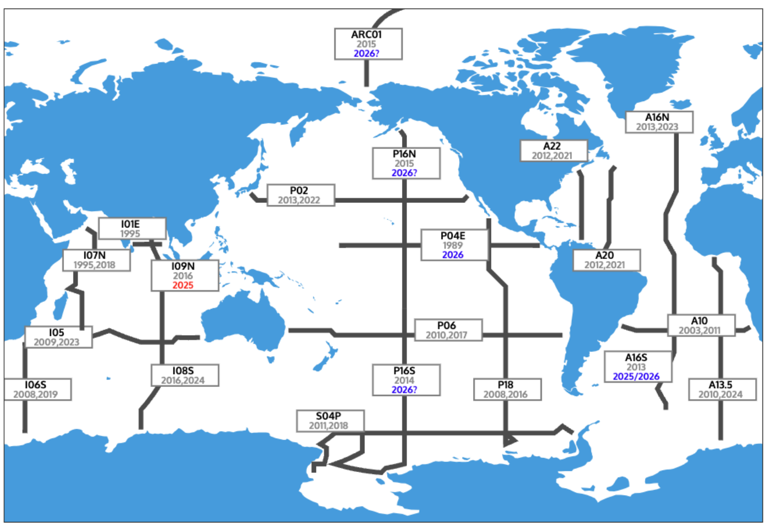
The Western Boundary Time Series (WBTS) project continuously monitors important western boundary currents in the subtropical North Atlantic Ocean, allowing scientists to regularly assess the state of the Atlantic Meridional Overturning Circulation (AMOC). It is also a cornerstone of the international RAPID/MOCHA/WBTS program array which supports basin-wide, full-water-column transport measurements of the AMOC at 26.5°N using a combination of moored and shipboard measurement techniques. The AMOC is driven by regional differences in heat and salt, as well as ocean mixing and wind forcing at and near the ocean surface. This circulation impacts many global and regional scale phenomena such as climate and weather patterns, sea level changes, extreme events, carbon sequestration, and ecosystem dynamics. Due to the longevity of WBTS measurements (42+ years), the project provides a system for monitoring changes in the ocean heat and freshwater content and transport on multiple time scales (from daily to multidecadal). WBTS measures the northward-flowing surface intensified Florida Current, the northward-flowing subsurface intensified Antilles Current, and the southward-flowing Deep Western Boundary Current. These western boundary currents constitute the bulk of both the upper and lower limbs of the AMOC, in the subtropical North Atlantic.

WBTS is NOAA's longest term observing system for a western boundary current in existence (continuous monitoring of the Florida Current began in 1982). Today, the WBTS observing system combines continuous real-time cable measurements of the Florida Current transport along with regular cable calibration cruises, moorings, and satellite altimetry. Annually, shipboard measurements are made from eight to ten GPS dropsonde cruises (conducted via small boat) and six 2-day hydrographic surveys of the Florida Current at 27°N, conducted bimonthly aboard the R/V *F. G. Walton Smith*. Additionally, quasi-annual (approximately every 9 months) hydrographic surveys along 26.5°N of the Antilles and Deep Western Boundary Currents are performed aboard the NOAA Ship *Ronald H. Brown*, or similar vessel. In 2004, WBTS began continuous moored measurements of transports along 26.5°N, near the western boundary, using pressure equipped inverted echo sounders (PIES). In 2008, shallow water pressure gauges were added to either side of the Straits of Florida at 27°N for use in determining the Florida Current transport from the sea level pressure gradient.



GO-SHIP Repeat Hydrography

The U.S. GO-SHIP (Global Ocean Ship-based Hydrographic Investigations) program is part of the International GO-SHIP network of sustained hydrographic sections, carrying on the legacy of the former WOCE and CLIVAR repeat global hydrography programs. GO-SHIP occupies global trans-basin hydrographic sections routinely sampled over the last 50 years with aims to document and monitor changes in heat, fresh water, carbon, nutrients, oxygen, and trace gases in the ocean. These sections are led by NOAA and NSF investigators, with NOAA AOML leading observation efforts in Physical Oceanography (CTD; Temperature, Salinity, Oxygen), Carbon, and Nutrient parameters on select GO-SHIP lines in partnership with NOAA PMEL. Despite advances in autonomous hydrographic sampling over the last several decades, ship-based hydrography remains the gold-standard for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. This is especially important for the deep ocean at depths below 2000m (>50% of global ocean volume).



U.S. GO-SHIP (and AOML-affiliated) repeat sections. Since 2020, GO-SHIP Atlantic lines A13.5, A16N, A20 and A22, Pacific line P02, and Indian Ocean lines I05, I08S and I09N have been led by AOML personnel, with the scheduled Atlantic line of A16S, Arctic ARC01, and Pacific P16 and P04E lines in the near future.

Hydrographic measurements are needed to:

- Reduce uncertainties in global fresh water, heat, property and sea-level budgets,
- Determine the distributions and controls of natural and anthropogenic carbon,
- Determine ocean ventilation and circulation pathways and rates,
- Determine the variability and controls in water mass properties and ventilation,
- Determine the significance of a wide range of biogeochemical and ecological properties in the ocean interior,
- Validate and serve as calibration points for hydrographic instrumentation, such as moorings, Core, Deep, Biogeochemical Argo , and gliders, and
- Maintain the historical database of full water column observations necessary for the study of long-timescale changes.

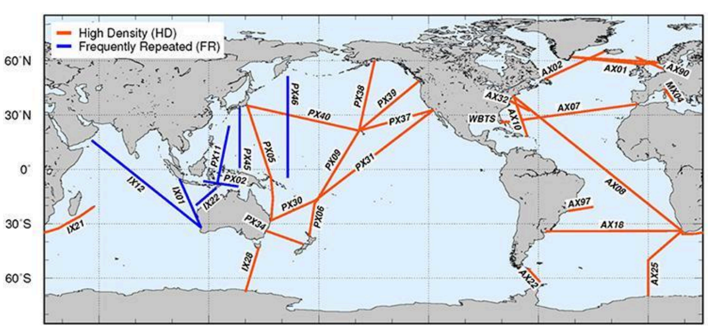
The XBT Network and Ship of Opportunity Program

The Expendable BathyThermograph (XBT) network is the most important component of the Ship Of Opportunity Program (SOOP), an international effort that supports the implementation of a network of cargo vessels, cruise ships, and research vessels to deploy scientific instruments that collect oceanographic observations. XBTs are deployed along fixed pre-established transects, which are repeated 4-5 times per year, to collect temperature observations of the upper 1km of the ocean with spatial resolution 5-30 km resolving mesoscale features. The XBT network currently in place has been recommended by the international scientific community. AOML deploys 5000-6000 XBTs among 16,000-20,000 deployed globally each year, 90% of which AOML is involved in some aspect of the logistics, operations, and data processing. AOML leads or co-leads, with our international collaborators, the implementation and operations of 12 active Atlantic Ocean transects.

Most of the data obtained through this project are distributed into the GTS within 24 hours of acquisition, providing critical input for weather and climate forecast models and scientific applications. XBT data are distributed to NOAA/NCEI and to other data distribution centers. This project also includes continuous development of new technologies to achieve cost-effective operations. The engineering group at AOML designed an XBT probe autolauncher, allowing XBT transects being conducted by one person, and developed a software for real-time data acquisition and transmission that is employed on ships of SOOP, UNOLS, and U.S. Coast Guards vessels. A recent development of portable weather stations allows for collecting surface concurrent meteorological data for studies of air-sea coupling in the strong boundary current regions.

Current XBT network is mainly focused on:

- Monitor the state and spatial and temporal variability of key surface and subsurface ocean currents and boundary currents;
- Monitor the state and variability of the Meridional Heat Transport (MHT) and Meridional Overturning Circulation (MOC) across ocean basins;
- Provide together with other observational platforms assessments of the variability of the global upper ocean heat content;
- Provide critical input for weather and climate forecasts models and scientific applications;
- Conduct temperature profile observations in US shelf waters in support of hurricane research and forecasts.



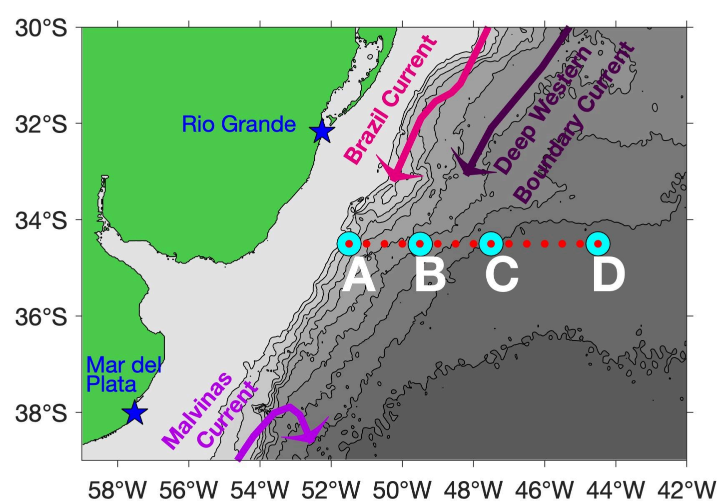
The current global XBT network (recommended by the XBT Science Team)

Southwest Atlantic Meridional Overturning Circulation Array

Variations in the Atlantic Meridional Overturning Circulation (AMOC) have been linked to changes in critical climate variables such as precipitation, surface air temperature, sea level, and extreme weather (e.g., drought, heat waves, hurricane intensification) across the globe. Models indicate that variations in the transport of freshwater across the South Atlantic by AMOC partially controls the stability of the AMOC itself. However, little data has previously been available for the study of the flows in this region, and how they link to AMOC variations in the North Atlantic. Direct knowledge of how the AMOC varies is limited by the difficulty of making basin-wide measurements. AOML is at the forefront of this challenging field, working with national and international partners to develop and implement several critical measurement systems that provide data on the AMOC at important locations. One such project is the Southwest Atlantic Meridional Overturning Circulation (SAM) array.

SAM seeks to capture the daily variability of key components of the AMOC in the subtropical South Atlantic Ocean. The array consists of a zonal line of four pressure-equipped inverted echo sounders (PIES) deployed near the western boundary at 34.5°S. Data from these instruments are used to monitor the Brazil Current and the Deep Western Boundary Current as they carry components of the AMOC along the western boundary of the basin, and most recently have been used to detect deep and abyssal water mass changes. Coupled with annual or semiannual hydrographic observations collected on Argentine or Brazilian research vessels, these data are providing better understanding of the processes involved in MOC, boundary currents, and water mass variability in the South Atlantic.

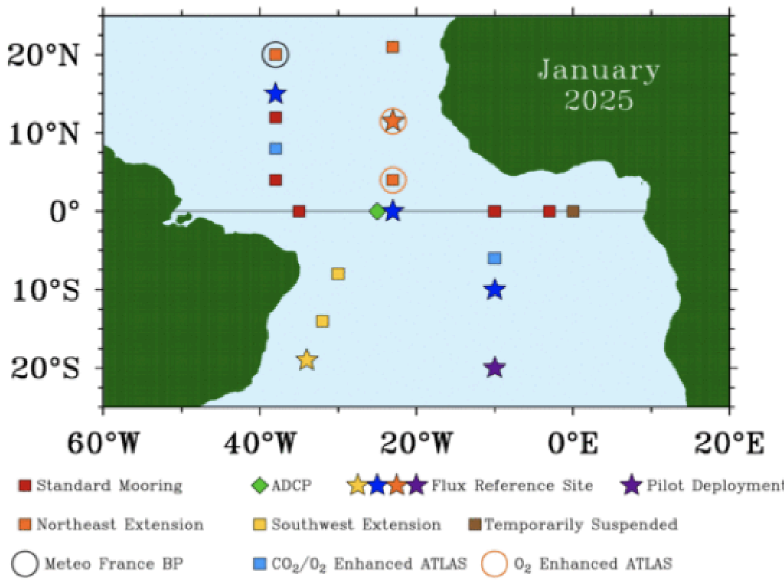
Additional collaborations with Argentine, Brazilian, French, German, South African, and Spanish partners has led to a line of moorings across the entire basin called the South Atlantic MOC Basin-wide Array (SAMBA). SAMBA observations are used to produce continuous time series of the trans-basin MOC flows at this latitude. SAMBA is part of an international effort, the South Atlantic Meridional Overturning Circulation (SAMOC) initiative, to observe the dynamics and variability of the overturning circulation system at multiple latitudes in the South Atlantic.



Looking forward, AOML is developing Adaptable Bottom Instrument Information Shuttle Systems (ABIISS) at SAM sites. The systems consist of a prototype submerged frame that releases a data pod at predetermined intervals as specified by the user. These systems will help retrieve data from the subsurface moorings alleviating some of the pressure on crewed research vessels for data recovery.

The PIRATA Northeast Extension: Observing Tropical Atlantic Variability

The Prediction and Research moored Array in the Tropical Atlantic (PIRATA) is a joint project of Brazil, France, and the United States. PIRATA aims to improve our knowledge and understanding of ocean-atmosphere variability in the tropical Atlantic. Implementation of PIRATA started in 1997 with an array of moored buoys, similar to the Tropical Atmosphere-Ocean (TAO) array in the equatorial Pacific. Starting in late 2005, extensions were added to the array in key regions, including the US-led PIRATA Northeast Extension (PNE).

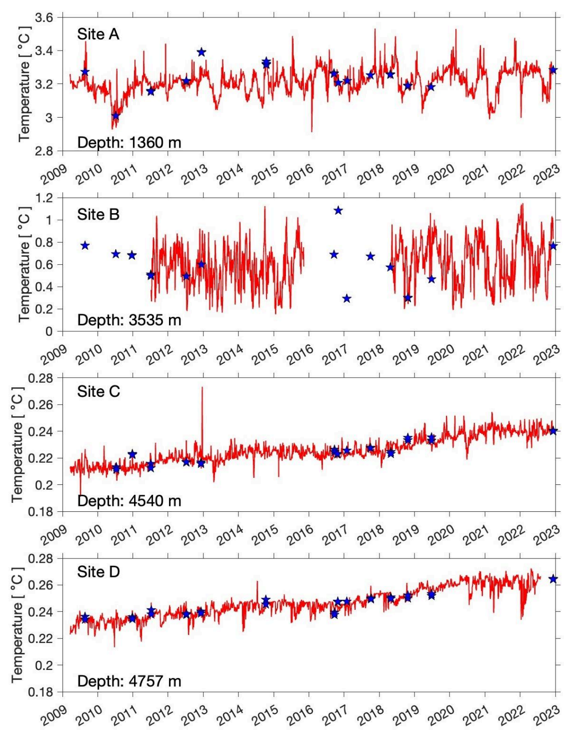


PNE is a joint AOML and PMEL effort that extends the array into the tropical North Atlantic, a region of strong climate variations that affect rainfall and storm landfalls in the surrounding regions of Africa and the Americas. Important processes in this region include the formation of Cape-Verde type hurricanes, seasonal migration of the Intertropical Convergence Zone (ITCZ) and the Guinea Dome, interannual to decadal variations of the ITCZ migration associated with rainfall anomalies in Africa and the Americas, off-equatorial heat advection by Tropical Instability Waves, and overturning-related ventilation of the oxygen minimum zone. AOML organizes and leads the annual cruises to maintain the PNE moorings and collect meteorological and oceanographic observations in the region, while PMEL provides the equipment and technicians for the mooring operations.

The Tropical Atlantic Current Observations Study (TACOS) is a PhOD-funded study focused on advancing understanding of ocean circulation and mixing and its impact on sea surface temperatures and the atmosphere. TACOS uses acoustic current meters augmented to an existing NOAA PIRATA Northeast Extension mooring to provide a novel time series of horizontal velocity and its vertical shear in regions with strong ocean-atmosphere coupling on weather and climate timescales, observing phenomena including inertial oscillations, internal waves, and tropical instability waves. TACOS deployments to date have focused on the ITCZ, Atlantic hurricane main development region, and the Atlantic oxygen minimum zone.

Innovative Analysis of Deep and Abyssal Temperatures from Bottom-Moored Instruments (DeepT)

The ocean plays a major role in the distribution of heat in the climate system, yet direct observations of temperature variability in the deep ocean are very sparse. A 2020 study led by scientists at AOML demonstrated that an innovative use of temperature sensors located within the sphere of a pressure-equipped inverted echo sounder (PIES) mooring can provide hourly near-bottom temperature measurements over extended time periods to detect long-term abyssal temperature changes. Warming of Antarctic Bottom Water (AABW) was detected at a rate of 2 m℃/year in the subtropical South Atlantic.



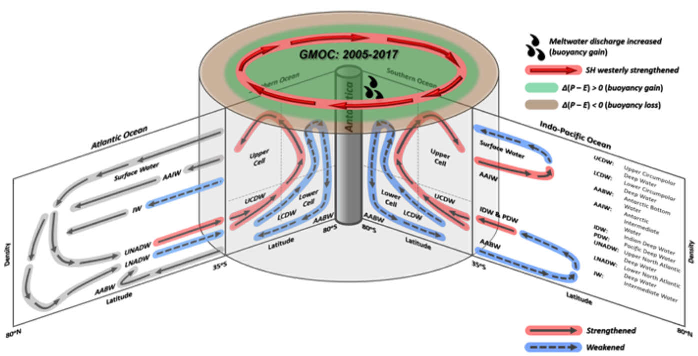
The results of the study led to a new NOAA-funded project entitled “Innovative analysis of deep and abyssal temperatures from bottom-moored instruments” or DeepT. The DeepT project is analyzing near-bottom temperature variations from existing long-term (15-25 year) arrays of PIES moorings maintained in the North and South Atlantic by NOAA. These arrays include the AOML’s Western Boundary Time Series (WBTS) and Southwest Atlantic Meridional Overturning Circulation (SAM), including UCSD’s Meridional Overturning Variability Experiment (MOVE) and the University of Miami’s Meridional Overturning Circulation and Heatflux Array (MOCHA). These observations will help scientists to understand deep temperature variations, and forcing mechanisms and implications, predict future deep ocean temperature changes, and serve as a benchmark to validate ocean models. The deep temperature records will also serve as a reference data set for interpreting future deep temperature variations as new deep observational platforms are brought online, such as a global deep Argo array. As part of a collaboration with French partners, PIES will be deployed with a microcat affixed to them to simultaneously observe near-bottom temperature and salinity variations of the AABW.

Overturning Circulation and Societal Impacts

The Atlantic Meridional Overturning Circulation (AMOC) is the Atlantic component of the global ocean conveyor belt, a large-scale ocean circulation system that carries heat, salt, carbon, and other biogeochemical elements along its paths. Therefore, the AMOC is a crucial component of the global heat, salt, nutrients and carbon balances that affect the associated regional climate, sea-level, and marine ecosystems, and thus has significant societal, environmental and economic implications.

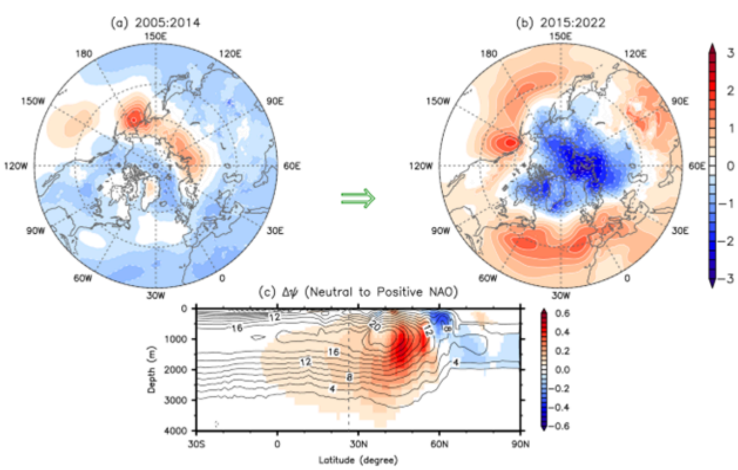
As the surface ocean warms and polar ice sheets melt due to increasing anthropogenic greenhouse gases in the atmosphere, the AMOC transport is expected to decline significantly throughout the 21st century, increasing the risk of disrupting the global redistribution of ocean properties that sustains marine ecosystems, carbon cycle, sea-level, climate, and extreme weather. It is therefore vital to accurately monitor any changes or potential shifts in the AMOC. Since the AMOC is the basin-integrated transport of multiple ocean current systems, monitoring the AMOC requires an observational network that spans the entire Atlantic basin at multiple latitudes. AOML’s PhOD scientists in collaboration with national and international partners are leading several programs to monitor the AMOC, namely Western Boundary Time Series (WBTS), Southwest Atlantic MOC (SAM), GO-SHIP, and eXpendable BathyThermograph (XBT) network.

PhOD scientists also monitor interdecadal changes in the historical AMOC by using long-term hydrographic data. They reconstructed and analyzed the global MOC to report a reorganization of the global MOC pathways emerging from the South Ocean since the mid-1970s, highlighting the expansion and strengthening of the upper cell and the contraction and weakening of the lower cell in the Southern Ocean.



A summary schematic of the global MOC in 2005–2017. Major changes in the global MOC and the associated increases in SH westerly and Antarctic meltwater discharge and P − E changes in 2005−2017 in reference to 1955–1974 are indicated. Lee et al. (2023)

Recently, PhOD scientists combined direct observations and multiple climate models to report that an extensive weakening of the AMOC occurred in the 2000s primarily driven by anthropogenic forcing, but has stalled since the early 2010s due to the development of a strong positive North Atlantic Oscillation.



Sea level pressure anomalies in December-May for 2005-2014 and 2015-22 derived fromERA5, and the implied changes in the natural AMOC component. Lee et al. (2024).

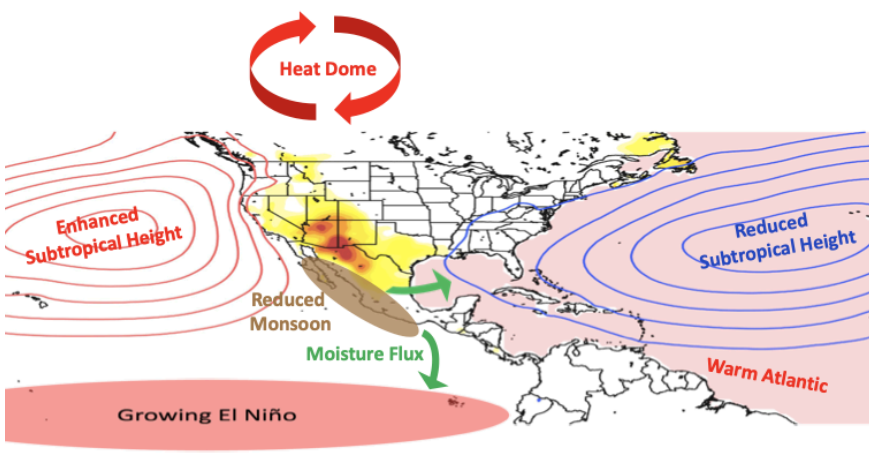
The Oceans as Predictors of Heat Waves

The number of heat waves and their severity has increased in recent decades and is projected to continue increasing into the 21st Century. In fact, extreme heat is already the leading weather-related cause of death in the U.S. (https://www.weather.gov/hazstat/). One of these severe heat wave events occurred over the southwestern United States (US) and Mexico, which extended from mid-June to early August of 2023, affected over 100 million people, and was responsible for over 200 deaths. The compounded effect of extreme heat and drought was responsible for $14.5 billion in economic loss (https://www.ncei.noaa.gov/news/national-climate-202312), making this event the costliest weather and climate disaster of 2023. This event featured prolonged extreme surface temperatures, with Phoenix, Arizona experiencing both the longest continuous stretch of daily maximum temperature exceeding 40°C (55 days, 24 June - 17 August) and the warmest nighttime minimum temperature on records (36.1°C). The heat wave was far reaching, setting new all-time record temperatures throughout the southern US and Caribbean (e.g., New Orleans, Louisiana and San Juan, Puerto Rico).

A recent study by AOML scientists demonstrated a physical link between the long duration extreme heat over the southwest U.S. and the record warm North Atlantic sea surface temperatures (SSTs) and a growing El Niño in the Pacific. Through observational records and model simulations, the study shows that the extremely warm 2023 interbasin Pacific-Atlantic SSTs were responsible for the persistence of the heat wave in the region.

The study of heat waves has important implications for society. Excessive heat puts significant stress on human health, resulting in increased morbidity and mortality, with some of the most notorious events being responsible for hundreds and even thousands of deaths in the most extreme cases. Sectors like healthcare, agriculture, energy, etc. would benefit from an improvement in the knowledge and predictions of these far-reaching adverse events.

Extreme weather webpage: https://www.aoml.noaa.gov/extreme-weather/



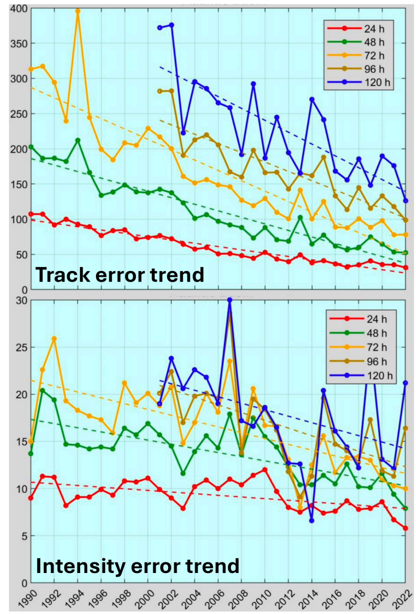
Schematic representation of the role of the Atlantic-Pacific warm sea surface temperatures on the occurrence of the longest-lasting heat wave event in the southwestern U.S.

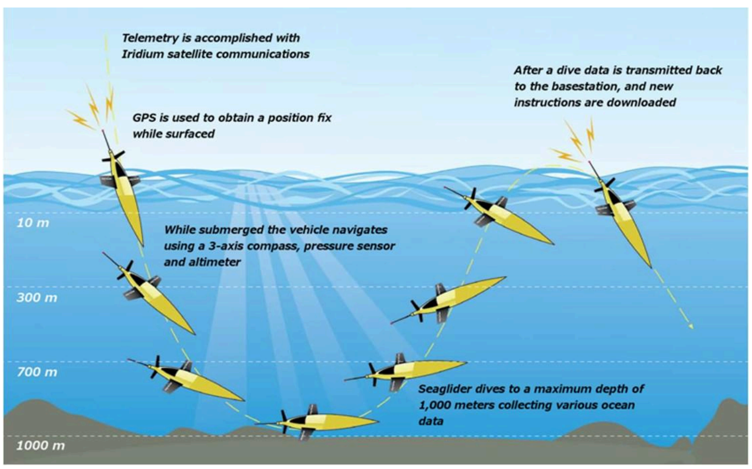
Monitoring the Ocean to Improve Hurricane Intensity Forecasts

In the last two decades, improvements in hurricane intensity forecasts have not been as pronounced as those in hurricane track forecasts.

Quick changes in hurricane intensity, such as Rapid Intensification (RI), are often associated with specific ocean conditions under tropical cyclones.

AOML plays a key role in collecting observations of the ocean conditions relevant to hurricanes using drifters, Argo floats, XBTs, and gliders.





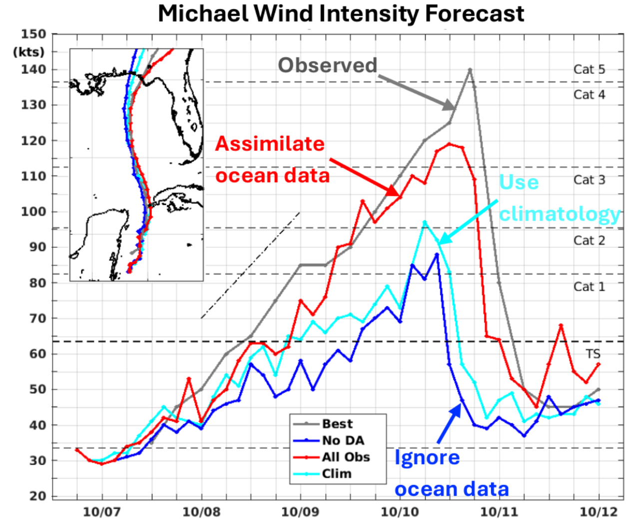
Since 2014, AOML gliders have provided on average every year:

- 7,300 temperature and salinity profiles
- along 8,000 km in the Caribbean Sea and Tropical North Atlantic
- during 560 glider-days

Gliders are autonomous, remotely-operated vehicles that collect and transmit profiles of the ocean's temperature and salinity in real-time to operational centers such as NOAA's National Weather Service.

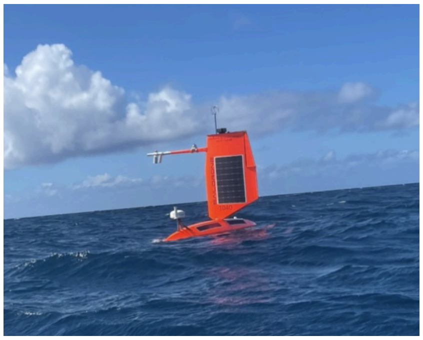
Glider data have been shown to improve the ocean's characterization and are used to initialize ocean-atmosphere forecast models. Together with Other ocean observations, gliders have led to a Significant improvement in intensity forecasts (e.g., Hurricanes Gonzalo, 2014; Maria, 2017; Michael, 2018; Isaias, 2020).

Michael Wind Intensity Forecast



Glider webpage: https://www.aoml.noaa.gov/hurricane-glider-project/

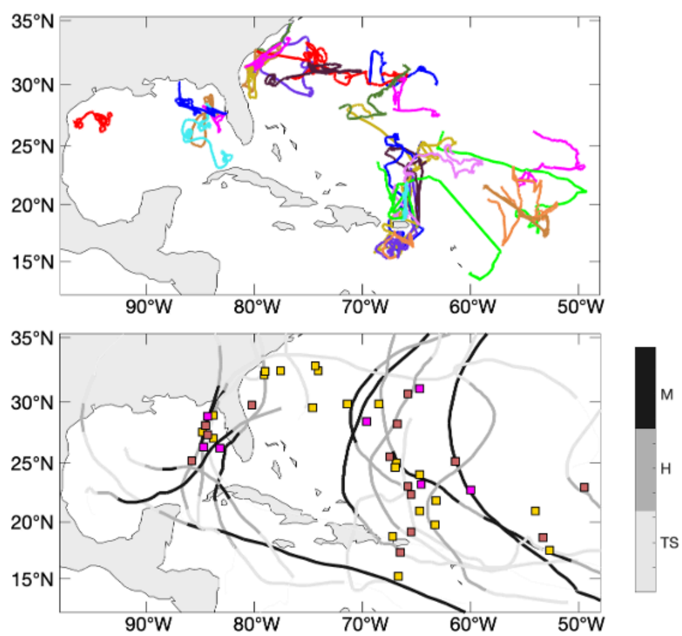
Saildrone hurricane observations



Top: Hurricane saildrones are propelled by the wind acting on a rigid sail called a wing, and the sensors are powered by solar energy. Bottom: Picture from saildrone SD-1045 in Hurricane Sam (2021).

Since 2021, AOML has partnered with NOAA/PMEL and Saildrone, Inc. to operate uncrewed surface vehicles in the western Atlantic Ocean, Caribbean Sea, and Gulf of America during the Atlantic hurricane season, with the goal of directing them into hurricanes to acquire measurements of the upper ocean and near-surface atmosphere. With shorter wings and more rugged sensors than standard saildrones, the hurricane saildrones are specifically designed to withstand the strong winds and large breaking waves in the eyewalls of major hurricanes. Measurements include 3-D wind velocity, air temperature, humidity, surface pressure, surface wave height and period, ocean surface temperature and salinity, oxygen and chlorophyll concentration, and ocean currents in the upper 80 m. One-minute averages of most data are transmitted in near-real-time and made available to global forecast centers. High-resolution data (1- to 20-Hz) from hurricanes are transmitted as soon as possible following storm intercepts, and the full high-resolution datasets are downloaded after the vehicles are recovered.

36 saildrones have been deployed during the project: 5 in 2021, 7 in 2022, and 12 in 2023 and 2024. They were steered into tropical cyclones, measuring sustained tropical storm-force winds (≥34 kt) 42 times and hurricane-force winds (≥64 kt) 7 times. Data are being used to understand the ocean's physical and biogeochemical responses to hurricanes, to validate remote-sensed and modeled winds, waves, and surface heat fluxes, and to estimate the air-sea momentum flux and drag coefficient in extreme conditions and their relationships with surface waves. The saildrone data are used routinely by NOAA/NHC & OPC forecasters for situational awareness, and we are working with NOAA/EMC to assimilate the real-time data into their operational forecast models.



Tracks of all saildrones during 2021-2024 (top) and tropical cyclones in which at least 34 kt sustained wind speed was measured (bottom, gray lines). Also shown in the bottom are locations of TC intercepts colored by maximum sustained wind measured: 34-49 kt (yellow), 50-63 kt (orange), and 64+ kt (magenta).

Oceanographers Help Improve Outlooks of U.S. Tornado Outbreaks

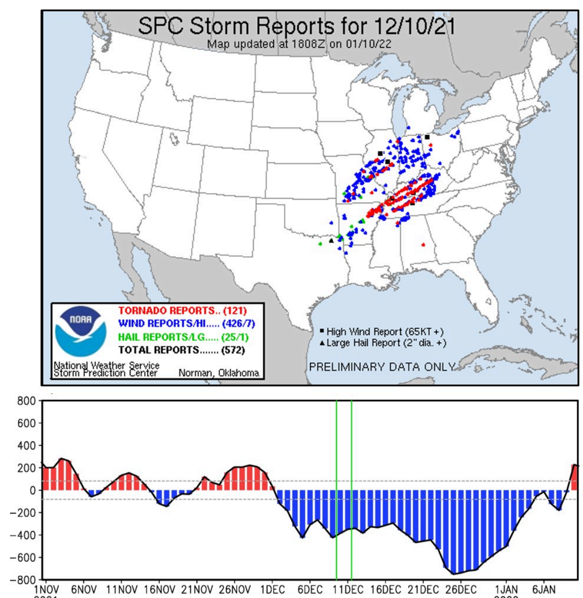
Tornadoes are among the deadliest and costliest natural disasters in the US. Due to their short lead-time and life span, predicting the occurrence of tornadoes beyond 2~3 days is extremely challenging. Since 2016, PhOD scientists have provided NOAA's National Weather Service with a seasonal probabilistic outlook for US tornado activity. This seasonal probabilistic outlook for tornados (SPOTter, *Lee et al., 2021*) is used as one of the forecast tools for the NOAA Climate Prediction Center's experimental Seasonal Severe Weather Outlook.

Recently, PhOD scientists have expanded the outlook to the subseasonal timescale using previously identified physical links between regional modes of climate variability and US tornado activity. The subseasonal outlook targeting week-2 forecasts for May to June, has been shared with NOAA's subseasonal severe weather TIGER team.

However, the occurrence of significant tornadoes is not only limited to spring but also to winter. For instance, in December 2021, the most destructive winter tornado outbreak, known as the Quad-State Tornado Outbreak, caused 89 fatalities, 672 injuries, and at least $3.9 billion in property damages.

A recent study by PhOD scientists demonstrated that the Quad-State Tornado Outbreak occurred under an exceptionally strong and prolonged negative Pacific-North American (PNA) pattern, which created favorable conditions for tornado outbreaks. This study showed that a prolonged (>6 days) negative PNA produces an atmospheric ridge, an area of high atmospheric pressure, along the southern and eastern US seaboard, which helps warm the Gulf of America. The warm Gulf of America sea surface temperatures and the atmospheric ridge produce favorable atmospheric conditions for US tornado outbreaks over a broad region of the central and eastern US where the Quad-State Tornado Outbreak predominantly occurred.

PhOD scientists will continue improving Subseasonal-to-Seasonal (S2S) tornado forecast skill by identifying regional climate modes of variability that affect US tornado activity.

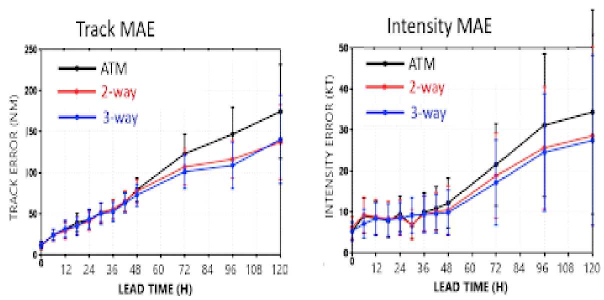


The upper panel shows the SPC storm report for December 10, 2021. The lower panel shows the time series of daily PNA index from Nov/01/2021 to Jan/10/2022 (Kim et al., 2024). The black dashed lines in the lower panel are the thresholds of positive and negative PNA events. Green lines represent the period of the Quad-States Tornado Outbreaks (Dec/10–11, 2021).

Oceanographers Advance Earth System Modeling to Improve Hurricane Predictions

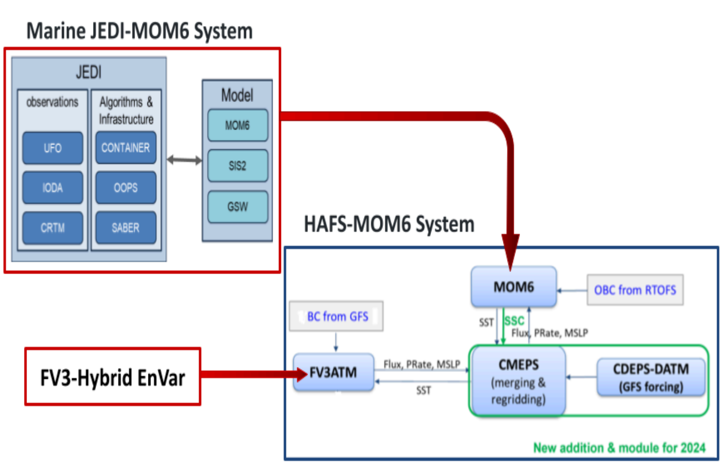
In order to have a high-fidelity tropical cyclone (TC) forecast model, accurate predictability of the co-evolutions between the atmosphere and ocean is essential. As numerous studies have presented in the past, the ocean meso-scale features directly influence the TC intensity changes. The changes can take place in a matter of 18 hours, whereas the flux in the air-sea interaction zone can be modified in less than 4 hours, in response to the thermal dynamics at the sea surface (Halliwell et al. 2015). For such strongly dynamically coupled weather events, not only combining the integration of the Earth system components and also a capability to resolve the associated physical and dynamical processes should increase fidelity of a forecast system.

As part of the modeling effort, PhOD scientists perform R2O for the Hurricane Analysis and Forecast System (HAFS) by integrating HYCOM (Kim et al., 2024) in 2023, followed by MOM6 in 2024. A recent publication by PhOD scientists demonstrated not only improved Hurricane predictions (Kim et al. 2022) but also better realization of the oceanic processes in the upper layer by adding a wave coupling. This is one step forward of one of our major efforts which is building an advanced, and evidence based Earth system model for hurricane predictions.



Track and intensity improvements by 3-way coupling over 2-way and un-coupling by 5-6 % and ~25%, respectively.

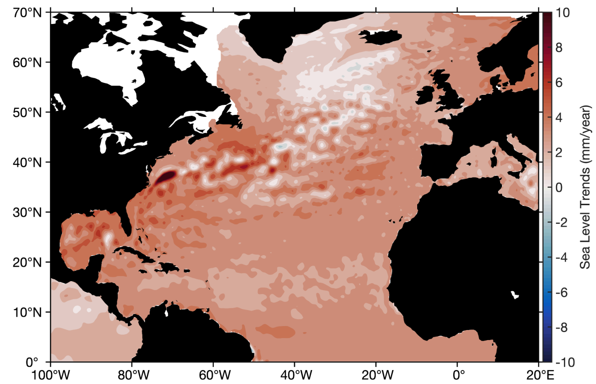
The 2nd major effort in PhOD is advancing data assimilation (DA). The Earth system modeling requires a special care for the balance of the system. To achieve it, PhOD scientists focus on development of ocean DA, namely, Marine JEDI interfaced with MOM6, followed by a strongly coupled DA system, in close collaboration with Hurricane Research Division, University of Oklahoma, CIMAS/UM, NCEP EMC, and JCSDA. These plans are part of the HAFS modular transition plan.



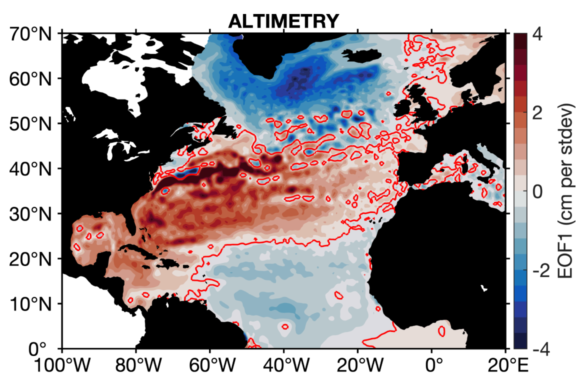
Coupled Hurricane Analysis and Forecast System (HAFS) (blue square box) with data assimilation systems (red boxes) for the ocean model using Marine JEDI-MOM6, and the atmosphere model with hybrid EnVar.

Regional sea level changes and coastal impacts

The global mean sea level (GMSL) rise caused by ocean warming and terrestrial glacier melt is one of the most alarming aspects of climate change. However, ocean and atmosphere dynamics make sea level change spatially and temporally nonuniform, exhibiting regional patterns of dynamic (after the GMSL is removed) sea level change with alternating signs over different time periods. PhOD scientists have studied regional sea level changes with a primary focus on the North Atlantic Ocean.



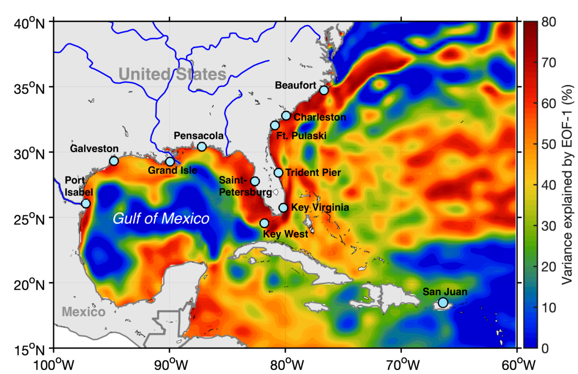
Regional sea level trends over the 1993-2023 period.



The tripole pattern of interannual dynamic sea level variability in the North Atlantic.

It has been shown that the interannual dynamic sea level changes in the North Atlantic display a tripole spatial pattern, with the subtropical gyre varying out-of-phase with both the subpolar gyre and the tropics. The subtropical band of tripole was characterized by an overall dynamic sea level decrease in 1993-2010 and a rapid sea level rise since 2011, largely driven by ocean heat divergence and convergence, respectively, associated with the Atlantic Meridional Overturning Circulation and large-scale wind forcing.

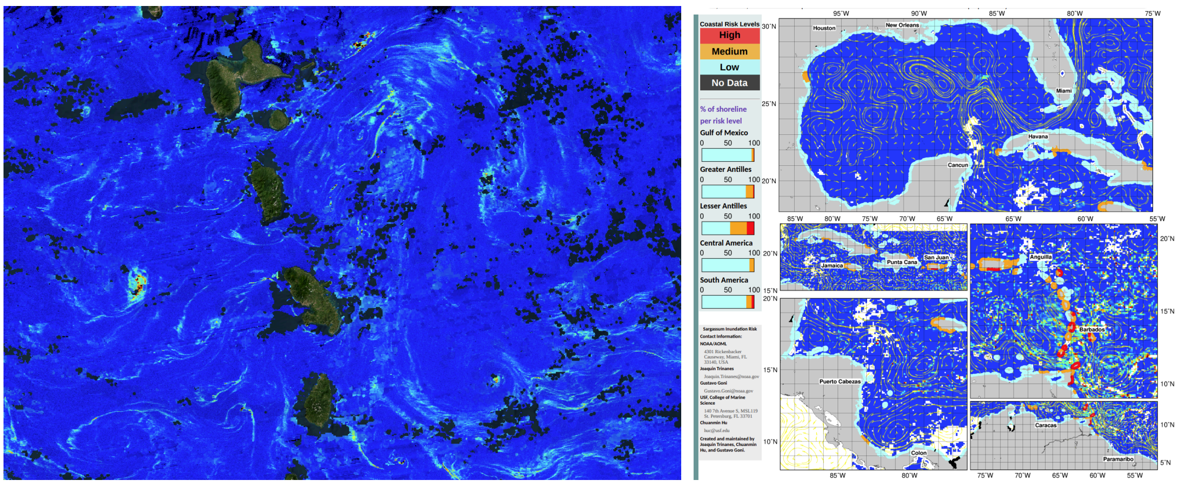
PhOD scientists found that the tripole-related gyre-scale heat content and sea level changes explain up to 80% of the interannual sea level variance along the U.S. southeastern coast. Due to the GMSL rise, the tripole has significantly impacted the frequency of flooding events along the U.S. East and Gulf coasts since the mid-2000s. Specifically, the tripole-related changes in 2015–2019 were responsible for up to 5 flood days per year, which makes up 30–50% of the total number of flood days.



Fraction of the local interannual dynamic sea level variance explained by the North Atlantic tripole.

Sargassum transport and inundation risk

Beginning in 2011, the Caribbean has faced significant challenges due to massive influxes of pelagic Sargassum. These influxes have caused significant problems, disrupting tourism, fishing, and local economies, and impacting coastal ecosystems and human health. These now recurring events, highlight the need of implementing robust monitoring and management strategies to mitigate their multiple impacts.



FigX. Multisensor distribution of Sargassum mats in the Lesser Antilles on May 14th, 2024.

In a joint effort involving AOML/PhOD, NOAA CoastWatch, and the University of South Florida (USF), we utilize satellite sensors like OLCI, MODIS and VIIRS to detect Sargassum mats. This allows us to infer the distribution and density of Sargassum across the tropical Atlantic, Caribbean Sea, and Gulf of America. This solution provides critical information on the timing, scale, and potential impacts of Sargassum influxes, enabling data-driven decisions such as beach clean-up operations and tourism advisories, and facilitating effective communication with stakeholders including local governments, businesses, and communities.

The Sargassum Inundation Risk (SIR) fields integrate satellite-derived data to estimate the likelihood of Sargassum inundation along coastal areas, categorizing the risk into low, medium, and high. These reports provide valuable and actionable information to prepare for and mitigate the impact of Sargassum inundation events.

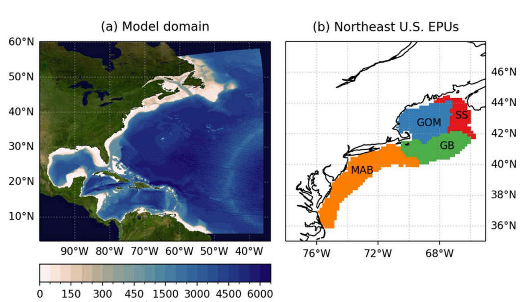
NOAA Climate, Ecosystems, and Fisheries Initiative (CEFI)

The NOAA Climate, Ecosystems, and Fisheries Initiative (CEFI) is an effort to provide decision-makers with the information they need to prepare for, and adapt to, changing ocean and coastal conditions. Through development of state-of-the-art high-resolution regional ocean and ocean biogeochemical models, and delivery of model output to an end-to-end decision support system, CEFI aims to provide robust forecasts at seasonal and decadal timescales, as well as projections of future oceanic conditions across marine ecosystems to provide resource managers, fishing communities, ocean industries, and other stakeholders with information, tools, and advice to help reduce impacts and increase resilience to rapidly changing ocean conditions.

Scientists across our Ocean Chemistry and Ecosystems Division (OCED) and Physical Oceanography Division (PhOD) at AOML are leading the effort to deliver multi-decadal projections of changing ocean conditions across the Northwest Atlantic region (NWA12), which encompasses the Grand Banks and the entire Caribbean Sea. Within this region, we are modeling how environmental conditions will change under future climate scenarios to provide essential information to resource managers and key fisheries communities across the region. We are creating an ensemble of climate change projections across several models and future scenarios, to represent the range of uncertainty for the NWA12 domain.

Key Impacts:
Warmer oceans, rising seas, eutrophication and deoxygenation are a few of the key threats to fisheries and natural resources exacerbated by climate change. Across the Atlantic and Pacific Oceans and the Great Lakes, fisheries are integral to the U.S. economy and their degradation due to climate change will affect not only reefs and fish stock populations but people, businesses and communities - and large-scale food security. By combining models of ocean dynamics, biogeochemistry, and sea ice, we are able to project changes in temperature, salinity, sea ice formation and melting, and phytoplankton biomass across the Northwest Atlantic region, that will ultimately drive changes in fisheries and other key marine resources.

Who We Collaborate With: CEFI is a cross-NOAA initiative. We collaborate with NOAA Geophysical Fluid Dynamics Laboratory (NOAA/GFDL), NOAA Southeast Fisheries Science Center (NOAA/SEFSC), NOAA Northeast Fisheries Science Center (NOAA/NEFSC), NOAA Physical Sciences Laboratory (NOAA/PSL), CIMAS, NGI, and the MOM6 community



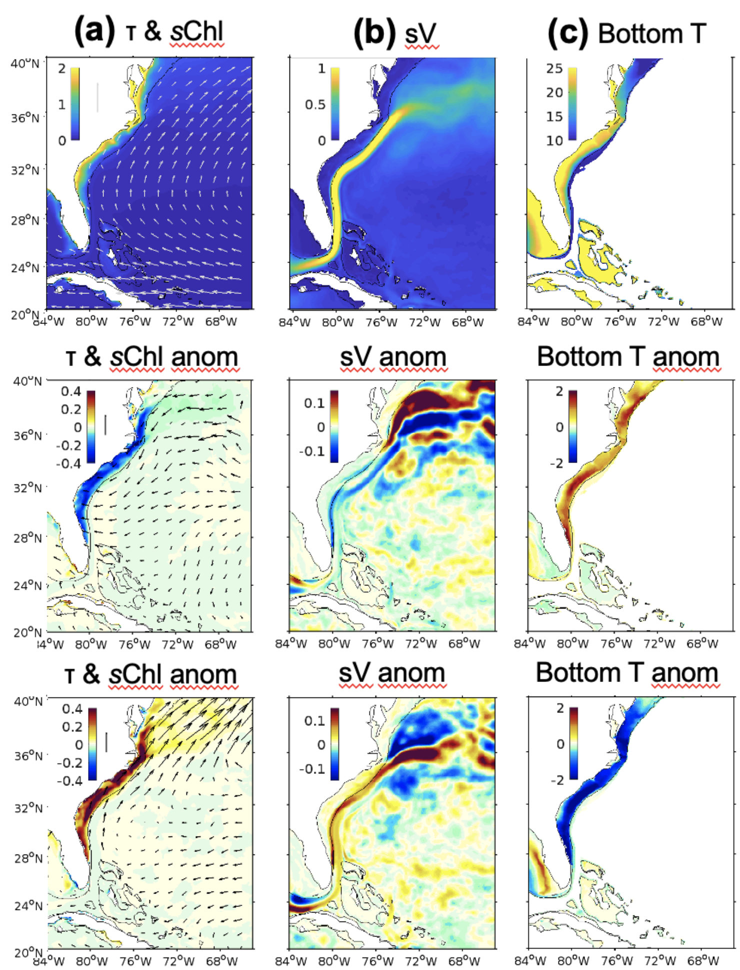
The NWA12 Domain, which encompasses the United States East Coast and the greater Atlantic Ocean. Derived from Ross, A., et al. (2023).

Modeling ocean biogeochemical patterns in the Southeast U.S. Coast, Gulf of America, and Caribbean Sea

Goal: Describe interannual to multidecadal changes in biogeochemical patterns over the Caribbean Sea, Gulf of America, and South Atlantic Bight using high-resolution regional model outputs validated against available observations.

Currently, we are investigating drivers of phytoplankton and carbonate system variability in the South Atlantic Bight, using outputs from the MOM6-COBALT Northwest Atlantic model.

The model outputs showed coherent interannual variability patterns of bottom temperature and coastal biogeochemical fields, linked to changes in wind-driven upwelling. The surface Gulf Stream flow played a major role in the cross-shelf interchanges of physical and biogeochemical properties.



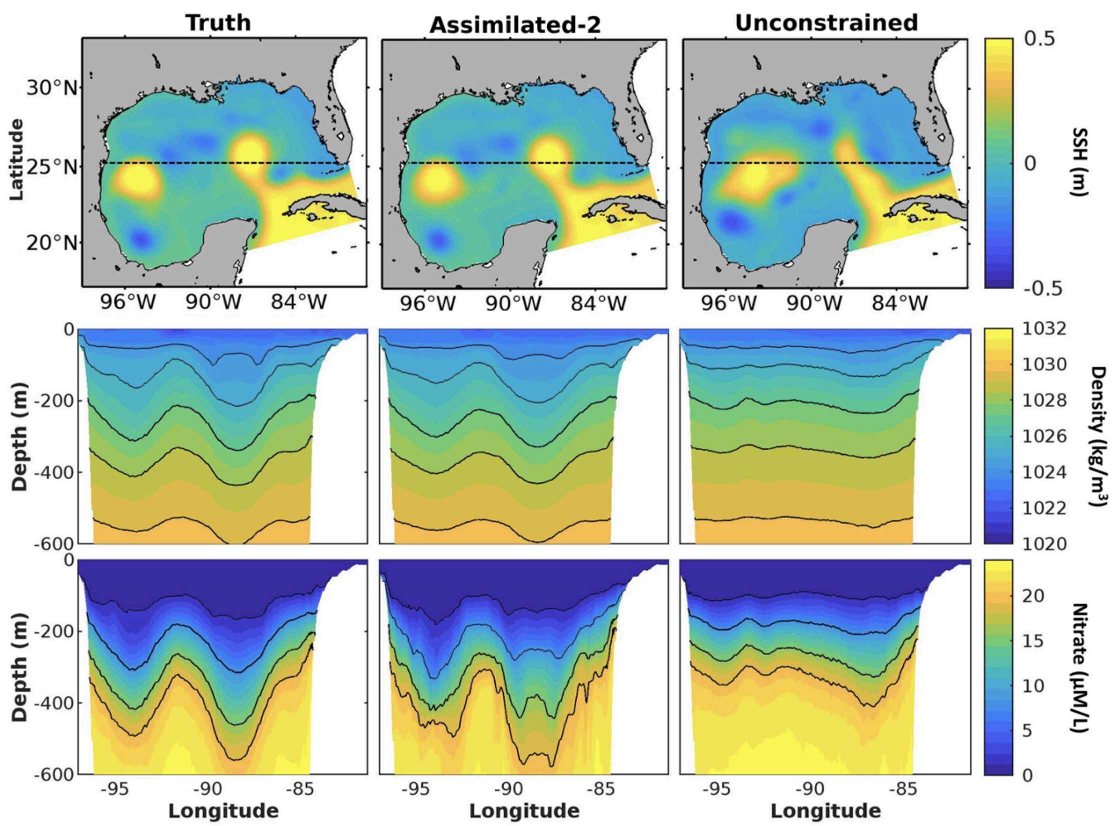
Toward building a subseasonal-to-seasonal red tide and hypoxia warning system for the West Florida shelf

Goal: To build a numerical modeling framework, validated against in situ observations and satellite data, which will be the base of a subseasonal to seasonal warning system of red tide and hypoxia over the West Florida Shelf.

Using a twin experiment approach, we evaluated if a simple physical data-assimilation method improves the representation of biogeochemical tracers in a regional ocean-biogeochemical model.

Results showed that a realistic mesoscale variability reduced significantly the biases in biogeochemical tracers.

Thus, physical data-assimilation can be an affordable tool to generate ocean-biogeochemical products.



Characterizing and forecasting coastal ecosystem responses to multiple stressors for management (FRESCA project)

Goal: To investigate how five key stressors (ocean acidification, hypoxia, HABs, warming, and eutrophication) are impacting marine ecosystems of South Florida.

We configured a 1/36° resolution ocean-biogeochemical model for South Florida, build up in the regional MOM6-COBALT model system, referred to as SFL36.

Results showed that SFL36 reproduced reasonably well patterns in temperature, salinity, circulation, and biogeochemical variables.

This south Florida modeling effort contributes to expanding the ocean-biogeochemical modeling capabilities off the U.S. coast, providing a valuable tool to investigate marine ecosystem variability.