Monitoring Impacts of the Gulf Stream and its Rings on the Physics, Chemistry and Biology of the Middle Atlantic Bight Shelf and Slope from the *MV Oleander*

Magdalena Andres*[1], Senior Scientist, 0000-0002-5512-2844
Thomas Rossby[2], Emeritus Professor of Oceanography, 0000-0003-0730-7753
Eric Firing[3], Emeritus Professor of Oceanography, 0000-0002-7745-6888
Charles Flagg[4], Emeritus Research Professor
Nicholas R. Bates[5,6], Professor of Oceanography[5] and Senior Scientist/Director of Research[6], 0000-0002-0097-0336
Julia Hummon[3], Oceanographic Researcher, 0000-0001-7524-8754
Denis Pierrot[7], Research Physical Scientist, 0000-0002-0374-3825
Timothy J. Noyes[5,6], Courtesy Affiliate[5] and Research Fellow[6], 0000-0001-9750-9193
Matthew P. Enright[6], Research Specialist, 0009-0001-2151-4989
Jeffery K. O'Brien[1], Senior Engineer, 0000-0001-7227-6266
Rebecca Hudak[1], Information Systems Associate, 0000-0002-0017-8330
Shenfu Dong[7], Oceanographer, 0000-0001-8247-8072
D. Christopher Melrose[8], Research Oceanographer, 0000-0001-9195-3162
David Johns[9], Director of Research Facilities, 0000-0003-3270-6764
Lance Gregory[9], CPR Survey Operations Manager

[1]Woods Hole Oceanographic Institution, MA, USA
[2]University of Rhode Island, RI, USA
[3] University of Hawaii, HI, USA
[4] Stony Brook University, NY, USA
[5]School of Ocean Futures, Julie Ann Wrigley Global Futures Laboratory, Arizona State University (ASU), Tempe, Arizona, USA
[6]ASU-Bermuda Institute of Ocean Sciences, Bermuda
[7] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, USA
[8] NOAA Northeast Fisheries Science Center, Narragansett, RI, USA
[9] Marine Biological Association, United Kingdom

*Corresponding author: mandres@whoi.edu, 266 Woods Hole Rd. Woods Hole, MA 02543, USA

Abstract Sustained observation is key to measuring variability and identifying long-term trends. Here we illustrate how a partnership with a merchant marine container vessel in service between New Jersey and Bermuda twice per week has given scientists a unique window into upper ocean currents, water properties and marine ecology for over three decades. Scientific observations collected from *MV Oleander*, operated by Bermuda Container Line/Neptune Group, are enabling cross-disciplinary research, allowing for ground-truthing satellite measurements, and contributing to global observing programs—including the Global eXpendable BathyThermograph (XBT) Network, the Surface Ocean CO_2 Atlas (SOCAT), and the Continuous Plankton Recorder (CPR) Survey. This successful cooperation serves as a model for Science Research on Commercial Ships (Science RoCS), a multi-institution group of researchers, engineers, and data managers whose goal is to transform ocean science by outfitting a fleet of commercial ships with scientific sensors, including acoustic Doppler current profilers (ADCPs) that regularly scan subsurface ocean currents to measure mesoscale and submesoscale circulation beneath a vessel as it is underway in regular service (Rossby, 2012).

The regional circulation in the Northwest Atlantic is dominated by the Gulf Stream, a subtropical western boundary current whose warm, salty waters course along the continental slope of the southeastern US in a narrow (~100 km width), intense jet that serves both to close the wind-driven gyre and carry the warm limb of the Atlantic Meridional Overturning Circulation poleward. After passing Cape Hatteras, North Carolina, the deep-reaching Gulf Stream begins to meander, serving as a moving boundary between the watermasses, ecosystems and chemical regimes of the Slope and Sargasso Seas (**Figure 1a**). Warm and cold core rings are intermittently shed from meander crests and troughs, respectively, and drive transport across the sharp Gulf Stream front that separates the deep thermocline (~800 m depth) and salty, warm Sargasso Sea waters to the south from the shallow thermocline (~200 m depth) and relatively cooler, fresher Slope Sea waters to the north. Rings can influence biological and chemical distributions as well as air/sea fluxes. Warm core rings (WCRs), which carry Sargasso Sea waters into the Slope Sea, are deep-reaching and cannot move directly onto the shallow Middle Atlantic Bight (MAB) shelf (**Figure 1b**). They do, however, interact with the upper slope and outer shelf through ageostrophic processes that impact the Shelfbreak Jet (SBJ) and that exchange waters across the shelf break. The Gulf Stream also sheds warm filaments called "shingles" (von Arx *et al.*, 1955) into the Slope Sea. These submesoscale features are not as deep-reaching as WCRs, nor are their currents as strong, but they can nevertheless influence the biology and chemistry of the Slope Sea and shelf waters. Shingles can be difficult to resolve with the limited temporal and spatial resolution of satellite observations.

Scientific equipment has been hosted since the early 1970s on three different container ships operating consecutively on the "Oleander Line," a longstanding route between Elizabeth, NJ and Hamilton, Bermuda (Rossby *et al*., 2019). Presently the sensors on the newest *MV Oleander*, which came into service in early 2019, are providing co-located water-column, sea surface and atmospheric measurements (**Figure 2**) across the MAB shelf, Slope Sea, the meandering Gulf Stream, and Sargasso Sea.

Discrete temperatures profiles are measured monthly with 48 XBT probes launched with an Autonomous eXpendable Instrument System (AXIS, Fratantoni *et al*., 2017) mounted to the *MV Oleander's* stern. These give us an unparalleled view of the upper ocean thermal structure including the main thermocline. Near-real time temperature data are returned to shore via the Iridium satellite network. Velocity profiles and acoustic backscatter intensity to ~200-m depth are continuously scanned during each crossing with a 150 kHz ADCP. Individual pings are 5-minute averaged to give velocity profiles with along-track resolution that is about 2-km. A sample of the ADCP data is sent to shore daily via Starlink. The full dataset is downloaded during each port call.

MV Oleander is equipped with an underway scientific seawater line with the intake at ~5.8 m depth that supplies flow-through instrumentation, such as a Sea-Bird 38 for near-surface temperature and a Sea-Bird 45 thermosalinograph (TSG) for salinity. There is a carbon dioxide (CO_2) system measuring partial pressure and fugacity of CO_2 (pCO_2 and fCO_2) in surface seawater and boundary layer air, with other sensors occasionally measuring alkalinity and pH. In addition, underway near-surface atmospheric data are recorded with a weather station. The underway data are recorded at 1-4 Hz (except for pCO_2, recorded every 2 minutes) and are transmitted to shore via Starlink at 10-minute intervals.

Each month, *MV Oleander* tows a CPR at ~10 m depth to sample plankton in the upper water column with a 280 micron mesh gauze. CPR cartridges are returned to shore after 3 or 4 months and are analyzed to identify and count organism taxa and, where possible, species. The gauze is cut into slices representing ~10 nautical miles of tow, with each slice sampling roughly 3 m^3 of seawater. To avoid interference, the monthly CPR tows and XBT sections are generally conducted during separate crossings.

Concurrent measurements from *MV Oleander's* scientific sensors underscore the interplay of ocean physics, chemistry and biology at temporal scales spanning events to seasons and spatial scales spanning shingles to regional recirculation cells. As an example, the velocity profiles recorded during the transit on 3-4 August 2024 provide context for the complex along-track property distributions (**Figure 3**). The vessel crossed a ~200-m thick Gulf Stream shingle in the Slope Sea and a deep-reaching cyclonic cold core ring (CCR) in the Sargasso Sea. In this late summer section, heating has muted near-surface temperature contrasts, so the shingle is only slightly warmer than the ambient Slope Sea waters and the CCR does not stand out as particularly cold relative to the Sargasso Sea. However, near-surface salinities combined with the subsurface temperature profiles (with the 12°C isotherm used to identify the depth of the thermocline) clearly delineate fronts that align with the submesoscale (shingle) and mesoscale (CCR and Gulf Stream) circulation features.

The correspondence between these circulation features and the along-track variability in fCO_2 is striking. The core of the fresh, cyclonic CCR stands out as a region of elevated fCO_2 (450 µatm) within the otherwise lower fCO_2 waters of the surrounding Sargasso Sea (*i.e.*, the oligotrophic subtropical gyre of the North Atlantic Ocean). The salty shingle in the Slope Sea, which grows westward as it continues to draw waters from the eastward-flowing Gulf Stream, has lower fCO_2 (440 µatm) and, like the Gulf Stream, is more saline than the ambient Slope Sea. Concurrent satellite ocean color measurements (see inset to **Figure 3a**) of *chlorophyll a* (*chlr-a*) show that—in contrast to the core of the Gulf Stream, which has low *chlr-a* (~0.1 mg m^{-3})—this shingle is associated with a filament of elevated *chlr-a* (~0.3 mg m^{-3}), suggesting bio-physical interactions rather than simple horizontal advection of Gulf Stream watermasses by the shingle. Since these features are long-lived compared to *Oleander* sampling intervals, it will be possible to examine the plankton distributions within these features as sampled by the CPR, which was towed on the previous Bermuda-bound transit on 28-27 July 2024, once the cartridge is returned to shore. The concurrent underway data (near-surface salinity and velocity profiles) will help identify the exact locations of the fronts and circulation features during that transect (which marked the 535th CPR tow from an *Oleander*).

The (sub)mesoscale variability of fCO_2 in the along-track data is superimposed on strong regional-scale contrasts between MAB coastal waters (~450 μatm), Slope Sea (~470 μatm), Sargasso Sea (~420 μatm), waters north of Bermuda (~430-470 μatm), and the waters on the Bermuda reef and lagoon (>490 μatm). While it is known that the assemblages of plankton species in the Sargasso Sea and Slope Sea vary, and that rings can host species not found in the surrounding waters, a thorough comparison of the circulation features with the plankton survey and with underway near-surface data (including fCO_2) remains to be undertaken.

Global observing programs and studies of long-term changes and interannual-to-decadal scale variability continue to benefit from scientific observations collected aboard *MV Oleander.* These enduring observations allow scientists to resolve long-term changes in the Northwest Atlantic on the MAB shelf (*e.g.*, Forsyth *et al.*, 2015) and in the open ocean (*e.g.*, **Figure 4**).

The Oleander Program contributes to the Global XBT Network, which provides repeated upper ocean (0-900 m) temperature measurements along fixed transects at eddy-resolving scales in regions critical for monitoring and understanding upper ocean dynamical and thermodynamic processes. Deployment of XBTs began in the 1960s and data collected from XBTs became the largest contributor to the upper ocean thermal record during the 1970s−1990s. Since the operation of the Argo array in early 2000s to sample the ocean interior, the focus of the XBT network has been to monitor boundary currents, gyre circulation, and meridional transport of heat and mass from trans-basin sections (*e.g.*, Goni *et al.*, 2019). Some XBT transects have been occupied continuously for more than 30 years, providing an unprecedented long-term climate record at spatial and temporal scales that remains unmatched and cannot be reproduced at present by any other observing platform. XBT profiles have been collected from *MV Oleander* (referred to as transect AX32) for nearly 50 years. Starting in 1977, data were mainly collected in the MAB shoreward of the Gulf Stream. Since 2009, XBTs have been deployed along the entire section with resolution varying from 15 km within the Gulf Stream to 25-50 km in the ocean interior. Building on this monitoring effort, the Oleander Program has also been measuring velocity profiles since 1993 (Rossby 2019) with the historical (1993-2018, https://oleander.bios.asu.edu/) and new (since 2023, https://currents.soest.hawaii.edu/home/data/) processed data available.

The pCO$_2$ system and associated sensors aboard *MV Oleander* allow for evaluation of surface seawater CO$_2$-carbonate chemistry and air-sea CO$_2$ gas exchange over weekly, seasonal and longer timescales, and across different ocean regions. Such data collection is important for understanding physical and biogeochemical variability at the Bermuda Atlantic Time-series Study (BATS) site (1988 to present; Bates and Johnson, 2023) near the island of Bermuda. The pCO$_2$ data contribute to the international SOCAT (https://socat.info/) effort which provides a global, quality-controlled data set and gridded product every year to the scientific community (*e.g.*, Bakker *et al*., 2022). This product, in turn contributes to annual global carbon budget analyses (Friedlingstein *et al*., 2023). It is also the source of multiple other products (see https://socat.info/index.php/products-using-socat/) and publications (see https://socat.info/index.php/publications/). The *MV Oleander* data set provides unmatched coverage (100 transects/year) that is uniquely suited to help quality control other regional data sets.

The CPR Survey seeks to establish the location and abundance of plankton globally. Sampling from ships running southeastward from NJ towards Bermuda—referred to as the MB route—began in 1976 with the *MV Oleander* recruited in 1981 (Jossi *et al*., 2003). Operations, initially managed by NOAA Fisheries, are now carried out by the Marine Biological Association (*e.g.*, Helaouet *et al*., 2024).

To advance a sustained global observing system that also resolves local and regional processes, Science RoCS (https://sciencerocs.org) aims to emulate the partnership established with Bermuda Container Line/Neptune Group on a broad scale (Macdonald *et al*., 2024). The industry has signaled that it is willing to help as scientists seek to expand their ability to collect sustained observations of the atmosphere and upper ocean waters to advance science and address pressing global challenges. With its integrated system of scientific sensors, *MV Oleander* serves as an interdisciplinary observatory in the Northwest Atlantic that can be replicated elsewhere to aid oceanographers, who have only limited access to the seas. The successes of Oleander operation over the last 50 years demonstrate that partnering with the merchant marine can greatly increase this access.

Acknowledgements: The National Science Foundation (NSF) Division of Ocean Sciences (OCE)-funded Oleander Program supports the operation of the ADCPs, weather station, TSG, and associated infrastructure, as well as the operation of AXIS, with the XBT probes supplied by NOAA/AOML. Operation of the pCO_2 system is funded by NOAA/AOML and the operation of the CPR and analysis of the samples is presently supported by NOAA through the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS). The US Office of Naval Research funded the REMORA purchase. Oleander science is made possible by the continued generosity of Bermuda Container Line/Neptune Group and the invaluable expertise and support of the *MV Oleander* captains, chief engineers and crew.

Bakker, D.C.E. *et al*., 2022. Surface Ocean CO_2 Atlas Database Version 2022 (SOCATv2022) (NCEI Accession 0253659), https://par.nsf.gov/biblio/10409726.

Bates, N.R., and Johnson, R.J., 2023. Forty years of ocean acidification observations (1983–2023) in the Sargasso Sea at the Bermuda Atlantic Time-series Study site. *Frontiers in Marine Science*. 10. 10.3389/fmars.2023.1289931

Forsyth, J.S.T., M. Andres, and G.G. Gawarkiewicz, 2015. Recent accelerated warming of the continental shelf off New Jersey: Observations from the CMV Oleander expendable bathythermograph line, *Journal of Geophysical Research Oceans*, 120, 2370– 2384, doi:10.1002/2014JC010516

Fratantoni, D., J. O’Brien, C. Flagg, and T. Rossby. 2017. AXIS: An Autonomous eXpendable Instrument System. *Journal of Atmospheric and Oceanic Technology* 34:2,673–2,682, https://doi.org/10.1175/JTECH-D-17-0054.1.

Friedlingstein, P. *et al*., 2023. Global Carbon Budget, 2023, *Earth System Science Data*, 15, 5301–5369, 2023, https://doi.org/10.5194/essd-15-5301-2023.

Goni, G., *et al.*, 2019. More than 50 years of successful continuous temperature section measurements by the Global Expendable Bathythermograph Network, its integrability, societal benefits, and future. *Frontiers in Marine Science,* 6:452. doi: 10.3389/fmars.2019.00452

Helaouet, P., L. Sheppard, and D. Johns, 2024. Continuous Plankton Recorder phytoplankton and zooplankton occurrence and count data from The CPR Survey in the Western North Atlantic Ocean from 1958 to 2021 (Version 4) [Data set]. Biological and Chemical Oceanography Data Management Office (BCO-DMO). https://doi.org/10.26008/1912/BCO-DMO.765141.4

Iselin, C. O'D., 1940. Preliminary report on long-period variations in the transport of the Gulf Stream system. *Papers in Physical Oceanography and Meteorology*, 8(1), 40.

Jossi, J.W., A.W.G. John, D. Sameoto, 2003. Continuous Plankton Recorder sampling off the east coast of North America: history and status. *Progress in Oceanography*, 58, 313-325, doi:10.1016/j.pocean.2003.08.010.

Macdonald A.M., L. Hiron, L. McRaven, L. Stolp, K. Strom, R. Hudak, S. Smith, J. Hummon, and M. Andres, 2024. A framework for multidisciplinary science observations from commercial ships, *ICES Journal of Marine Science*, 0, 0(1-12), doi: 10.1093/icesjms/fsae011

Rossby, T., C.N. Flagg, K. Donohue, S. Fontana, R. Curry, M. Andres, and J. Forsyth, 2019. Oleander is more than a flower: Twenty-five years of oceanography aboard a merchant vessel. *Oceanography*, 32(3):126–137, https://doi.org/10.5670/oceanog.2019.319.

Rossby, T., 2012 *OceanScope: A Proposed Partnership Between the Maritime Industries and the Ocean Observing Community to Monitor the Global Ocean Water Column.* Report of SCOR/IAPSO Working Group. Paris: SCOR.

von Arx, W.S., 1955. On the fine-structure of the Gulf Stream front, *Deep Sea Research*, 8, 46-65.

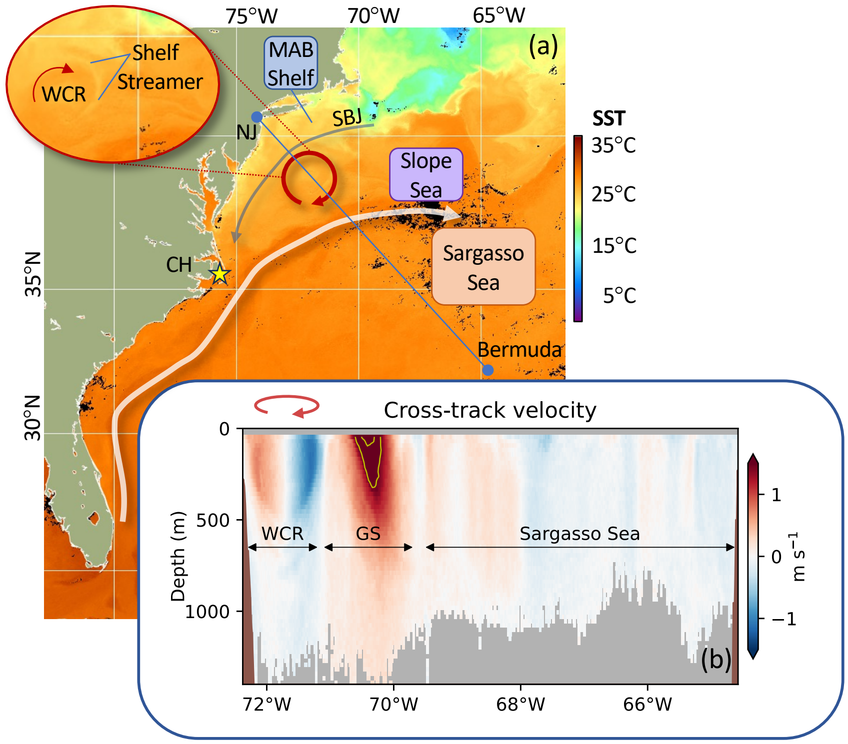

Figure 1. (a) Schematic of Northwest Atlantic circulation superimposed on a composite SST map produced by NOAA from the Advanced Very High Resolution Radiometer and the Visible Infrared Imaging Radiometer Suite (AVHRRR/VIIRS) merged from 23-26 July, 2021; inset shows a close-up of a WCR with a streamer of cooler (and fresher) waters from the MAB shelf wrapping around the anticyclonic ring. (b) Cross-track component of ocean velocity (heading 47°) measured during the concurrent Bermuda-bound *MV Oleander* transit with an Ocean Surveyor 38 kHz ADCP (OS38), with the 1.5 and 2.0 m s^{-1} isolines (yellow) and bathymetry (shaded brown). Grey shaded regions have less than 30% good data returns. The WCR is deep-reaching and surface intensified: ~16 Sv is being circulated within the upper 1000 m of the ring, and most of this (88%) is concentrated in the upper 500 m. The Gulf Stream is carrying ~81.6 Sv (integrated from the surface to 1000-m depth and from 71.1°W to 69.6°W).

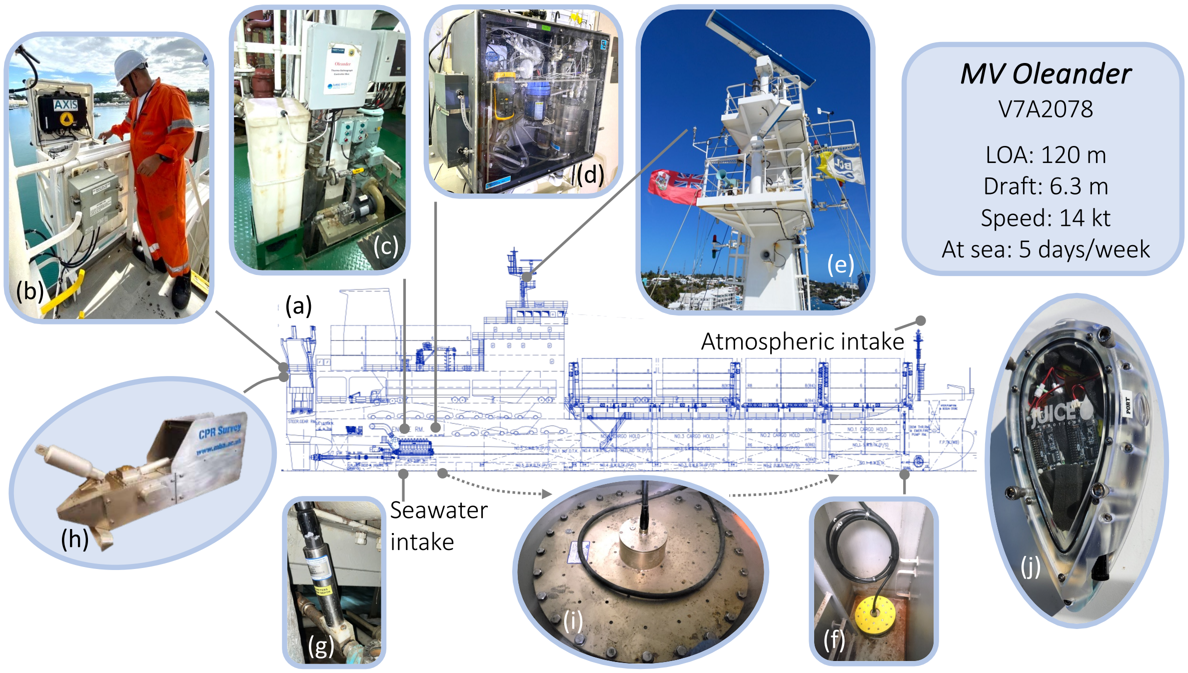

Figure 2. (a) General arrangement drawing showing locations of scientific sensors and infrastructure presently operating on *MV Oleander*: (b) AXIS on the stern being reloaded with XBT probes; (c) underway scientific seawater system in the engine room; (d) Seabird SBE45 TSG to record seawater salinity (left) and a General Oceanics 8050 *p*CO2 Measuring System (right), with a LICOR® 7000 analyzer calibrated every 2-3 hours with 4 standard gases with concentrations ranging from 0-470 ppm traceable to the WMO scale; (e) Vaisala WXT536 weather sensor mounted on the flybridge mast to measure air temperature, humidity, sea level pressure, rainfall and wind speed and direction; (f) hull-mounted Teledyne RD Instruments 150 kHz Ocean Surveyor ADCP (OS150) with a 3/8 inch thick polycarbonate acoustic window for protection; (g) SBE38 temperature probe near the seawater intake to provide near-surface ocean temperature before the seawater pipes pass through the hot engine room; and (h) CPR which is lowered by the crew using the ship's mooring winch and is towed behind the vessel. Not shown are the GPS and ABXTWO antennas which are necessary for accurate ship position and heading to calculate ocean velocities. Also shown are the former and planned locations for (h) the OS38 which was installed during the ship build but has only rarely given good velocity sections, with some profiles reaching beyond 1000-m depth (*e.g.*, **Figure 1b**). The OS38 was removed during the January 2024 drydock and will be reinstalled in a forward location with less bubble noise and with a 1½ inch acoustic window for protection. The new site was chosen based on analysis of videos of the bubble field

using the commercially available REMORA (j) with programable forward- and side-facing cameras built by Juice Robotics LLC. This magnetically-mounted camera system was installed by commercial divers for two transits in fall 2023 to help identify the locations of bubble clouds entrained under the vessel that can cause noise in ADCP measurements.

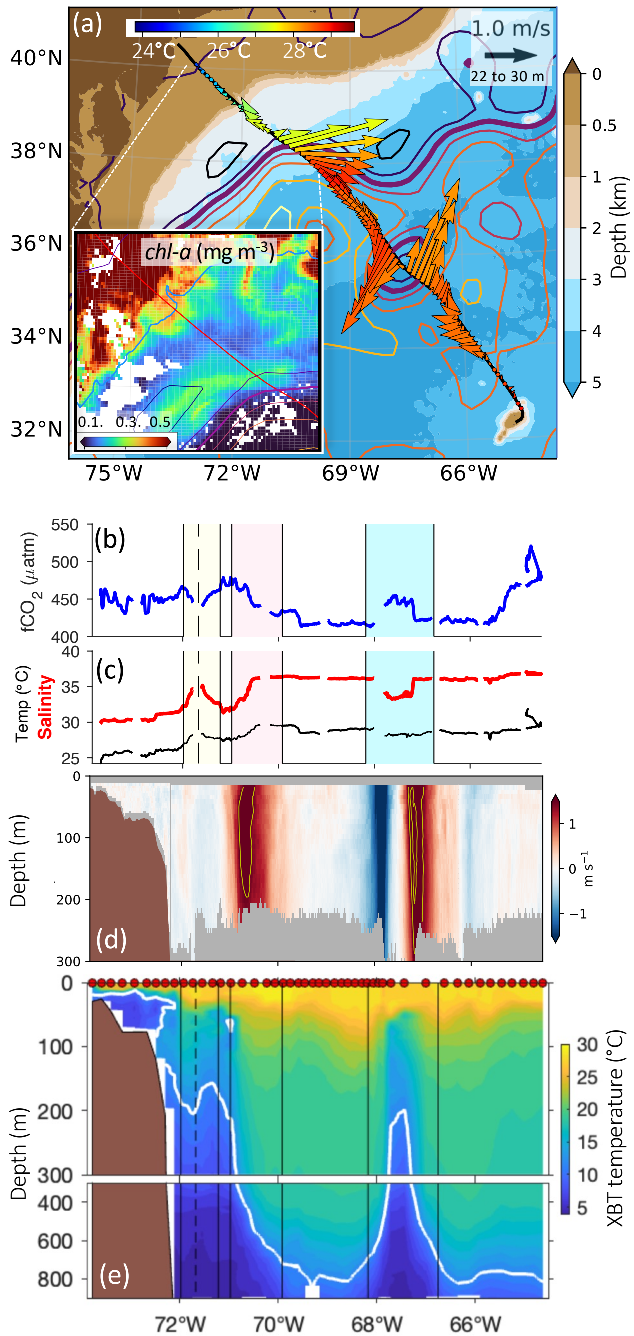

Figure 3. Observations spanning 3-4 August 2024. (a) Near-surface velocity vectors (averaged from 22 to 30-m depth) from the OS150 with colors indicating temperature as measured internally, superimposed on bathymetry (shading). Inset shows *chlr-a* from NOAA's Sentinel-3A-OLCI for 2 August 2024 with the *MV Oleander* route (red) and 200 m isobath (blue). Also plotted are SSH contours for 3 August 2024 from the mapped satellite altimetry from Copernicus Marine Service product SEALEVEL_GLO_PHY_L4_NRT_008_046 contoured at 0.25-m intervals, with the

0.25-m contour highlighted as a proxy for the Gulf Stream core (thick purple). (b) Underway fCO_2 with the shingle (yellow), Gulf Stream (pink), and CCR (blue) highlighted. (c) Underway near-surface salinity (thick, red) and temperature (thin, black) with shading as in (b). (d) Cross-track velocity profiles (heading 47°) with the 1.5 and 2.0 m s^{-1} isolines (yellow) highlighted. (e) Temperature section in the upper (surface to 300-m depth) and mid-depth (300-900 m) water column, as observed with XBT probes launched by AXIS at the locations indicated (red dots), with the 12°C (white) and boundaries of the circulation features noted above (vertical lines).

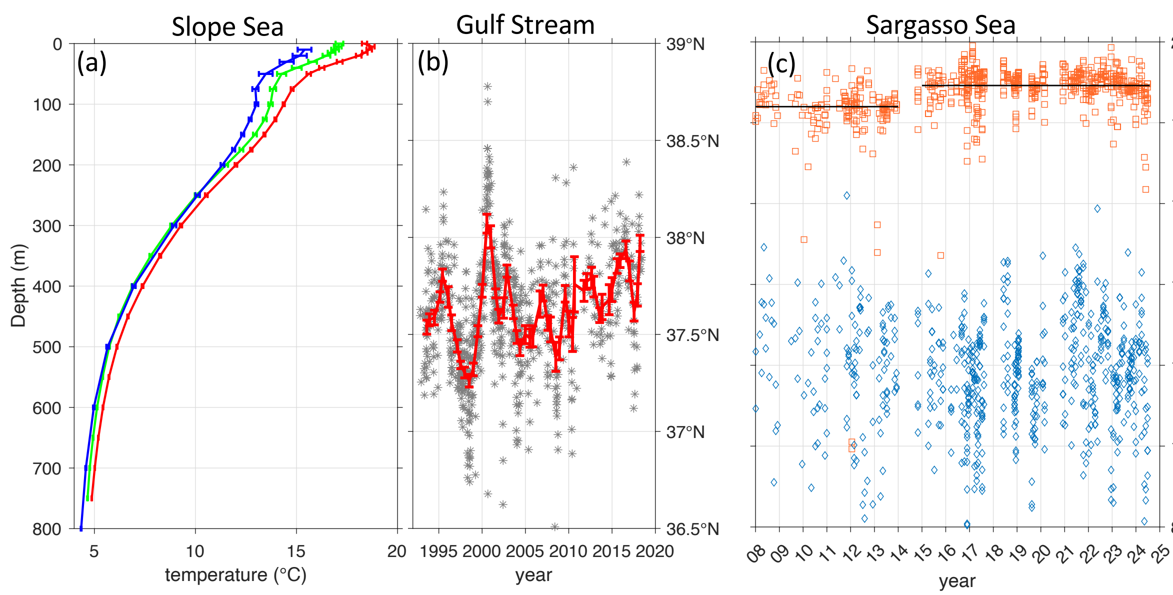

Figure 4. Long-term changes in the Northwest Atlantic as observed by *MV Oleander*. (a) Warming in the upper 750 m of the Slope Sea is evident from deseasoned and spatially-averaged temperature profiles for 1937-1940 (blue) from 35 hydro-casts (Iselin, 1940), 1994-2003 from 147 XBT profiles (green), and 2014-2023 from 284 XBT profiles (red). The horizontal bars represent the mean standard error. These mean temperature profiles demonstrate significant warming that is consistent with other studies and is concentrated in the last 3 decades. (b) Latitude of maximum velocity of the meandering Gulf Stream as measured during individual transits (gray stars) with the annual average stepped every 6 months superimposed (red). The cause of the strong lateral shifting in the 1990s and early 2000s may reflect large variations in dense water formation in the Labrador Sea. The gradual northward shift of the Gulf Stream implies a shrinking Slope Sea, whose cause remains under investigation. (c) Temperature at 300-m depth from XBT profiles

taken within the Sargasso Sea (red squares) where what used to be called “18°C water” is now 19°C, with a sudden 0.5ºC increase in the mean around 2015. Corresponding temperatures at 800 m depth (blue diamonds) show no trend but do exhibit substantial scatter since this is the depth of the main thermocline in the Sargasso Sea. The 1°C standard deviation in temperature at this depth corresponds to about 40 m of thermocline heave.