Deep-reaching cyclones and their interactions with the Gulf Stream, warm core rings, and the New England seamounts

PS24D-1772

Ysabel Wang*[1,2], Magdalena Andres[2], Sean Chen[3]

[1]Massachusetts Institute of Technology, [2]Woods Hole Oceanographic Institution, [3]Imperial College London; *ysabel@mit.edu

Mesoscale eddies in the Slope Sea

Warm Core Rings (WCRs)

WCRs are anticyclonic eddies that shed from Gulf Stream (GS) meander crests due to baroclinic instabilities. They are visible in satellite products by their warm sea surface temperature (SST) and high-pressure or positive sea surface height (SSH) anomalies. WCRs can entrain streamers – cold, fresh, productive shelf water – into the warm, salty, nutrient-poor Slope Sea, the region directly north of the GS and adjacent to the continental shelf. Shelf streamer export is a significant contributor to the heat and salt budgets of the region and also impacts cross-slope circulation and physical and biogeochemical properties instantaneously and cumulatively.

Slope Sea cyclones

Deep-reaching, coherent cyclones form within troughs of large-scale meandering currents such as the GS. When a trough develops as the current meanders southward, the combined effects of the pressure drop and density increase throughout the water column lead to the formation of these cyclones in the Slope Sea. First observed to frequently form around 68°W (Savidge & Bane, 1999a), cyclones also form at 64°W and 58°W (Chen et al, 2025, under review). They are visible in satellite altimetry due to their low-pressure or negative SSH anomalies and are easily identified in *in situ* measurements by their positive vorticity and strong (up to 50 cm/s) subsurface currents (Godin, 2024).

Godin, O. A., Tan, T. W., Joseph, J. E., & Walters, M. W. (2024). Observation of exceptionally strong near-bottom flows over the Atlantis II seamounts in the northwest atlantic. Scientific Reports, 14 (1), 10308.
Savidge, D. K., & Bane Jr, J. M. (1999a). Cyclogenesis in the deep ocean beneath the gulf stream: 1. description. Journal of Geophysical Research: Oceans, 104 (C8), 18111–18126

Interactions between WCRs and the GS

When the southern edge of a WCR interacts with the GS for >1 day, such as during a spiral streamer formation (Zhang & McGillicuddy, 2020) where buoyant GS water is entrained into the WCR, the trajectory of a shelf water streamer that is continuously entrained by the WCR during the interaction can be injected into the GS North Wall, as opposed to wrapping around the ring (Fig. 1). The transfer of buoyant GS water to the WCR also increases the ring's baroclinicity and radial pressure gradient (Cherian & Brink, 2016), resulting in a greater transport of shelf water (Cenedese et al., 2013; Wang et al., in prep). These events tend to be succeeded by interactions between the ring and Slope Sea cyclones (Fig. 1).

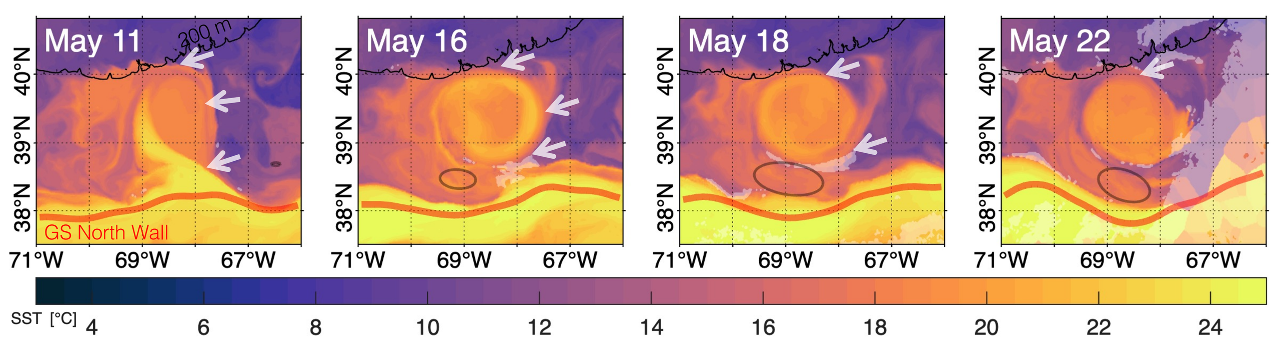


Fig. 1: SST images on May 11, 16, 18, and 22 during an interaction between the WCR and the GS North Wall (thick red line) that was immediately succeeded by an interaction with a Slope Sea cyclone (black contour, -30cm SSH). During the WCR-GS interaction that resulted in a spiral streamer (Zhang & McGillicuddy, 2020), the WCR continuously entrained shelf water (white arrows). The 200-m isobath (black contour) separates the shelf and slope.

Cenedese, C., Todd, R. E., Gawarkiewicz, G. G., Owens, W. B., & Shcherbina, A. Y. (2013). Offshore transport of shelf waters through interaction of vortices with a shelfbreak current. Journal of physical oceanography, 43 (5), 905–919.
Cherian, D. A., & Brink, K. (2016). Offshore transport of shelf water by deep-ocean eddies. Journal of Physical Oceanography, 46 (12), 3599–3621.
Zhang, W., & McGillicuddy Jr, D. (2020). Warm spiral streamers over gulf stream warm-core rings. Journal of Physical Oceanography, 50 (11), 3331–3351.890

Acknowledgements and more information

This work is supported by the Office of Naval Research (ONR) grants N000142212112 titled "New England Seamounts Physical Oceanography: Characterizing Variability at Scales Spanning the Mesoscale to the Internal Tide" and N000142212575 titled "A Distributed Network of Internal Wave Resolving Moored Arrays for Assessing Tide-Resolving Model Fields and Improve Forecasts in the Coastal Ocean."

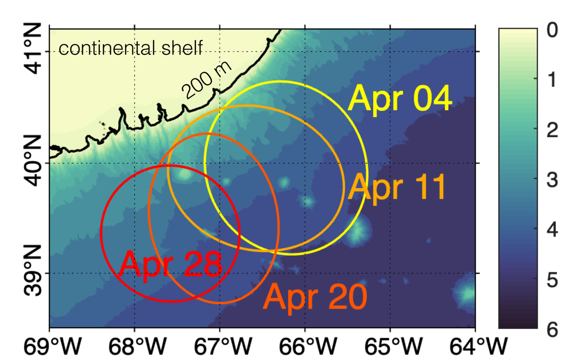
For more information on this study and related work, scan this QR code:

SUMMARY

- Interactions between WCRs and Slope Sea cyclones influence cross-scale circulation and exchange
- WCR-cyclone interactions can modify the ring's structure, giving rise to submesoscale ageostrophic motion in the ring's periphery where shelf water streamers are located
- From 2021-2025, 85% of interactions between WCRs and the GS North Wall were immediately succeeded by WCR-cyclone interactions that modified the ring's structure
- These transient events impact the physical and acoustic properties of the Slope Sea and GS North Wall and cumulatively impact cross-shelf and cross-slope exchange

Interactions between WCRs and cyclones

Satellite and *in situ* observations suggest that an encounter between a WCR and a Slope Sea cyclone can modify a ring's structure (Figs. 2 & 3). Here we focus on one WCR from 2023, but historical satellite measurements reveal that WCR modification during an interaction with a cyclone is not a unique occurrence (see QR code). Cyclone interactions also tend to immediately succeed WCR-GS interactions; from 2021-2025, this occurred 85% of the time. Fig. 2 shows the evolution of the ring's radius and eccentricity during the interaction in April 2023, as determined from SSH and SST. The impact of the interaction on the ring's subsurface velocity structure is seen in Fig. 3. A comparison between the early (T1 – April 7-8) and late (T2 – April 17) stages of the interaction reveals that the azimuthal and along-axis velocities in the offshore section of the ring had intensified by T2.



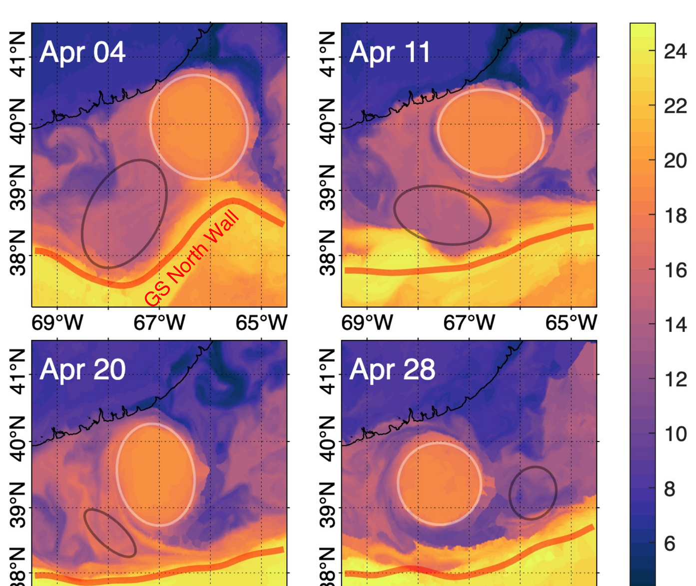


Fig. 2: (top) Bathymetry map in the Slope Sea with the evolution of the WCR's SST-derived shape during its interaction with a cyclone on April 4, 11, 20, 28. **(right)** SST maps of the WCR (white contours) and deep cyclone (black contour, -30 cm SSH) interaction at different stages; the thick red line is the 25-cm SSH contour to estimate the GS North Wall. The 200-m isobath contour delineating the continental shelf is shown in black in all figures.

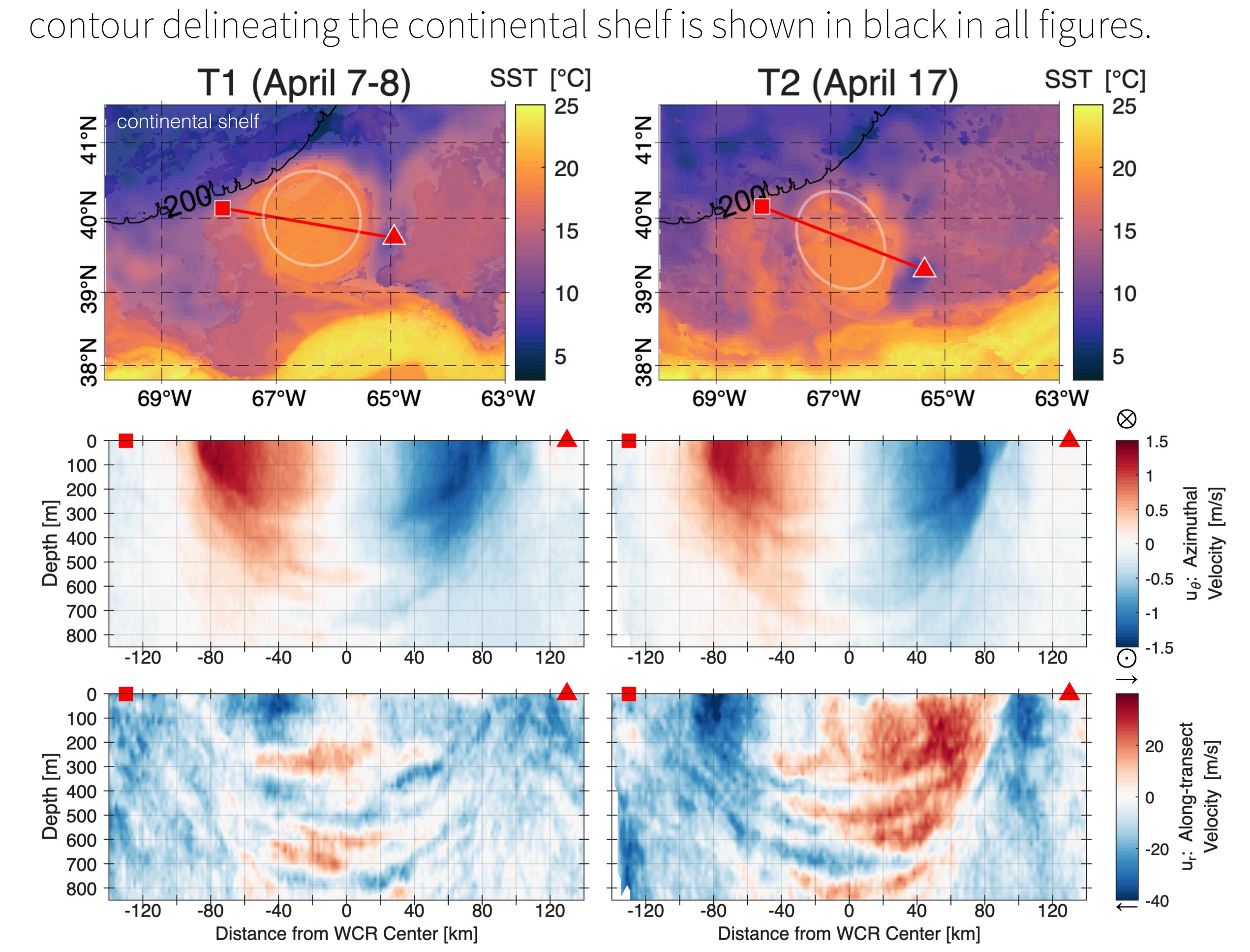


Fig. 3: **(top)** SST maps of the WCR during two transects (red lines) from April 7-8 (T1, left column) and April 17 (T2, right column). **(middle)** Azimuthal or spin velocities through WCR on T1 and T2. The red squares and triangles on each plot indicate the onshore and off-shore sections of the ring, respectively, in reference to the SST maps. **(bottom)** Along-transect velocities on through the WCRs on T1 and T2. The red and blue arrows show a region of convergence in the offshore section of the ring. Data were collected as part of the NESMA program.

Effects on cross-slope exchange

Modifications to the WCR velocity structure during its interaction with a cyclone result in shear and strain within and along the edge of the WCR. A shelf streamer that is present around the ring periphery at this time is also impacted by these mesoscale-driven modifications. One effect is frontogenesis that is caused by these deformation-induced horizontal motions that then induce submesoscale motion, such as subduction as in Zhang & Partida, 2018. During T2 (April 17), frontogenesis in the offshore streamer that had been entrained by the WCR is visible in the near-surface density measurements (Fig. 4), implying submesoscale motion in the subsurface. This represents a a mechanism by which mesoscale interactions (WCRs and cyclones) drive submesoscale processes (frontogenesis and ageostrophic motions in the shelf streamers).

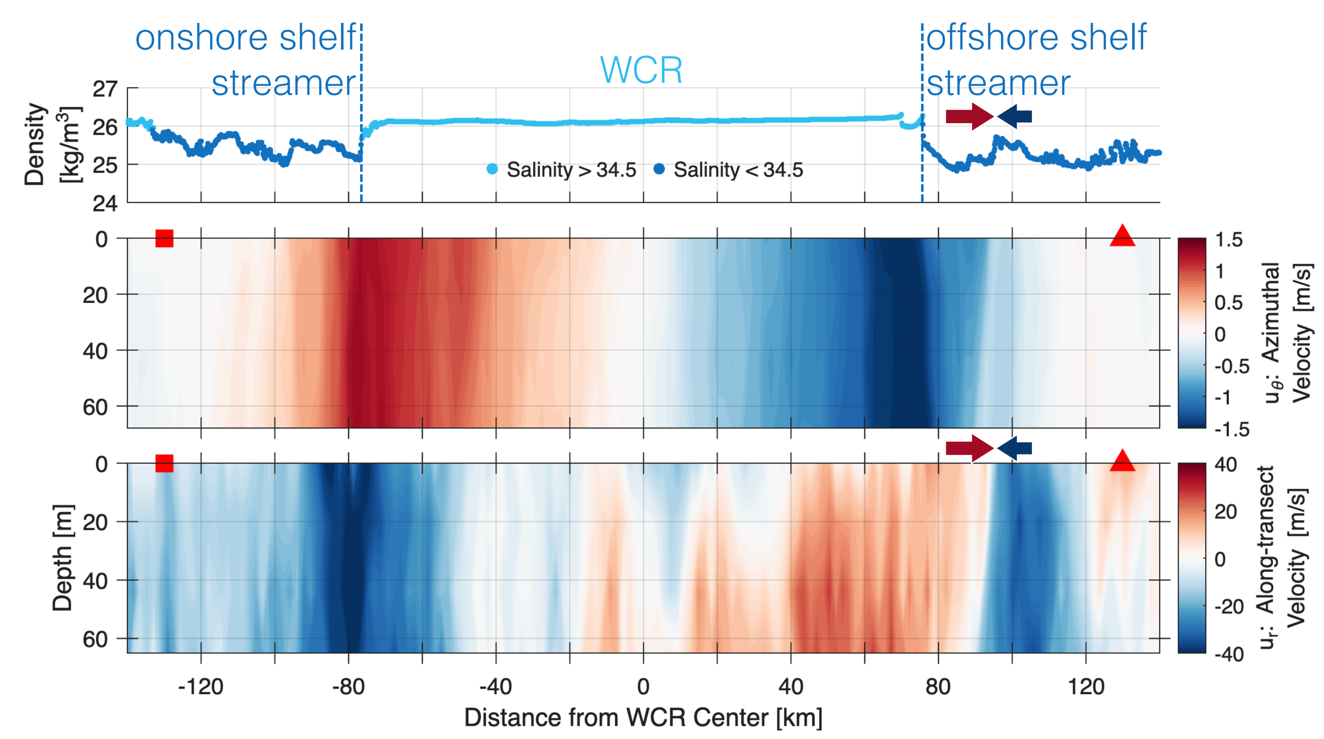
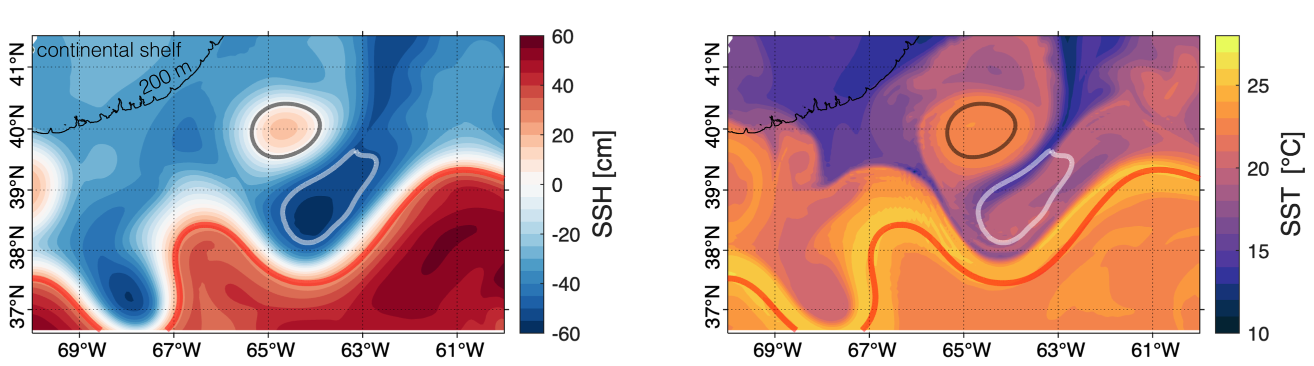


Fig. 4: (top) Near-surface density along the T2 transect (Fig. 2) showing the location of the WCR (light blue dots, salinity > 34.5) and shelf streamers (dark blue dots, salinity < 34.5). **(middle)** Azimuthal or spin velocity along the same transect in the upper 65 m of the transect. The red square and triangle indicate the onshore and offshore sides of the transect, in reference to Fig. 2. **(bottom)** Along-transect velocities through the same transect. The red and blue arrows, also present in the near-surface density plot and in Fig. 2, indicate a region of along-transect convergence within the offshore streamer that suggests frontogenesis.

Zhang, W., & Partida, J. (2018). Frontal subduction of the mid-atlantic bight shelf water at the onshore edge of a warm-core ring. Journal of Geophysical Research: Oceans, 123 (11), 7795–7818.

Implications and future work

The 85% likelihood for WCR-cyclone interactions to immediately succeed WCR-GS interactions that tend to increase streamer transport (Wang et al., in prep) implies that a significant volume of shelf water is subject to submesoscale motions driven by the WCR's deformation. Assuming (1) that a WCR present in the western Slope Sea entrains a streamer 75% of the time, (2) an average lower-bound transport estimate of 0.26 Sv associated with WCR-GS interactions (Wang et al., in prep), and (3) that each WCR-cyclone interaction modifies a WCR's structure, then ~8.2 x 10^6 m^3/yr of shelf streamer water would be subject to mesoscale-induced submesoscale motion, potentially representing a mechanism for Slope Sea ventilation. Refinement of this estimate and investigation into the dynamics of the inter-action will involve further analysis of a realistic model (Fig. 5).



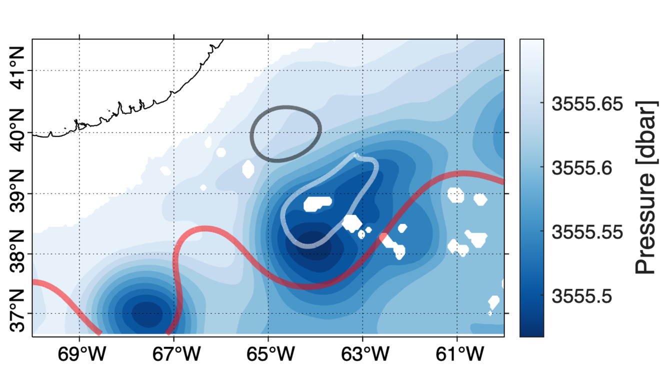


Fig. 5: Model output from Chen et al., 2025 of SSH (top left), SST (top right), and pressure at 3500 m (bottom left). All figures show SSH contours of 25 cm (red), 0 cm (black), and -50 cm (white) representing the GS North Wall, a WCR, and a deep cyclone, respectively.