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Shelf water entrainment by Gulf Stream warm-core rings between 75°W and 50°W during 1978–1999

Ayan H. Chaudhuri *, James J. Bisagni, Avijit Gangopadhyay

School of Marine Sciences, University of Massachusetts and School for Marine Science and Technology, University of Massachusetts, Dartmouth, 706 South Rodney French Boulevard, New Bedford, Massachusetts 02744, USA

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ABSTRACT

Previous work concerning Gulf Stream warm-core rings (WCRs) and their associated shelf water entrainments have been based upon single surveys or time series from individual WCRs. To date, estimates of annual shelf water volume entrained into the Slope Sea by WCRs and its interannual variability have not been made. Using a long time series of satellite-derived sea surface temperature (SST) observations of Slope Sea WCRs, we have completed an analysis of 22 years of WCR data (1978–1999) between 75°W and 50°W to understand the interannual variability of WCRs and their role in entraining shelf water. Satellite-derived SST data digitized at Bedford Institute of Oceanography are analyzed using an ellipse-fitting feature model to determine key WCR characteristics including WCR center position, radius and orientation. Key characteristics are then used to compute WCR swirl velocity by finite-differencing WCR orientations (θ) obtained from the feature model time series. Global mean WCR-edge swirl velocity calculated from all observations is 105.72 ± 10.7 km day^{-1} (122.36 ± 12.4 cm s^{-1}), and global mean WCR radius is 64.8 ± 6.2 km. Primary and derived WCR data are incorporated into a two-dimensional ring entrainment model (RM) using the quasi-geostrophic approximation of the potential vorticity equation. The RM defines ambient water as entrained by a WCR only if the gradient of relative vorticity term (horizontal shear) dominates the potential vorticity. Proximity of a WCR to the position of the shelf-slope front (SSF) is then used to determine whether the ambient water is entrained from the outer continental shelf. WCR-induced shelf entrainment derived from the RM displays considerable spatial variability, with maximum entrainment occurring offshore of Georges Bank, advecting a mean total annual shelf water volume of 7500 km^3 year^{-1} from the region. Estimates of shelf water fluxes display significant interannual variability, which may be in part due to the observed covariance between WCR occurrences and the state of the North Atlantic Oscillation (NAO). Increased (decreased) occurrences of WCRs are evidenced during positive (negative) phases of the NAO. The total mean annual shelf-wide WCR-induced shelf water transport is estimated to be 23,700 km^3 year^{-1} (0.75 Sv), accounting for nearly 25% of the total transport in the Slope Sea region neighboring the outer continental shelf.

1. Introduction

The Slope Sea is the oceanic region of the western North Atlantic (WNA) bounded by the Gulf Stream north wall (GSNW) to the south and the shelf-slope front (SSF) to the north (Bower and Rossby, 1989). It is characterized as an intermediate region surrounded by generally colder, fresher, and higher-nutrient shelf waters inshore of the SSF flank and warmer, saltier, and lower-nutrient open ocean waters offshore of the GSNW (Petrie and Yeats, 2000) (Fig. 1). The Gulf Stream (GS) is a turbulent jet that migrates into deeper waters after reaching Cape Hatteras, forming large-amplitude meanders downstream of Cape Hatteras from baroclinic and barotropic instability processes (Fig. 1). Large enough individual meanders (surface radii of 2–4 times the internal Rossby radius), can separate from the main GS current, loop back onto themselves and form independent rings (Saunders, 1971; Csanady, 1979). Rings that form from GS meander crests engulf parcels of warm, salty Sargasso Sea water in their core and begin to interact with their surrounding waters through either mixing or stirring processes (Parker, 1971; Churchill et al., 1993) (Fig. 1).

The common occurrence of GS warm-core rings (WCRs) in the Slope Sea, and their role in initiating cross-frontal events like shelf water entrainment in the WNA, have been well documented through satellite imagery, theoretical models and field observations. Halliwell and Mooers (1979) studied WCRs

* Corresponding author. Tel.: +1 508 910 6349; fax: +1 508 910 6371.
E-mail address: g_achaudhuri@umassd.edu (A.H. Chaudhuri).

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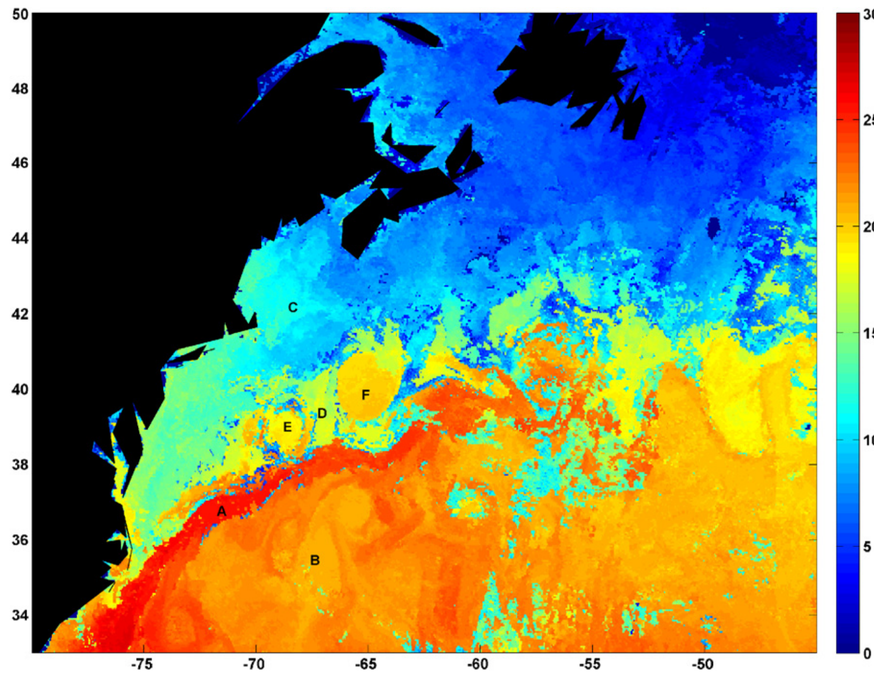

Fig. 1. *Satellite-derived SST for WNA*. 8-day composite satellite imagery of sea surface temperature (SST) for the western North Atlantic region on 06/11/1997 (*Source*: NASA JPL). The Gulf Stream (GS) (A) can be seen as a turbulent jet separating the warm Sargasso Sea (B) from the colder continental shelf (C). The Slope Sea (D) is shown as an intermediate region between the Gulf Stream (A) and continental shelf(C). The Slope Sea is engulfing two warm core rings (E,F) that are seen to entrain colder continental shelf derived water.

passing southward of the Northeast Channel to north of Cape Hatteras from 1975 to August, 1977, by performing spectral analysis on satellite-derived frontal charts of sea surface temperature (SST). A total of 14 rings were observed, having an average diameter of 100 km and mean southwestward propagation speed of 6 $cm\,s^{-1}$. Maximum ring activity was observed south and east off Georges Bank (GB), and the rings were seen to strongly interact with the SSF through the entire period. A 10-year statistical study from 1974 to 1983 by Brown et al. (1986) summarized that WCR structures display bi-modal behavior, such that longer-lived WCRs were located farther away from the GSNW and had mean lifetimes of 229 days, while shorter-lived WCRs were located closer to the GSNW, with mean lifetimes of 54 days. Auer (1987) created a 5-year ring climatology using Advanced Very High Resolution Radiometer (AVHRR) satellite imagery data from 1980 to 1984 and estimated that an average of 22 rings were formed between 75°W and 44°W each year. The maximum spatial frequency of GS WCRs was between 62°W and 65°W, with an average ring diameter of 130 km. The WCRs propagated west-southwestward at 2.4 $km\,day^{-1}$ with a surface diameter decay rate of -0.026 per week. The WCRs thus became smaller and slower over time and were eventually re-absorbed by the GS in the vicinity of Cape Hatteras; however 18% of WCRs were absorbed by other WCRs (Auer, 1987).

Theoretical models have been proposed to understand the dynamic and kinematic behavior of WCRs, including their evolution, translation and decay characteristics. Flierl (1977) using a linear quasi-geostrophic model based on the westward propagation of Rossby waves on a β-plane to study the propagation of rings, estimated propagation speeds of 1–3.5 $cm\,s^{-1}$. Csanady (1979) defined a frictionless finite displacement model to suggest that WCR formation is due to baroclinic instability growth dominated by strong boundary layer inertial forces conserving potential vorticity. The model estimated maximum WCR swirl velocity to be at the periphery of the ring, with magnitudes on the order of 1 $m\,s^{-1}$. He also proposed a diagnostic frictional model that incorporated contributions of interfacial friction and ambient water entrainment in the ring spindown process and estimated an initial decay rate of 0.05 day^{-1}. Olson et al. (1985) assimilated *insitu* data to calculate potential vorticity, kinetic energy and available potential energy using a diagnostic two-layer model assuming the ring thermocline to be at 10 °C. They observed that potential vorticity was conserved at the center of WCRs. Models describing possible mechanisms of horizontal entrainment in WCRs have been suggested by Stern (1987). The model demonstrated that a uniform stable vortex, if subjected to large = amplitude disturbances, can create large displacements of the vorticity structure at the outer boundary of the vortex. Subsequent lateral wave-breaking of vorticity isopleths can cause ambient water entrainment into the maximum azimuthal velocity field of the vortex. Chapman and Nof (1987) suggested that atmospheric influence in the form of differential vernal cooling or heating of ambient fluids around WCRs affects density gradients that make conditions suitable for lateral intrusions of surrounding water into the core of WCRs. Myers and Drinkwater (1989) constructed a ring entrainment index based on WCR activity, WCR radius of maximum swirl velocity, and proximity of WCRs to the shelf derived from satellite imagery, and linked the index to annual indices of fish stocks during 1973–1986. They observed reduced recruitment in 17 groundfish stocks due to increased activity of WCRs.

Field observations of WCRs have been recorded as early as Fuglister and Worthington (1951). Saunders (1971) used air-dropped expendable bathythermographs (AXBT) and current meter moorings to observe the formation of a WCR from a GS meander and measured surface currents of 30–75 $cm\,s^{-1}$ for a 100 km diameter WCR. Bisagni (1976) combined cruise deployed XBTs and infrared satellite imagery to observe structure and trajectories of WCRs passing through Deepwater Dumpsite 106 off the New York Bight during 1974 and 1975 and concluded that at least three WCRs affect the dumpsite every year, with mean residence time of 22 days. Other historical field-based observa-