An extraordinary breach of the Gulf Stream north wall by a cold water intrusion

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Received 24 April 2002; accepted 3 June 2002; published 1 August 2002.

[1] A breach of the Gulf Stream (GS) North Wall by a parcel of cold Middle Atlantic Bight shelf water was observed from October 2 to 5, 2001 by a sequence of NOAA AVHRR sea surface temperature (SST) images. Unlike the warm/cold core rings generated by GS meanders, the path of cold water eventually cuts into the GS. Subsequently, the cold water remained intact and eventually penetrated and transversed the entire width of the GS. This is readily apparent in the 3-day SST sequence. Analysis of wind data from a nearby CMAN station reveals a high (over 12.8 m/s) and persistent (3 days) alongshore wind event occurred prior to the breach. An 11-year time series (1991–2001) of local wind measurements show that this type of strong and persistent wind situation is uncommon, which may explain why the large-scale surface shelf water breach of the GS has not been previously reported. *INDEX TERMS:* 4576 Oceanography: Physical: Western boundary currents; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 4504 Oceanography: Physical: Air/sea interactions (0312)

1. Introduction

[2] The Gulf Stream is a powerful warm current in the northwest Atlantic. As a segment of the North Atlantic Current, it serves as a huge conduit transporting heat and moisture from the tropics to higher latitudes and therefore, plays an important role in the climatic variability of North America and Europe. In its northerly journey the Gulf Stream interacts with the surrounding waters. For example, after passing Cape Hatteras, the Gulf Stream is flanked by the Sargasso Sea to the east and the Slope Sea to the west. The interaction between the Gulf Stream and these water bodies produces a variety of spatially coherent structures such as cold and warm core rings, mescoscale frontal eddies, and shear waves. These processes directly influence the path and volume transport of the Gulf Stream. On the other hand, the Gulf Stream North Wall is often perceived as an open ocean barrier, separating the shallow coastal and continental shelf waters from the interior waters of the North Atlantic Basin that comprise the Sargasso Sea [*Grothues et al.*, 2002]. Real time monitoring the dynamical status of the Gulf Stream by satellites may provide significant information for the downstream circulation analysis and for the climate prediction of the North Atlantic and adjacent continents.

[3] At the point of its departure from the continental shelf the Gulf Stream separates two distinct physical and biogeographical provinces. The coastal region to the south is called the South Atlantic Bight or SAB and to the north the region is called the Middle Atlantic Bight or MAB. In the MAB continental shelf waters drift southward toward Cape Hatteras at a mean speed of 5–10 cm/s [*Churchill and Berger*, 1998]. Upon reaching Cape Hatteras, the shelf water can either extend past Cape Hatteras into Raleigh Bay and Onslow Bay [*Stefansson et al.*, 1971; *Pietrafesa et al.*, 1994] or it can be entrained along the North Wall of the Gulf Stream [*Ford et al.*, 1952; *Churchill and Berger*, 1998] where it often stretched into long filaments. In this investigation we find that neither of the two preceding scenarios occurs. Instead, the shelf water breaches the North Wall and penetrates into and though the Gulf Stream. Although cold core rings, which contain shelf and slope water and are formed from Gulf Stream meanders, are frequently observed in satellite sea surface temperature (SST) images on the Sargasso Sea side (further downstream of Cape Hatteras). It is to our knowledge that the breach of the North Wall by the shelf water in a large scale near Cape Hatteras has not been reported in the literature. In this article, we present and examine a sequence of SST images that capture this extraordinary event. We suspect that the breach is set up by a persistent and strong alongshore wind event and, not by a Gulf Stream meander.

2. Satellite Observations

[4] A sequence of five SST images acquired between 21:30 UTC on October 2 and 7:00 UTC October 5, 2001 and obtained from the National Oceanic and Atmospheric Administration (NOAA) CoastWatch archive are used in this study. These SST images are produced from the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA's series of Polar-orbiting Operational Environmental Satellites (specifically, NOAA-14 and NOAA-16). AVHRR data have a resolution of 1.1 km at nadir and are mapped to almost full resolution, approximately 1.3 km/pixel at 30°N latitude, [*Li et al.*, 2001b]. SST values are calculated using a split window Non-Linear SST (NLSST) algorithm [*Walton et al.*, 1998; *Li et al.*, 2001a]. All SST images used in this work were subsequently remapped to a common frame using a Mercator projection and then subsetted to a region of emphasizing the phenomena (Figure 1).

[5] The evolution of this remarkable breach of the Gulf Stream North Wall is captured in the sequence of five SST

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0094-8276/02/2002GL015378$05.00

images depicted in Figure 1. The warm surface waters of the Gulf Stream are indicated by the golden brown colors and the cooler waters of the continental shelf and slope region are denoted by the green and yellow hues. The penetration region is highlighted in the adjacent frame. To our knowledge no such intrusion of this magnitude has been recorded or documented. Furthermore, an inspection of all available imagery (over 10,000 frames) in NOAA's CoastWatch Satellite Active Archive, from 1992 to 2002, reveals no other similar events.

[6] The initial intrusion began as a fairly typical interaction between continental shelf waters, exiting from the continental shelf, near Cape Hatteras and a Gulf Stream frontal eddy (Panel 1). Mesoscale eddies form frequently in this region and often draw coastal waters to them as they migrate past the Carolina Capes region [*Glenn and Ebbesmeyer*, 1994]. Typically as the eddy progresses further downstream from Cape Hatteras the intrusion of coastal water is stretched into an elongated filament that propagates or is dragged along with the Stream, attached to the North Wall [*Churchill and Berger*, 1998]. An intrusion or breach of the North Wall into the core of the Gulf Stream does not occur. In the second panel we see the intrusion expanding and the apparent penetration into the Stream deepening. By approximately 21:30 UTC on October 3 (Figure 1, panel 3), however, an extensive breach penetrating to the opposite is observed. This is an extraordinary occurrence. The intrusion appears to have matured fully by 06:58 UTC on October 4 about 34 hours after the onset of the breach. At this point, the intrusion occupied an area of 5,770 km^2. Isolated from its source, the shelf water intrusion is carried northeastward and entrained into the core Gulf Stream. A remnant of the breach is left behind on eastern side of the stream in the Sargasso Sea (Figure 1, Panel 5).

3. Coastal Meteorology Near Cape Hatteras

[7] The regional meteorology near Cape Hatteras has been addressed by numerous authors [*Weber and Blanton*, 1980; *Weisberg and Pietrafesa*, 1983; *Pietrafesa et al.*, 1994]. Collectively, they found that during the fall season, the mean synoptic surface winds are generally to the southwestwards, and are spatially coherent over the MAB region.

[8] Wind data were obtained from the Chesapeake Light Tower (CHLV2), a station in NOAA's Coastal Meteorological Automated Network (CMAN). Other wind measurements are available in this region but it has been shown that the coherence of wind stress calculated at CHLV2 and the wind stress calculated from nearby stations is very high [*Shaw et al.*, 1994]. Therefore, the measurements form CHLV2 are sufficient for this study. The time series for CHLV2 winds are shown in Figure 2. The alongshore wind

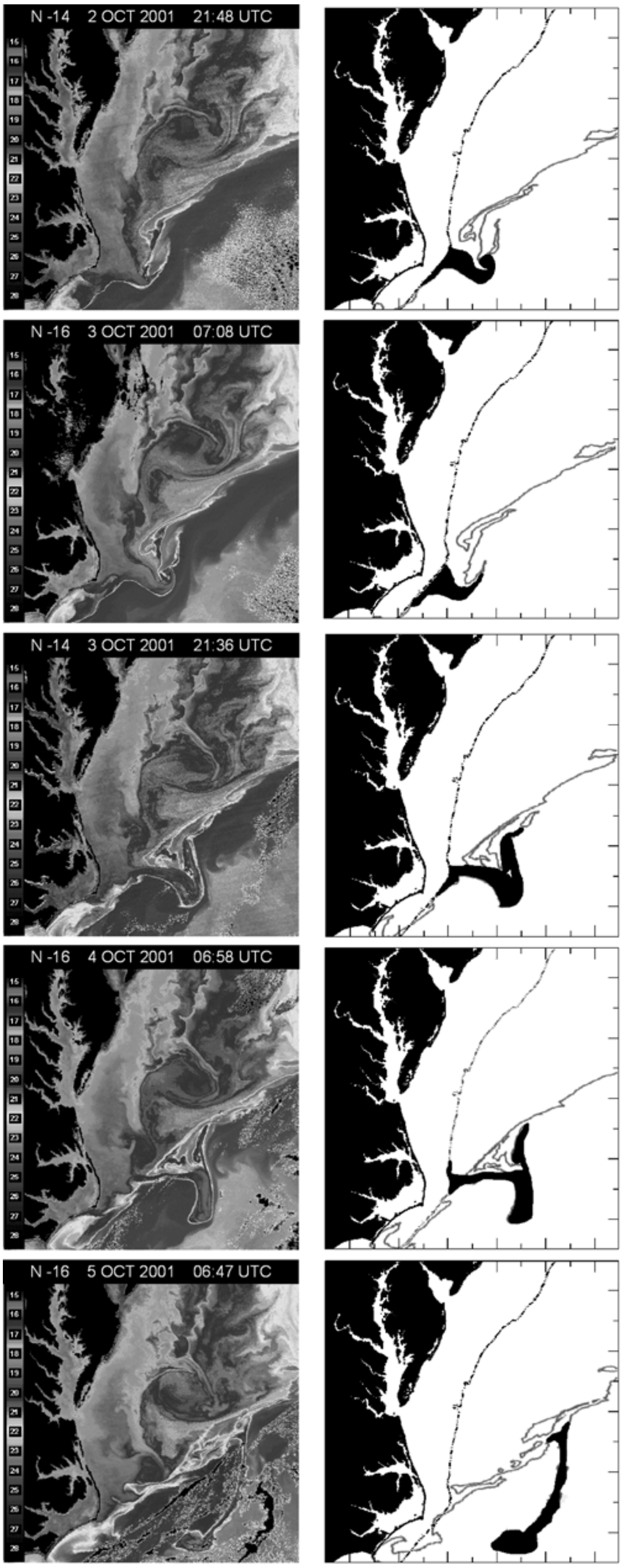

Figure 1. (opposite) AVHRR sea surface temperature images show the Gulf Stream North Wall breach event by cold water intrusion. The 100 m isobath is denoted by the black broken line. The black shaded area in the right column represents the intrusion area from the 100 m isobath east. The gray contour line represents the 24°C SST isotherm, which denotes the surface expression of the North Wall. Image upper left corner is (N 39°30′,W 39°30′), lower right corner is (N 34°30′,W 71°30′).

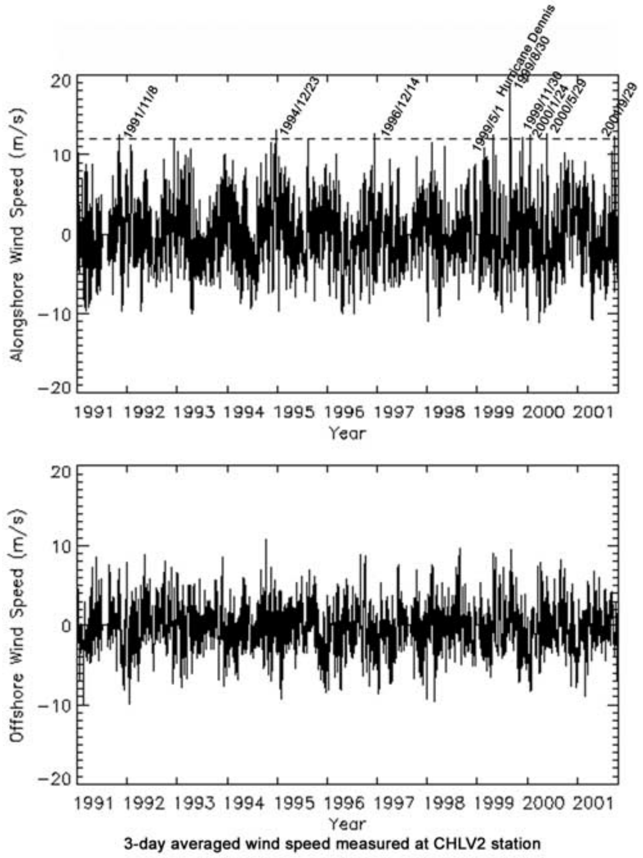

Figure 2. 3-day averaged alongshore (upper panel) and cross shore (lower panel) wind measurements at NOAA CHLV2 C-MAN station. Dates with strong (speed over 12 m/s line in the upper panel) and persistent winds (lasting for 3 days) are indicated.

direction is defined as parallel to the local bathymetry contour. A Gaussian filter was applied and any fluctuations with periods shorter than 24 hr are removed. In the analysis, the wind time series was sub sampled into 3-day data. From Figure 2, we see that prior to the Gulf Stream breach on October 2 2001, a persistent alongshore wind with a speed over 12.8 m/s had been blowing for 3 days (September 29–October 1). Over the 11-year period, extending from 1991 to 2001 similar wind situations (i.e. over 12 m/s alongshore wind for 3 days) occurred only 9 times, and among them, this is the only time that it happens in the early fall when the stratification of the upper ocean is well established.

4. Breach Mechanism

[9] We have two hypotheses concerning the dynamical mechanism of this breach event. First, the sea level set up by the strong persistent alongshore wind overcomes the Gulf Stream North Wall, resulting a breach; and, second the wind enhances both alongshore and cross shore sea level gradients; upon the relaxation of the wind, a geostrophic current driven by this sea level pressure gradient breaks through the Gulf Stream North Wall. To understand the latter breach mechanism, the Rossby radius of deformation, R = c/f, is calculated, where c is the wave velocity, i.e., $(gH)^{1/2}$, and f is the Coriolis parameter, which varies with latitude and is on the of order is 10^{-4} s^{-1} at mid latitudes. At the shelf break, the water depth, H, is approximately 100 m. The calculated scale of R is about 300 km, which is an order of magnitude larger than the observed breach length. This indicates that the rotation effects on the water column are small, and thus the second hypothesis is not the dominant breach mechanism. The first breach hypothesis is then the most likely explanation. This is to say that the wind mechanically drives the early fall shallow mixed surface layer in the MAB along the isobath to the southwest which then induces a high water level gradient near Cape Hatteras. In this region the continental shelf becomes much narrower and Diamond Shoal blocks most of the water from going further south in such a short period of time. The cold water jet associated with this sea level gradient anomaly eventually overcomes the sea level barrier of the Gulf Stream North Wall after 3 days of strong alongshore wind, and breaches the Gulf Stream North Wall on October 2, 2001. After that, the cold water jet maintained its penetration and crossed the entire Gulf Stream path. The wind dies down the next day after the breach event occurs, the sea level pressure gradient is then relaxed and the Gulf Stream North Wall reestablished.

5. Summary

[10] An extraordinary breach of the North Wall of the Gulf Stream is documented in a sequence of NOAA CoastWatch AVHRR images near Cape Hatteras, North Carolina. This is the first observed Gulf Stream North Wall breach event, to our knowledge, observed in SST imagery. Wind analysis shows that even for the persistent alongshore wind events that usually happen in the fall and winter season in this region, the consecutive three-day alongshore winds with speed over 12 m/s are rare. In fact, this is the only time that such a wind event occurs in over a decade at this time of the year. In the early fall, the upper mixed layer is shallow and the wind mechanically drives the MAB shelf water toward Cape Hatteras. In the vicinity of Cape Hatteras, the continental shelf becomes narrower so that the alongshore sea level gradient becomes great. The cold water jet associated with this sea level gradient anomaly near Cape Hatteras eventually overcame the sea level barrier of the Gulf Stream North Wall after 3 days of strong alongshore wind, and breached the Gulf Stream North Wall on October 2, 2001.

[11] **Acknowledgments.** Funding supporting this study was provided by the NOAA/NESDIS Ocean Remote Sensing Program and the NOAA CoastWatch Program. AVHRR SST imagery were generated by the CoastWatch Program and obtained from the NESDIS Satellite Active Archive. Wind data is downloaded from http://www.ndbc.noaa.gov.

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