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Direct interaction between the Gulf Stream and the shelfbreak south of New England

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Sea surface temperature imagery, satellite altimetry, and a surface drifter track reveal an unusual tilt in the Gulf Stream path that brought the Gulf Stream to 39.9°N near the Middle Atlantic Bight shelfbreak—200 km north of its mean position—in October 2011, while a large meander brought Gulf Stream water within 12 km of the shelfbreak in December 2011. Near-bottom temperature measurements from lobster traps on the outer continental shelf south of New England show distinct warming events (temperature increases exceeding 6°C) in November and December 2011. Moored profiler measurements over the continental slope show high salinities and temperatures, suggesting that the warm water on the continental shelf originated in the Gulf Stream. The combination of unusual water properties over the shelf and slope in late fall and the subsequent mild winter may affect seasonal stratification and habitat selection for marine life over the continental shelf in 2012.

It has long been known that the outer continental shelf and shelfbreak region south of New England is affected by Gulf Stream water masses. While the meridional position of the Gulf Stream has been shown to influence currents near the shelfbreak in the southern portion of the Middle Atlantic Bight[1], this has not been observed south of New England[2]. Instead, Gulf Stream influence south of New England is typically indirect and occurs via the formation and subsequent westward drift of warm core rings[3–6]. On the southern flank of Georges Bank, Lee & Brink[7] observed a warm core ring formation event in which Gulf Stream water directly abutted the shelfbreak, and Churchill *et al.*[8] described the thermohaline fields associated with a warm core ring in close proximity to the bank. Hare *et al.*[9] examined cross-slope drifter velocities near warm core rings and found that cross-slope transport was important in the life cycles of a number of fish species.

In mid-December 2011, two of the authors (GGG and AJP) were informed by commercial fishermen (Norbert Stamps, David Spencer, and Fred Mattera) that conditions at the outer continental shelf south of New England were unusual with high surface temperatures (over 21°C) and extremely strong currents. This motivated efforts to determine the cause of these atypical conditions on the outer shelf. In the following, we describe a combination of observations that confirm the presence of atypical water masses at the shelfbreak and that suggest that the Gulf Stream interacted directly with the slope and shelfbreak region. We first present in situ bottom temperature measurements at depths of 77 m and 87 m on the outer continental shelf that confirm anomalously warm conditions existed during two events in late October–early November 2011 and mid-December 2011. Moored profiler measurements at the 500-m isobath confirm that Gulf Stream water masses were located over the continental slope during late autumn 2011; the presence of these waters was likely the cause of warm near-bottom temperatures at the edge of the continental shelf. Sea surface temperature (SST) and sea surface height (SSH) fields are then used to show that the Gulf Stream shifted from an eastward orientation to a northeastward orientation that carried warm water far northward of its mean position. This conclusion is further supported by a contemporaneous surface drifter track. Finally, we discuss the events in terms of previous observations, and we speculate on the possible impact of these events on the seasonal evolution of temperature over the outer continental shelf and the possible implications for marine organisms.

Results

Anomalous conditions over the continental shelf and slope south of New England. Time series of near-bottom temperatures on the outer continental shelf were recorded with sensors mounted on lobster traps (Figure 1). At

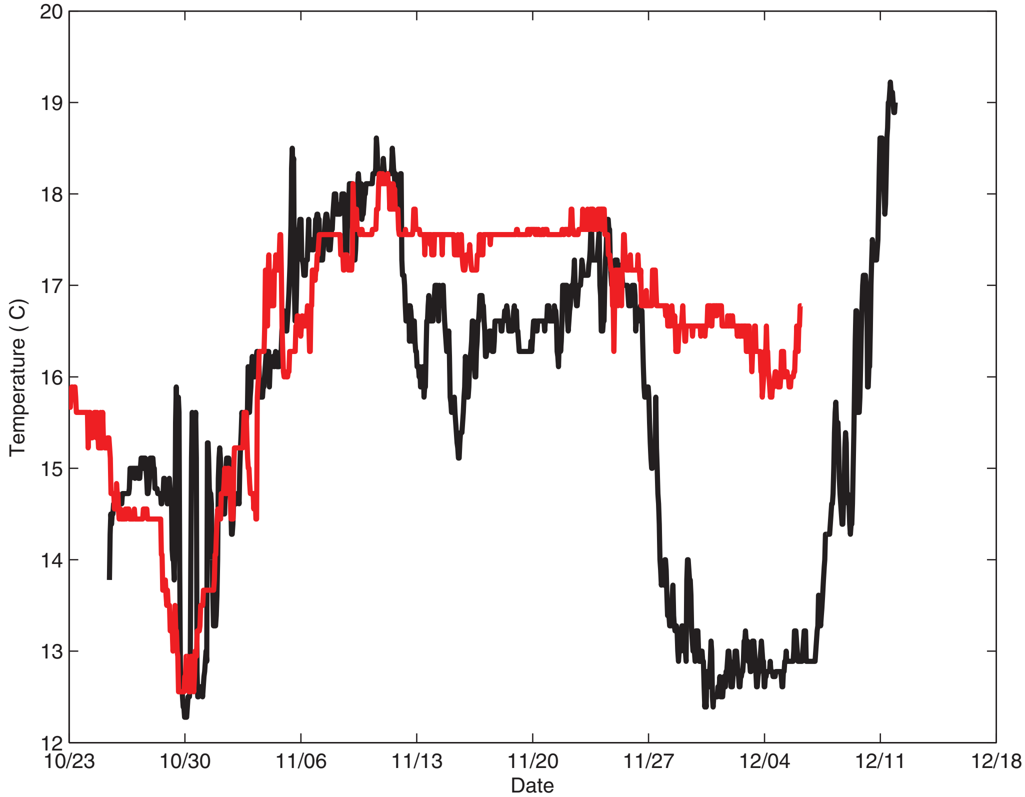

Figure 1 | Time series of bottom temperature on the outer continental shelf. Data from site OC01 is shown red, and data from site TA51 is shown black. The temperature probes were attached to lobster traps at the 77-m and 87-m isobaths, respectively. The two warming events occurred 30 October–10 November and 7–12 December.

site TA51, located at 40.34°N, 68.91°W at a depth of 87 m, the sensor measured two rapid warming events (black curve). The first event occurred 30 October–10 November, and the second event occurred 7–12 December, with the thermistor recovered at the end of this time period. The sudden increases in temperature for the two warming events were 6.2°C and 6.7°C, respectively. The first warming event was also recorded at site OC01 (red curve), located at 40.23°N, 70.1°W at a depth of 77 m, where the temperature increased by 5.7°C from 30 October to 10 November.

Near-bottom temperatures of over 18°C on the outer shelf are extremely high for late autumn. Based on historical data[10], the climatological mean bottom temperature at the 75-m isobath is 13.93°C in November and 13.53°C in December. Relative to these climatological values, the maximum temperatures of 18.22°C and 19.22°C recorded at OC01 and TA51 (Figure 1) represent warm temperature anomalies of 4.29°C and 5.69°C, respectively. Warm near-bottom temperatures (>18°C) are not only unusual in comparison to climatological data, but also in comparison with the rest of the near-bottom temperature observations from lobster traps; a survey of observations from approximately 50 sites since 2001 shows that near-bottom temperatures above 18°C occur infrequently. Observations at the OC01 site from 2004, 2006, and 2009–2012 show that the maximum temperature in December 2011 is the warmest bottom temperature ever recorded at this site, with the second highest temperature being 17°C in 2009. Maximum values in the other years were below 16°C. On three other occasions at other sites, near-bottom temperatures of 17.5, 18.0, and 19.0°C were recorded at the 82-m, 76-m, and 88-m isobaths, respectively. These events occurred in November of 2008, 2006, and 2009, respectively. While the high (>18°C) bottom temperatures at these sites are unusual for the outer shelf and upper slope, they are typical of the warm Gulf Stream[11]. For comparison, the sub-tropical mode waters south of the Gulf Stream are 18°C, with salinity of 36.5 and 26.5 kg m^{-3} potential density[12].

Moored profiler data over the continental slope confirm the presence of water mass properties typical of core Gulf Stream waters in mid-December. Selected profiles of temperature and salinity from December 2011 appear in Figure 2 along with mean climatological profiles. Profiles from 5 December and 21 December indicate salinities greater than 35.5 at depths of 80–200 m, with maxima near 100 m (Figure 2b). On 8 and 20 December, however, maximum salinities reached 36.62 and 36.54 at depths of 84 m and 92 m, respectively. On 20 December, salinities exceeding 35.5 extended from the highest point of the profile, at 30 m, to 250 m depth. Maximum salinity anomalies were 1.51 at a depth of 85 m on 8 December, 1.27 at a depth of 95 m on 20 December, 0.81 at a depth of 95 m on 21 December, and 0.71 at a depth of 85 m on 5 December. The corresponding temperature profiles (Figure 2a) indicate the warmest water exceeding 20°C was present on 8 December, while relatively warmer water extended deeper on 20 December. Temperature anomalies at 45 m depth range from 4.90°C on 5 December to 7.67°C on 8 December. The basic pattern of the temperature-salinity relationship is similar between the four profiles but reflects the increase in maximum temperature and salinity between 5 December and 20 December and decrease on 21 December (Figure 2c).

Changes in Gulf Stream orientation. SST observations combined with the track of a surface drifter suggest that the Gulf Stream was diverted to an extreme northward position near 67°W during the events of unusual temperature and salinity at the shelfbreak described above. Figures 3a and 3b show maximum SST observed during 12–21 October and 1–15 December, respectively. During the first time period, a drifter launched near Cape Fear, NC (35°N)

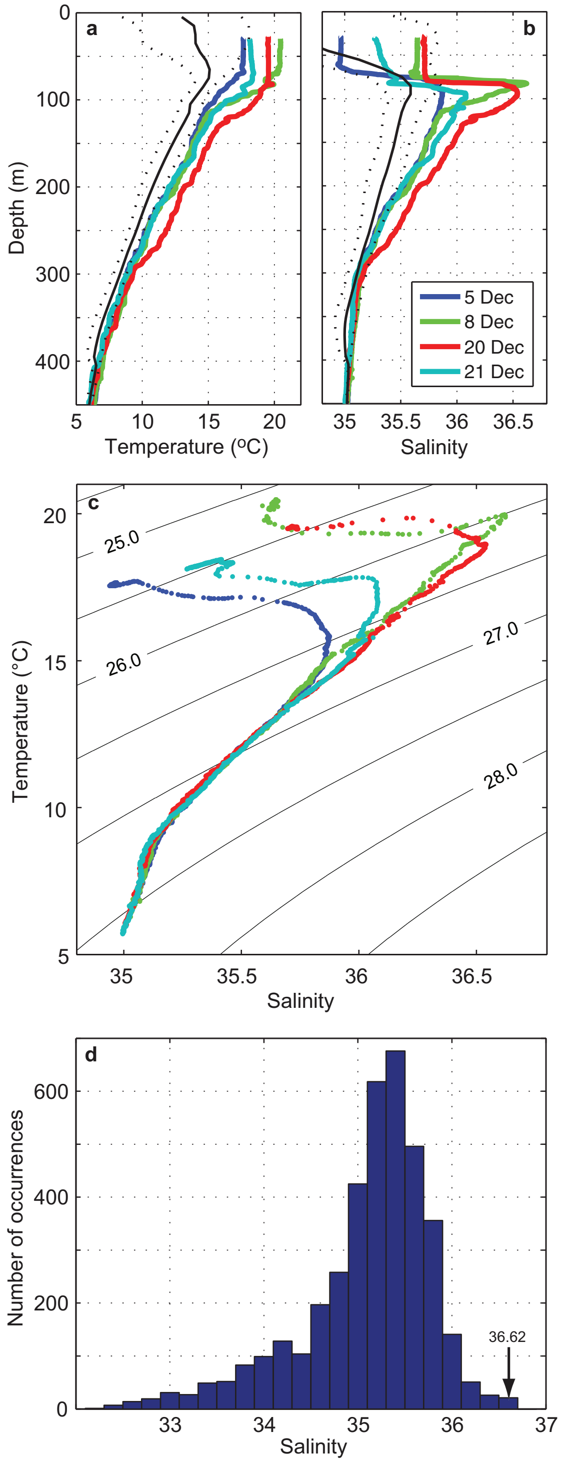

Figure 2 | Temperature and salinity data from the continental slope. Selected vertical profiles of (a) temperature and (b) salinity from the Ocean Observatories Initiative moored profiler located at the 500-m isobath (39.92°N, 70.749°W). In (a–b), mean climatological profiles are indicated by the solid black curves with dotted lines indicating one standard deviation about the mean. (c) Temperature-salinity diagrams for the same profiles with contours of density drawn (black). (d) Histogram of salinities at depths of 50–100 m over the continental slope from historical observations; the maximum salinity value measured by the moored profiler is indicated by the arrow.

reached a point near the southern flank of Georges Bank in only 8 days. The drifter followed the northern boundary of the maximum SST closely until 38°N, where a cold core ring to the south of the Gulf Stream diverted the warmest water southward without affecting the northeastward orientation of the drifter trajectory (Figure 3a). Drifter speeds (Figure 3c) exceeded 2 m s^{-1} south of 38°N and 1.7 m s^{-1} between 38°N and the maximum northward position at 39.88°N, 66.99°W, and the drifter maintained an average course of 51° from Cape Fear to near Georges Bank (Figure 3c). The drifter track confirms a continuous, high-speed path by which Gulf Stream waters reached the shelfbreak at Georges Bank. Drifter speeds of 1.2–1.5 m s^{-1} are typical in the Gulf Stream near Cape Hatteras[13]. The SST field from December (Figure 3b) indicates the presence of warm water abutting the southern flank of Georges Bank and the continental shelf south of New England. During both time periods, warm surface waters from the Gulf Stream extended well north of the climatological Gulf Stream positions determined by Drinkwater *et al.*[14] from observations of SST gradients (dashed lines in Figure 3).

Satellite altimetry indicates that the Gulf Stream interacted directly with the shelfbreak over the course of the two events. Leading up to the events, the 40-cm SSH contour was close to the Gulf Stream's climatological mean path[15] west of 68°W (Figure 4a, 1 September) while meanders were pinching off warm and cold core rings to the east. In October, the angle of the Gulf Stream path between 72°W and 68°W changed markedly from about 84° to nearly 45° (northeast). The cause is not known, but may be related to the presence of a cold core ring south of the current, centered on 36.7°N, 68.3°W, or to conditions at the separation point near Cape Hatteras. By mid-October, this northeastward orientation of the Gulf Stream delivered high velocity flow very far north, consistent with the drifter track. The 40-cm contour reached 39.9°N at 68.0°W (Figure 4b, 21 October), 200 km north of its mean position and only 70 km offshore of the 200-m isobath (i.e., the shelfbreak), and likely forced the warming event recorded by both thermistors on the outer shelf beginning in November. Paradoxically, 68°W is where the Gulf Stream path exhibits a minimum in variance of its annually-averaged meridional position[16]. In fact, since the beginning of the satellite record in late 1992, the monthly mean Gulf Stream position (determined from the maximum meridional gradient of SSH) has never been this far north at 68°W (see Figure 11 of Kelly *et al.*[17]). The 40-cm contour approached the shelfbreak again in mid-November, this time in a meander crest (Figure 4c, 24 November), with the 10-cm SSH contour staying within 25 km of the shelfbreak even as the 40-cm contour retracted to its climatological mean position in early December (Figure 4d). This second interaction occurred just before the second pulse of warm, salty water recorded at site TA51 and by the moored profiler in mid-December.

From early 2008 through mid-2011 the North Atlantic Oscillation (NAO) index was largely negative. The events described above are not likely related to the low-frequency, large-scale north-south shifts of the entire Gulf Stream path, which have been related to NAO variations with positive NAO leading a northerly path by several months to several years. While these low frequency shifts have been attributed to (1) changes in the strength of the Northern Recirculation Gyre, (2) variability in the Gulf-Stream/Deep Western Boundary Current crossover at Cape Hatteras or (3) arrival from the east of wind-driven baroclinic Rossby Waves[15,16,18,19], the events described above seem associated with a tilting mode of the Gulf Stream that contains energy at 250 days and 100 days[20]. In this tilting mode, the Gulf Stream path varies by pivoting about a node so that west of the node the Gulf Stream is south of its mean position while east of the node it is north of its mean position.

Discussion

The observations suggest that the warm (>18°C) temperatures near the bottom over the outer continental shelf in autumn of 2011

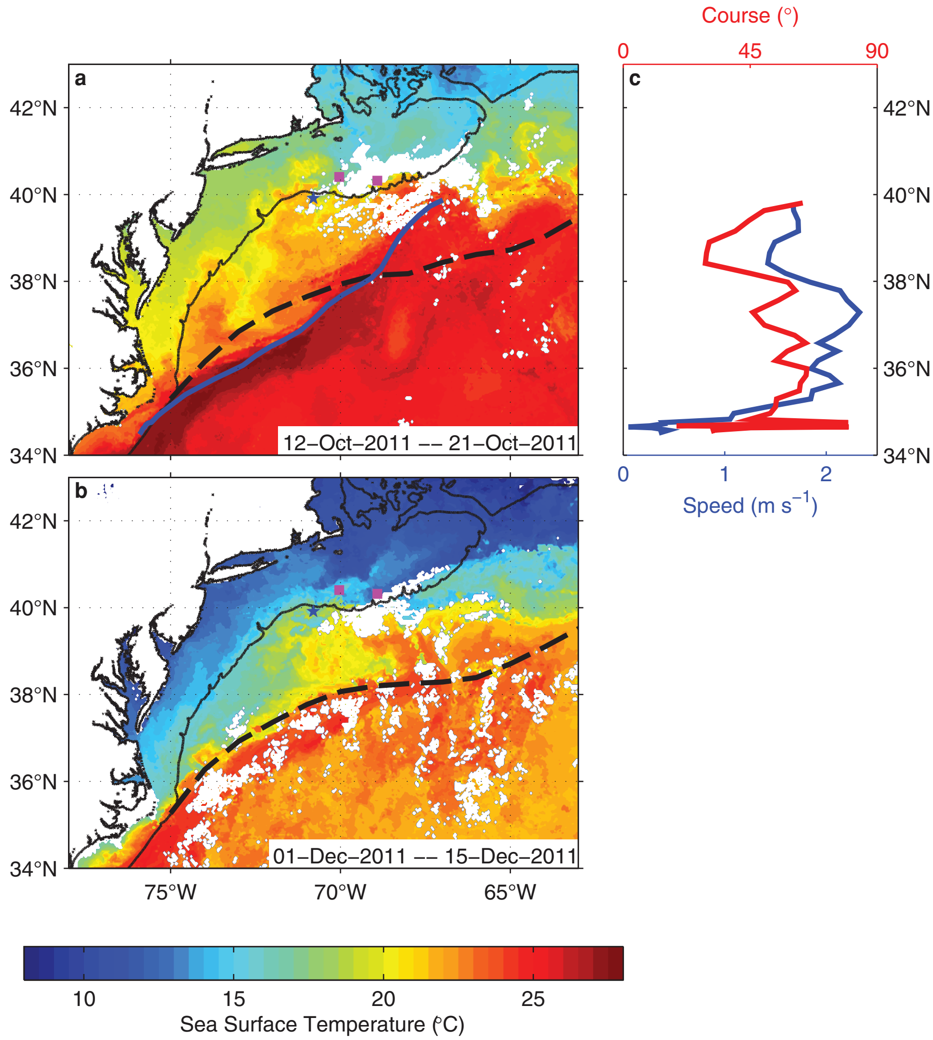

Figure 3 | SST measured by the MODIS instruments and data from the surface drifter. Maximum SST is shown for the periods (a) 12–21 October 2011 and (b) 1–15 December 2011. The coastline and shelfbreak (i.e., 200-m isobath) are indicated by the thin black contours. The dashed black lines in (a) and (b) denote the climatological mean location of the Gulf Stream North Wall in October and December, respectively, from Drinkwater *et al.*[14]. In (a), the blue line denotes the path of a surface drifter released off Cape Fear, NC (35°N) on 12 October 2011 that was entrained in the Gulf Stream and reached 39.88°N 8 days later. The speed (blue) and course (red) of the drifter are shown as functions of latitude in (c). In (a–b), the blue star indicates the location of the OOI test mooring, and the magenta squares denote the locations of the eMOLT observations.

resulted from direct interaction between the Gulf Stream and the shelfbreak. SSH observations suggest that two separate events influenced the continental shelf. In late October and early November, a shift in the orientation of the Gulf Stream toward the northeast brought the core of the Gulf Stream much farther north than usual. In December, subsequent large meanders brought a second pulse of Gulf Stream water into contact with the continental shelf.

The cross-slope velocities observed by the drifter in late October are extremely large relative to those typically associated with warm core rings over the slope. Hare *et al.*[9] examined eleven drifter tracks associated with cross-slope motions and found that the mean cross-slope speed was 0.5 m s^{-1}. In contrast, the drifter observations from October 2011 (Figure 3) show cross-slope (northward) speeds of 1.2 m s^{-1} extending to within 70 km of the southern flank of Georges Bank. None of the drifters examined by Hare *et al.*[9] had cross-slope speeds larger than 0.75 m s^{-1}.

High salinities at depths of 50–100 m over the upper continental slope were also unusual relative to the historical record. Figure 2d shows a histogram of all historical observations[10] from 50–100 m depth in the region [38°N 40°N] × [69°W 71.5°W]. Of 114,910 individual salinity measurements, only 37 observations exceeded 36.5, a rate of occurrence of only 0.032%.

We note that the anomalous tilt in the Gulf Stream occurred before the unusual atmospheric conditions in the winter of 2011–2012, with warm anomalies in the central and northeastern portions of the United States[21] and a strongly positive NAO. Further work will be necessary to examine what role, if any, this unusual Gulf Stream configuration played in the seasonal evolution leading to the mild winter of 2011–2012 in the eastern half of the United States.

Finally, the large near-bottom temperature changes over the outer continental shelf may have significant implications for the shelf ecosystem[22]. Nye *et al.*[23] have shown that temperature shifts of 2°C have resulted in major shifts in the silver hake (*Merluccius bilinearis*, a commercially important species) population from the upper continental slope south of New England to the northern Gulf of Maine. Migratory fish species such as bluefish (*Pomatomus saltatrix*) and striped bass (*Morone saxatilis*) appeared much earlier in the spring off the coast of Cape Cod than in previous years. The temperature

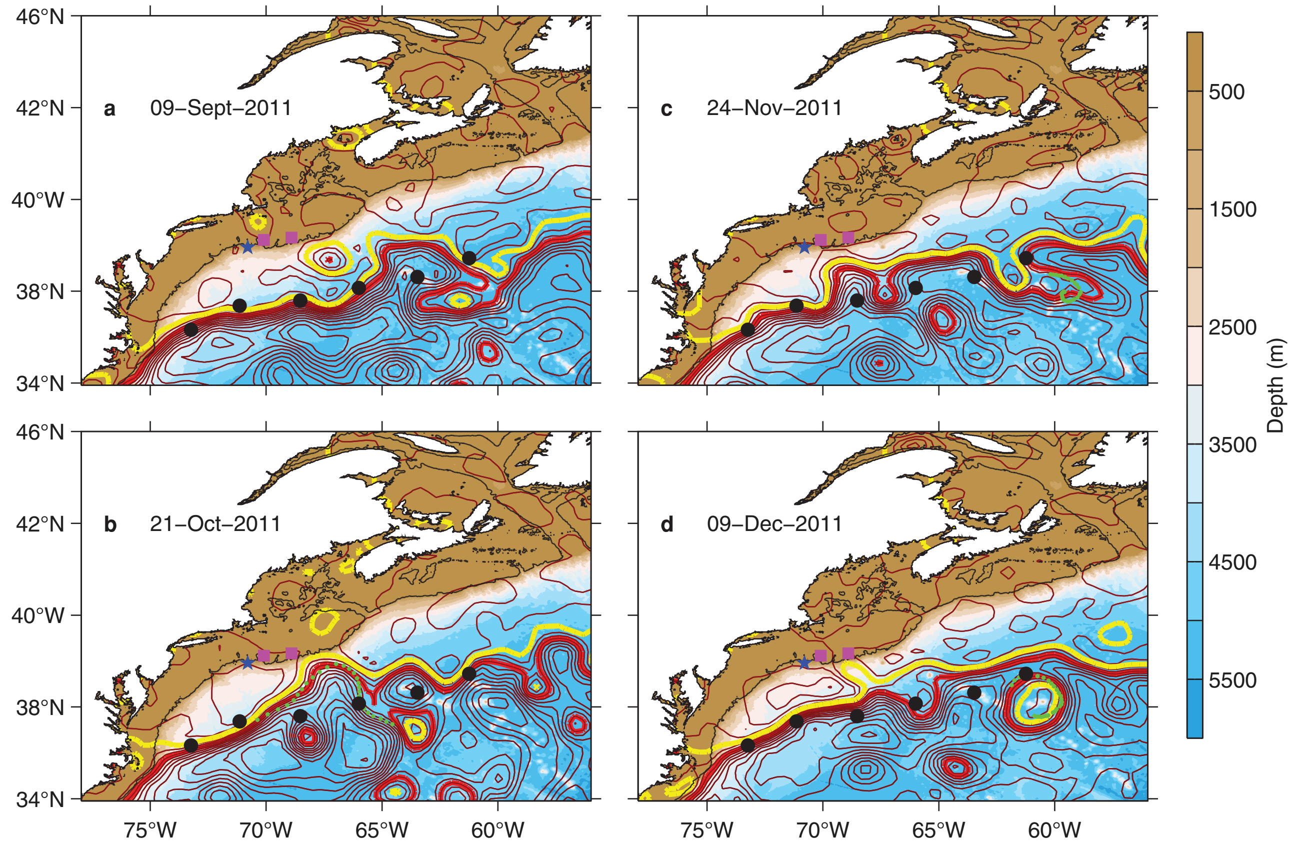

Figure 4 | Contours of satellite-derived SSH from Aviso's near-real-time merged absolute dynamic topography. Contour interval is 10 cm with 40-cm (heavy red) and 10-cm (yellow) contours highlighted. Black dots represent the mean Gulf Stream path determined from SSH gradients along descending altimeter tracks[15]. Green dots represent the drifter positions over 7 days centered on the individual SSH snapshots. Shading indicates bathymetry in meters, with the 200-m isobath shown by the black contour. Blue star and magenta squares denote the moored profiler and eMOLT sites as in Figure 3.

anomalies reported here were likely enhanced by the exceptionally mild winter of 2011–2012. Further work is necessary to determine the impact of this event on the seasonal evolution of stratification over the continental shelf in 2012, as well as the impact on the continental shelf ecosystem and marine organisms.

Methods

Near-bottom temperature measurements have been collected for more than a decade as part of the Environmental Monitoring on Lobster Traps (eMOLT) program (http://www.emolt.org/)[24]. As part of this program, VEMCO Minilog TR temperature probes with 0.1°C accuracy are distributed to lobstermen throughout New England, including the Gulf of Maine, Massachusetts Bay, Georges Bank, and the continental shelf south of New England. Two sites, designated OC01 and TA51 in the eMOLT program, were located over the outer continental shelf near the shelfbreak during autumn 2011. Probes were deployed at these sites by lobstermen Rob Connelly and Marc Palombo, respectively.

Climatological temperature and salinity profiles on the outer continental shelf and upper slope were computed for the months of November and December using the historical hydrographic database and methodology of Linder *et al.*[10]. The earliest data were collected in 1915, but the bulk of the data are from the period between 1990 and 2002; a total of 8270 stations from the autumn were used in the calculations. Stations between 69°W and 72°W that were located within 5 km of a specific isobath were averaged in the alongshelf direction. Between 15 and 50 stations were averaged together in bins that were 10 m in the vertical and 10 km in the cross-shelf horizontal direction to produce mean vertical profiles of temperature and salinity for each isobath.

The McLane Moored Profiler was deployed 12 km south of the shelfbreak at 39.92°N, 70.749°W (west of the eMOLT probes) as part of engineering tests conducted by the Ocean Observatories Initiative (OOI)[25]. Profile data were available from 4 December 2011 to 4 January 2012.

SST observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua satellites were obtained from http://oceandata.sci.gsfc.nasa.gov/. Maximum SST observed during 12–21 October and 1–15 December are shown in Figure 3 to reduce the effect of unmasked cloudy pixels and highlight the anomalously warm temperatures during these periods.

The surface drifter was built and deployed by students at Cape Fear Community College as part of the Marine Advanced Technology Education (MATE) program. The Davis-style[26] drifter obtained GPS fixes and transmitted its position via the GLOBALSTAR satellite constellation approximately every six hours. The drifter data are available online at http: //www.nefsc.noaa.gov/drifter by following the link to archived data and searching for drifter ID 110340761.

SSH was contoured from the gridded near-real-time merged absolute dynamic topography product, available at 1/3° resolution. These data were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes. The data were obtained from http: //www.aviso.oceanobs.com/duacs/.

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Author contributions

GGG provided the conceptual framework for the manuscript, wrote the initial draft, and analyzed the eMOLT data. RET analyzed drifter and SST data. AJP analyzed OOI moored profiler data. MA analyzed SSH data. JPM coordinates the eMOLT program. All authors contributed to preparation of final text and figures in a collaborative effort.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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