The Gulf Stream Structure and Meandering Based on the CTD and SADCP Measurements in 1989–1990 and 2014–2015

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Abstract: An review of field studies in the Gulf Stream region carried out by the authors in two periods with a break of 25 years is presented to summarize the results. The studies in the early period included hydrographic surveys in the area of a southern meander of the Gulf Stream (1989) and in the area of dividing of a single jet of the current into separate branches: in the Gulf Stream delta (1990). The second, recent, stage includes on-route surveys with SADCP profiler in 2014–2015 while crossing the meandering Gulf Stream at mid-latitudes to study its detailed high-resolution velocity field structure.

Keywords: Gulf Stream, meanders, rings, cores, CTD-survey, Gulf Stream delta, transport, SADCP, vertical and horizontal velocity shears.

Citation: Demidova, T. A., E. G. Morozov, and B. N. Filyushkin (2024), The Gulf Stream Structure and Meandering Based on the CTD and SADCP Measurements in 1989–1990 and 2014–2015, *Russian Journal of Earth Sciences*, 24, ES4005, EDN: FQIEYJ, https://doi.org/10.2205/2024es000920

1. Introduction

Despite the high degree of study of the Gulf Stream [*Baranov*, 1988; *Fuglister*, 1951; *Guo et al.*, 2023; *Muglia et al.*, 2022; *Richardson*, 2001; *Rossby et al.*, 2014; *Seidov et al.*, 2019], the results of experimental expeditionary work in the region are still in high demand due to its high synoptic and mesoscale variability. There are still many unresolved questions about the physics and mechanisms of formation of the Gulf Stream mesoscale eddies (without discussing processes on the scale of planetary interaction), instability in its frontal zones, vertical and horizontal mixing, etc. To address these issues, there is an increasing need to sharply increase the resolution of ocean models, requiring appropriate parameterization of them based on high-resolution in situ data. Validation of satellite data also requires a variety of field data.

Most of the huge accumulated volume of field measurements, and in particular, in the Gulf Stream region, is stored in World Databases. However, it is likely that a comparable amount remains in the internal collections of research organizations unknown to the scientific community. The Shirshov Institute of Oceanology, Russian Academy of Sciences, with its almost 80-year history of expeditionary activities is no exception.

Field studies of the Gulf Stream have been performed by authors in several cruises in two periods with a break of 25 years. The early period covers hydrographic surveys in 1989 and 1990. The works were parts of broader international projects devoted to the ocean-atmosphere interaction (Atlantex 90 Program [*Gulev et al.*, 1992]), to the circulation of the world ocean WOCE [*Ivanov and Morozov*, 1991]. The second, recent, stage included on-route surveys with SADCP profiler in 2014–2015 during crossing the Gulf Stream.

The goal of this paper is to present information and review of the results of the field studies of the Shirshov Institute of Oceanology in the Gulf Stream region.

2. Early studies of the Gulf Stream: 1989 and 1990

The most important role in the processes of heat and mass transport in the North Atlantic belongs to the eddies that form in the Gulf Stream system. These include cold and warm rings, as well as eddies of the cyclonic and anticyclic type that are formed in the

Research Article

Received: 21 May 2024
Accepted: 12 July 2024
Published: 18 October 2024

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frontal zone of the Gulf Stream [*Auer*, 1987; *Baranov*, 1988; *Ginzburg and Fedorov*, 1984; *Muglia et al.*, 2022]. Despite many specialized studies in the Gulf Stream region, the physical mechanisms of the interaction of eddies with each other and with the current itself are not completely understood. To a greatest extent, this is due to the rapid variability of processes and, in addition, it is not always possible to provide multidisciplinary measurements that combine satellite observations with hydrographic surveys and current measurements.

Such comprehensive studies were organized in two cruises of the Shirshov Institute of Oceanology, Russian Academy of Sciences in 1989 and 1990 in the northeastern Gulf Stream system to study its meanders and eddy formation as well as structure and locations of the Stream branches.

2.1. Measurements in 1989: CTD surveys in a Gulf Stream meander

Information about the experiment. In September–October 1989, during cruise 2 of the R/V "Akademik Ioffe", hydrographic studies were carried out on the southern periphery of the Gulf Stream in the area of its strong meandering at the site with coordinates 36.0°–39.5°N and 60.0°–62.1°W. In the modern understanding [*Seidov et al.*, 2019], the test site belongs to the Gulf Stream extension.

Two CTD surveys of the area were performed with an interval of 10 days. The first survey was from September 20 to 22, 1989 and the second one from October 2 to 5. On each survey, 18 CTD casts were made with a Neil Brown Mark III CTD probe. The surveys covered an area of 200 × 90 miles. The measurement accuracy was 0.005 °C for temperature and 0.001 S/m for electrical conductivity. The goal was to trace the evolution of the Gulf Stream and the meander on a monthly scale, which was first detected on the satellite sea image. The main objective was to experimentally determine their thermohaline structure at successive time intervals.

Analysis of hydrographic surveys at the sites was performed in conjunction with the results of current velocity measurements and three-hour standard weather data. Vertical profiling of current velocities up to a depth of 700 m was performed on the route of the ship with an onboard acoustic Doppler profiler of the RD-VM075 type (76.8 MHz) with CTD-casts. Velocity measurement accuracy according to the manufacturer was 0.5 cm/s + 0.2% of the measured value. However, due to high measurement error of the absolute speed velocity results in a qualitative picture only.

NOAA satellite materials, an image of the sea surface, corresponding to the beginning of the first hydrological survey, and a map of the results of the analysis of sea surface temperature at time of the surveys [*NOAA*, 1989] were used to interpret the measurement results.

Main results: temperature structure of meander and its development [after *Dykhno et al.*, 1992]. Two CTD-surveys covered a region with a cyclonic meander of the Gulf Stream previously detected on the satellite image. The first survey covered the central part of the meander in the southern part of the Gulf Stream jet. The second survey showed the changes that occurred in 10 days. Temperature distribution maps based on the CTD data at the two stages at a depth of 400 m are shown in Figure 1a,b. The density section corresponding to Figure 1a is shown in Figure 2.

It was shown based on the temperature and density distributions at different depths during the first survey that there was an inflow of cold water from the northwest. On the surface, the inflow only touches the northwestern part of the site. At a depth of 400 m (Figure 1a), the inflow occupies a significant part of the survey area, that is, cold water penetrates under warm water like a wedge. It was the deepest part of the meander, which spread to the southwest. The intrusion of cold waters under warm waters is also confirmed by the density meridional section along 62°7'W (Figure 2).

After 10 days (the time between surveys) the pattern of distribution changed. The second survey (Figure 1b) recorded a number of changes in the temperature and density structure and showed that the core of the Gulf Stream had moved north. This led to

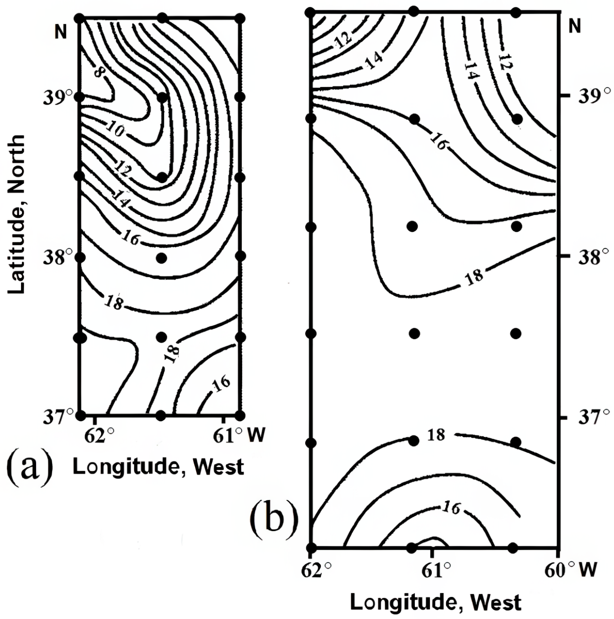

Figure 1. Maps of temperature at 400 m based on the data of the two CTD-surveys in the Gulf Stream region. (a) Survey 1 on September 20–22, and (b) Survey 2 on October 2–5, 1989. Black dots indicate CTD stations, curved solid lines show isotherms.

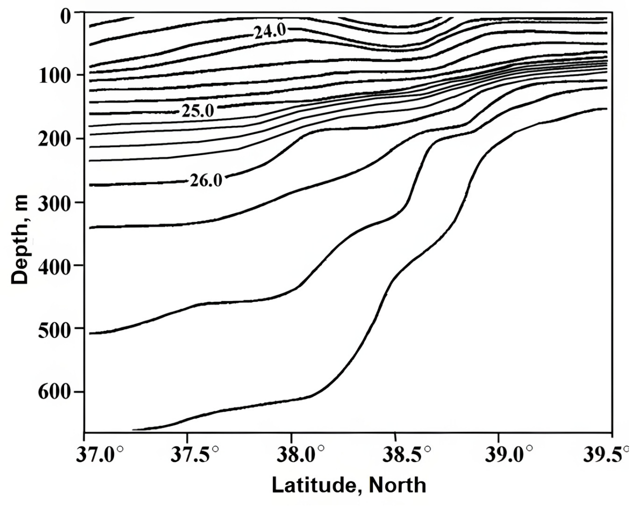

Figure 2. Section of density along 62°7′ W based on the data of the first survey on September 20–22, 1989. Solid lines show isolines of density σ_T.

an increase in the distance between the Gulf Stream core and the meander. Hence, the considered meandering of the Gulf Stream in the southern direction failed to transform into a new cold ring. Thus, it became clear from the thermohaline data that the inflow was determined by the flow of cold water of the meander, and that the meander was spreading to the southwest.

This inflow was also detected on the current velocity sections along the same meridian 62°7′W (not shown here). The velocity structure corresponds to the development of the meander in the southern direction and the resulting inflow of warm waters in the northern direction (since the meander carried cold water). In particular, a maximum speed of 70 cm/s was gained at the southern border of the inflow of cold water at 38°30′N. The joint analysis confirmed that the results reflected the development of a cyclonic meander.

2.2. Measurements in 1990: Survey in the Gulf Stream Delta

Information about the experiment. East of 50°W and south of the Great Banks, the Gulf Stream, being generally a unified flow, breaks up into several multidirectional branches. This is the region of the Gulf Stream delta.

The first branch, the North Atlantic Current, flows northward along the eastern side of the Grand Banks as a western boundary current reaching 50°N, where it meets the Labrador Current, turns more eastward, and crosses the Mid-Atlantic Ridge. The second branch of the Gulf Stream flows south-eastward from the region of the Grand Banks, crosses the Mid-Atlantic Ridge, and then flows eastward near 34°N as the Azores Current [*Richardson*, 2001].

In April–June 1990, we conducted CTD-surveys in the area of the Gulf Stream delta within the WOCE program. The experiment took place south of the Newfoundland Bank in the zone of interaction between the subtropical anticyclonic and subpolar cyclonic gyres limited by coordinates 52°N, 38°N, 50°W, 36°W. In a test site of 300 × 300 miles the measurements were done with a 30 miles interval between stations and also several transects with CTD-casts were made to cross individual jets. CTD-casts were carried out up to 2000 m deep at stations located along a contour covering the Gulf Stream delta, the upper parts of the North Atlantic Current and its branches with individual sections inside the contour. The survey was repeated in April, May, and June and included two eddy-resolving hydrographic surveys in the southwestern corner of the Gulf Stream test area. In addition, current measurements were taken at moorings along 36°W transect.

The main goal of the research was to expand our knowledge about the variability of processes in the Gulf Stream delta.

Main results [after *Ivanov and Morozov*, 1991]. The main results included determination of the location and evolution of the branches, their meanders, and quasi-stationary rings, as well as assessing the transport of the main flow and individual branches. In a generalizing work by [*Baranov*, 1988], the characteristic types of circulation in the Gulf Stream were distinguished and the transports of the main jets were given.

Table 1 shows the transports of various Gulf Stream jets based on the measurements in 1990 and according to [*Baranov*, 1988]. During the three stages of work from April to June 1990, the total transport of the Gulf Stream did not change strongly and remained within a range of 62–63 Sv, while the transports of each of the jets changed.

An example of the position of branches and detected two quasi-stationary rings are presented in Figure 3 that shows a scheme of individual branches split off from the single flow of the Gulf Stream, which is outlined at the left edge of the southwestern corner of the area. This survey was made in May 1990, during the second stage of measurements. The eddy-resolving survey area is distinguished by the condensation of station points in the lower left corner of Figure 3.

It was shown earlier in [*Clarke et al.*, 1980] based on the geostrophic calculations and instrumental measurements of currents that the barotropic component of the Gulf Stream transport is close to 40%. According to our current measurements on moorings, the barotropic component represents 60% of the transport.

Baranov [*Baranov*, 1988] proposed that two causes lead to branching of the Gulf Stream in the delta region. The first mechanism takes place when the Gulf Stream approaches the underwater ridge southwest of the Newfoundland Bank forming a cyclonic meander. Here, the current splits; the central and northern branches flow around the continental slope and continue to the northeast as the northern branch of the North Atlantic Current. The southern branch turns to the south and forms the southern branch of the Gulf Stream.

The other form of overflowing the ridge takes place regardless the flow consists of one or two branches. The northern part (Slope water of the upper layer) overflows the ridge and continues as the northern branch of the North Atlantic Current. The southern branch turns around the ridge reaching the bottom and forms a cyclonic meander in the final stage of its development. A cyclonic ring is formed in the center of the meander.

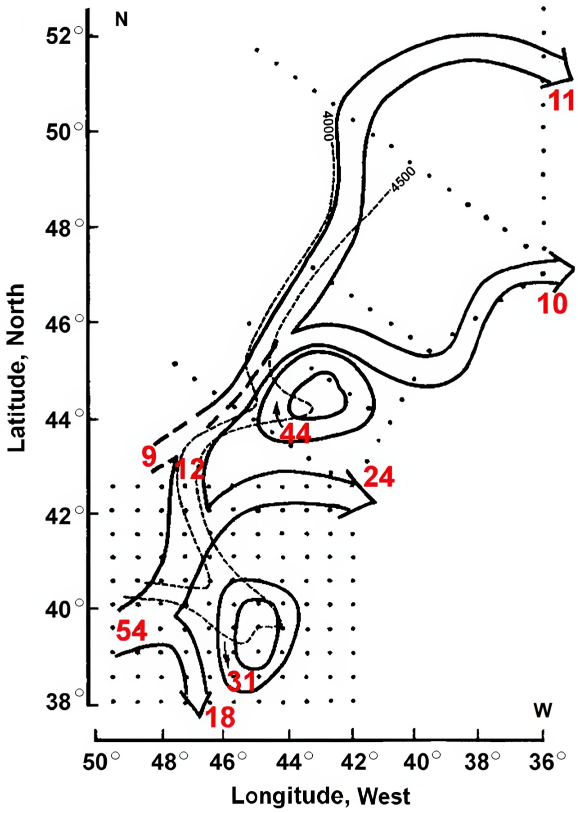

Figure 3. Scheme of the Gulf Stream branches based on the data in 1990. The dots indicate stations, dashed lines show isobaths of 4000 and 4500 m. Red numerals show transport of water in Sverdrups on May 28–June 13, 1990. Two quasi-stationary rings are also shown on the map.

Table 1. Transport in Sverdrups (Sv.) of the Gulf Stream branches as measured in 1990 [*Ivanov and Morozov*, 1991] and mean transports from [*Baranov*, 1988]

Currents, jets	1990	Mean transports from [*Auer*, 1987]
Slope Current 1	9	10–12
Gulf Stream	54	46.8
Southern Branch of Gulf Stream	18	21
North Atlantic Current	45	35.6
Northern branch	11	10–15
Central branch	10	10–15
Southern branch	24	15.6

3. SADCP studies of the Gulf Stream velocity in 2014 and 2015

The second part of our review includes our recent research with an onboard SADCP profiler in the middle of the Gulf Stream. In 2014, the Gulf Stream was crossed at about 39°N, 50°W by the ship heading 170° and in 2015 this occurred at 39.5°N, 61.0°W when the vessel was heading 150°. All data were analyzed together with available satellite materials.

In 2014 and 2015, detailed high-resolution velocity field structure of the meandering Gulf Stream and its fontal zones was studied with the shipborne RDI-Teledyne current profiler "Ocean Surveyor 75" (TRDI, 76.8 kHz) (SADCP). Two sections up to 700 m deep were carried out on the routes of the R/V "Akademik Sergey Vavilov" from St. John's (2014) and Halifax (2015) heading approximately southeast. Standard package was applied for data processing. The vertical space resolution was 8 m (a vertical bin) and the uppermost velocity measurement depth was 16 m. The results of velocity measurements with 15-min averaging of initial data over time are considered. Since the ship's speed was 9 to 13 knots, this provides horizontal space resolution of about 4–6 km.

3.1. Measurements in 2014: a cold ring

Information about the experiment. The crossing of the Gulf Stream was from September 30 to October 1, 2014 in the range of latitudes between 33° and 40°N. The ship's speed was 12–13 knots. When approaching the northern edge of the Gulf Stream, the ship appeared in a counter current, which slowed down the ship by two knots. This could most likely be caused by a strong northward current on a segment of the Gulf Stream sharply deviating to the north as is shown in [*Dzhiganshin and Polonsky*, 2009, Figure 1] on a typical snapshot of the Gulf Stream jet (~ 38° to 41°N, 51°W).

Main results. The meandering Gulf Stream on October 1, 2014 is shown on the map of the absolute dynamic topography in Figure 4.

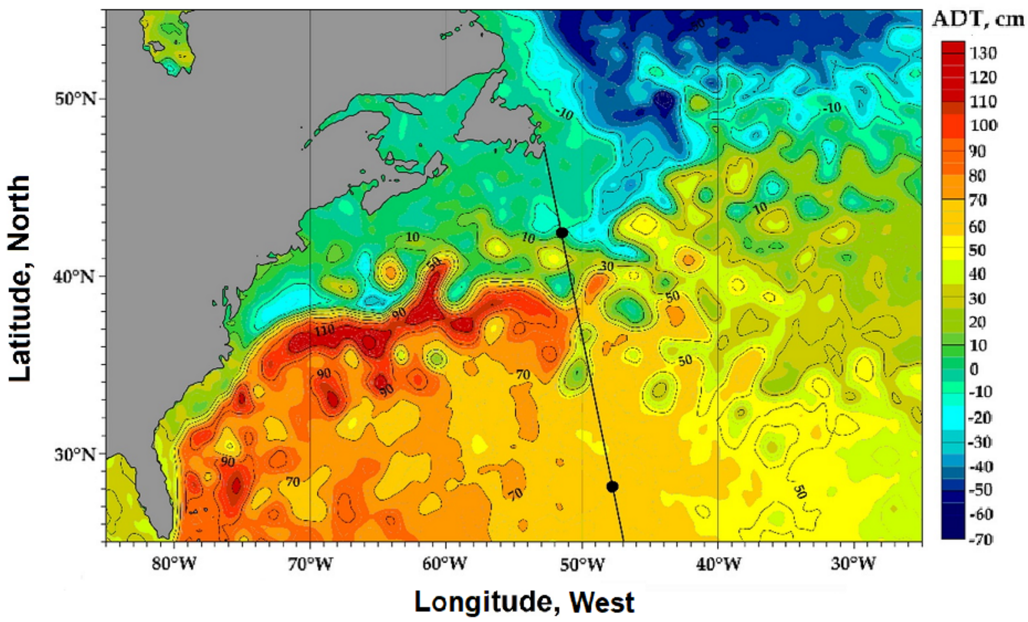

Figure 4. Absolute dynamic topography (ADT) of the Gulf Stream area on October 1, 2014 based on the satellite altimetry data. The ship's route is shown with a black line. Black circles on the line limit the position of the velocity section in Figure 5. Satellite altimetry gridded product [*Pujol et al.*, 2016] available from Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/).

A section of the meridional velocity component along the route is shown in Figure 5. The section crosses two positive velocity flows (Figure 5) in the latitude ranges on the surface 38.5°–40.0°N, 34.0°–36.6°N. According to the measurement data, they both extended from the surface to a measurement depth of 700 m. Within the depths of the section, the vertical geometric structure of both jets remains almost unchanged. The velocity shows gradual decrease with the depth. The preferential directions of transport in both cases are to the NNE (north-northeast) almost opposite to the motion of the vessel heading ~ 170° in a very unfavorable direction for the ship motion upstream.

The Northern flow (Figure 5) is about 130 km wide and corresponds to the main Gulf Stream jet with its core centered at latitude of 39°N with the maximum velocity magnitude 148 cm/s at the minimum accessible depth 16 m. The meridional components reached 135 cm/s in the core and, in general, significantly exceeded the latitudinal ones. An isotach

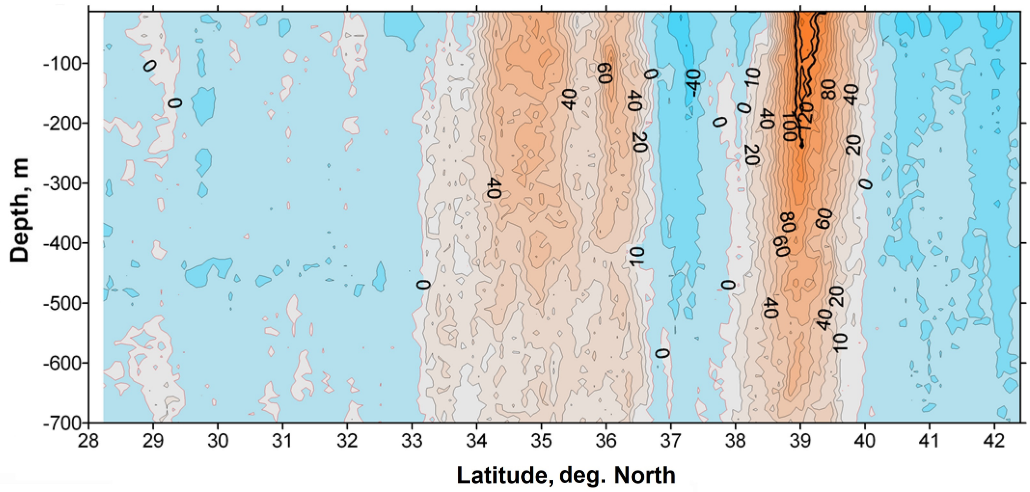

Figure 5. Section of meridional velocity across the Gulf Stream in the period September 30–October 1, 2014. Beige color shows positive downstream velocity, light blue shows countercurrent (negative velocity). North is on the right.

of 120 cm/s outlines the core in the depth range from the surface to ~ 150 m. Velocities above the core on the surface reached 150 cm/s.

The flow with positive velocities south of the main jet was 228 km wide on the surface (34.0°–36.5°N) and included two narrow cores of high speed exceeding 40–60 cm/s, extending to a depth of 300–400 m. On the dynamic topography map Figure 4, the latter correspond to two small isometric depressions of topography (green color relative to the surrounding ocean surface) within a less deepened meridionally elongated depression (lighter green color against orange background). Similar structures at 35°–36°N, which are quasi-stationary cold rings, are characteristic of the zone south of the southern front of the Stream and are also reflected as typical in the snapshot on generalized schematic maps [*Seidov et al.*, 2019, Figure 2]. The larger apparent width of the ring relative to the width of the main jet in Figure 5 is associated in our case with its elongated shape in a direction close to the direction of the section itself, although, in general, rings with a diameter larger than those of the Gulf Stream are widespread.

Thus, the southern flow with positive velocities on the section in Figure 5 is an evolving transformed cyclonic eddy of elongated form carrying relatively cold water. It penetrates at least to a depth of 700 m and has two small cores of about 300 m deep. Typical parameters of a young cold ring known from publications are as follows: ring diameters are about 200 km, rotation speeds are up to 2 m/s, translation motion speed is 2–3 cm/s, lifetime is 2–3 years. Temperature differences on the surface are 2–3°C.

As to Figure 5, the found cold ring is separated from the main jet of the Gulf Stream by a countercurrent of negative velocity with a width of over 130 km on the surface. Considering, as above, that the translation ring speed is 2–3 cm/s, one can say that the ring separation from the jet occurred much earlier than two months ago.

Countercurrents with relatively cold water to the north and relatively warm water to the south were recorded around the Gulf |Stream. Their speeds were up to 40 cm/s both north and south of the jet. South of the revealed ring structure there was warmer water with speeds up to 20 cm/s and rare patches to 30 cm/s.

3.2. Measurements in 2015: three cores, frontal high gradient zones

Information about the experiment. On September 14, 2015, we crossed the Gulf Stream almost normal to the current. The same OS-75 shipborne profiler as in 2014 was used for velocity measurements and the same parameters were set.

Main results. The sea surface temperature map based on satellite measurements on September 9, 2015 (a few days before crossing) is shown in Figure 6.

The NOAA 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) is a long-term Climate Data Record that incorporates observations from different platforms (satellites, ships, buoys, and Argo floats) into a regular global grid. The dataset is interpolated to fill gaps on the grid and from a spatially complete map of sea surface temperature. Satellite and ship observations are referenced to buoys to compensate for platform differences and sensor biases. [*Huang et al.*, 2021].

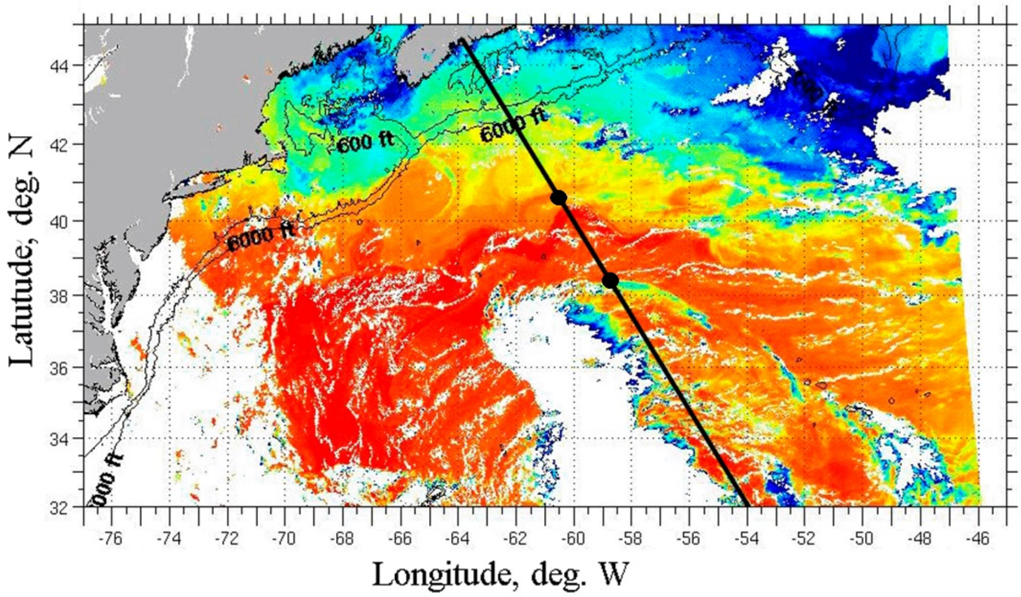

Figure 6. Sea surface temperature map of the Gulf Stream region on September 9, 2015. The route of the ship is shown with a black line. Black circles on the line limit the position of the velocity section in Figure 9 on September 14. Sea surface temperature gridded product [*Huang et al.*, 2021] available from Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/).

Figure 7 shows a map of absolute dynamic topography based on the satellite altimetry data on September 14, 2015. The map clearly reveals the state of the currents and meanders.

3.2.1. Estimation of the main direction of the Stream

Estimation of the main direction of the Gulf Stream transport was made using the polar diagram (Figure 8) based on the measurement data. One can see that the direction of most of high-speed values falls in the sector from 50 to 75°. The mean direction of transport of the Gulf Stream during its intersection was about 60°. Velocities along 60° will be further considered as longitudinal velocities directed downstream.

It is interesting to note that a certain confinement of the directions of the entire ensemble of medium-high velocities of 0.5–1.0 m/s to (blue dots) in two sectors 55°–60° and 65°–70° is seen. This fact may reflect the splitting of the flow with such velocities. This picture becomes clearer when separately considering the velocity directions in the Gulf Stream cores found in the section in Figure 9, the lower one ("main") (turquoise squares) and two near-surface cores, the northern one (purple circles) and southern one (orange triangles). The water in these cores propagates along mean directions of 65° (lower one), 60° (northern one), and 70° (southern one).

3.2.2. Section of the longitudinal component

A section of the longitudinal component of the current (direction of 60°) is shown in Figure 9a. Red color shows the regions with velocities directed along the main direction of the Stream; blue color corresponds to countercurrents (negative values on the

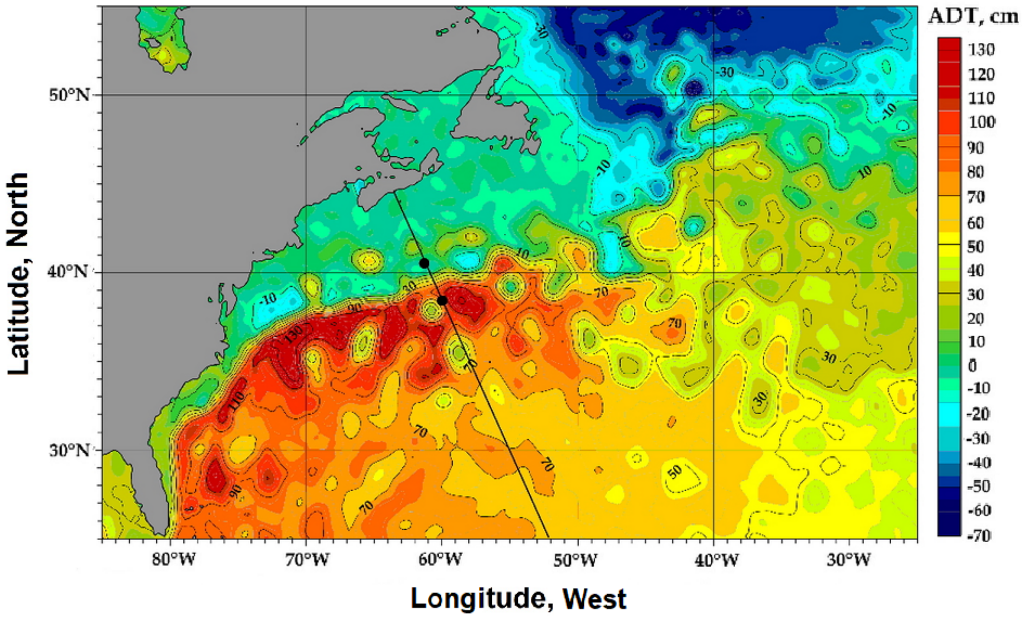

Figure 7. Absolute dynamic topography (ADT) of the Gulf Stream area on September 14, 2015. The ship route is shown with a black line. Black circles on the line mark the position of the velocity section in Figure 9. Same data source as in Figure 4.

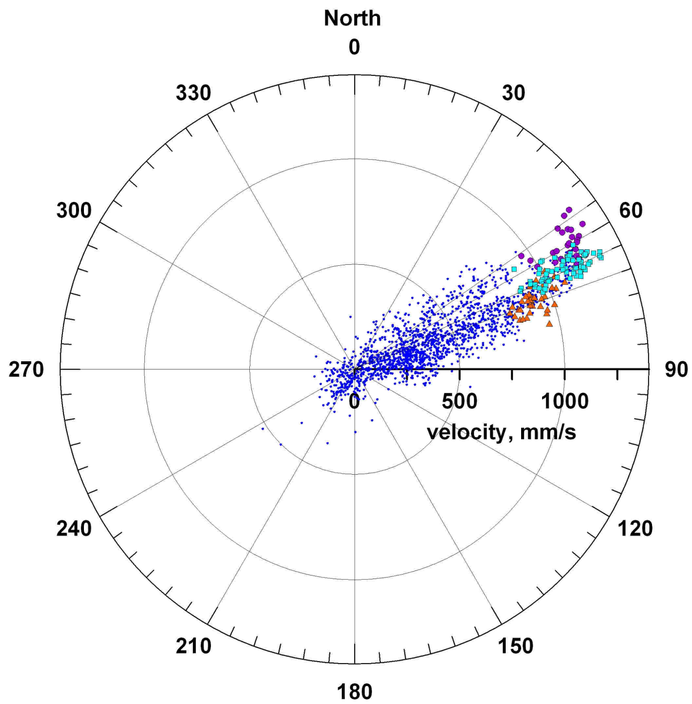

Figure 8. Polar diagram of the direction of currents measured by SADCP during the crossing of the Gulf Stream region on September 14, 2015. Blue dots refer to the entire stream, purple circles to the upper northern core, orange triangles to the upper southern core, and turquoise squares to the lower core (in Figure 9).

velocity scale). The geometric structure of the Gulf Stream (positive velocities) had a trapezoidal shape, narrowing from top to bottom. On the surface, the flow was fixed in the latitude interval 40.15°–38.75°N and had a width of 160–180 km across the flow; at a depth of 730 m its width decreased to 80 km (39.35°–39.20°N).

The maximum velocity on the surface did not exceed 140 cm/s, velocity of 143 cm/s was found at a depth of 190 m in the low core. At the maximum measurement depth of 730 m, the velocity was still about 30 cm/s and higher (Figure 9). The lower boundary of the Gulf Stream flow has not been determined due to the limitation of the depth of the signal.

The negative velocities of the background countercurrent in the presented cross-section gradually increased from the boundaries of the Gulf Stream in both directions, reaching −50 cm/s and higher at the southern and northern boundaries of the section. Such intense countercurrents probably reflect the high speeds of the peripheral edges of small rings. One can see on the map in Figure 7 that the ends of the profile from the south and north sides touch similar structures.

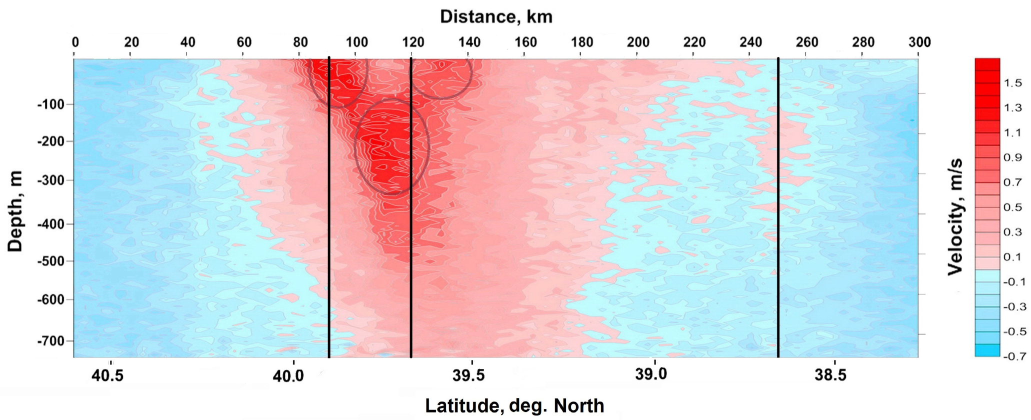

Figure 9. Cross-section of longitudinal (east-northeastern) component of velocity of the Gulfstream in 60° direction on September 14, 2015. Positive values (rose) indicate downstream flow. The vertical lines indicate position of the profiles in Figure 11. Three cores of warm flow are outlined by ovals.

Three cores of the Gulf Stream. The intense core of the warm current with velocities of the order of 1 m/s and more are well expressed in this area. It is clearly seen that it is divided into three separate smaller cores. A two-jet structure of currents is observed on the surface, which merges into one jet deeper than 100 m. This lower core with velocities of 120–140 cm/s, which occupies the central part of the Stream to a depth 100–400 m or even deeper, is characterized by a somewhat greater intensity and greater vertical thickness than the surface jets.

This core on its northern side borders a narrow transitional region in which high gradients of the velocity field are expected both in depth and horizontally, causing the likely development of both vertical and horizontal current shears. The presence of a strong velocity shear in this transition zone may ensure continuous contact of the external cold countercurrent (from the Labrador) with the main jet of the warm current. This is even better seen in Figures 10 and 11a in this area and we will discuss this later considering velocity variations on the horizontal and vertical profiles.

As follows from above when considering the polar diagram in Figure 8, the splitting of the lower main core towards the surface is accompanied by a notable change in the direction of the velocity of the upper jets. While the mean flow direction in the lower core is 65°, in the northern and southern near-surface cores it is 60° and 70°.

Isometric fragment. In the interval 38.6°–38.7°N at depths from 150 to 300 m, a quasi-isometric zone of low positive velocities (0.1–0.2 m/s) with a width of about 20 km is observed. Perhaps this is a previously separated small fragment of the main stream. This is presumably due to instability and meandering of the current.

Transport. The transport of the Gulf Stream within the measured boundaries was about 40 Sv (directed at 60°). This is lower than the known estimates of the Gulf Stream mean transports [*Baranov*, 1988, Table 1; *Dzhiganshin and Polonsky*, 2009; *Ivanov and Morozov*, 1991; *Rossby et al.*, 2014] since our measurements only penetrated down to 730 m, while the literature estimates of the Gulf Stream transport are usually given for the entire jet. An additional complication when comparing transports from different authors is the difference or lack of information about the time averaging of the data.

3.2.3. Horizontal profiles

Figure 10a,b and c show horizontal profiles of typical variations of longitudinal velocity (velocity normal to the cross section) at the depths of 16 m (a), 48 m (b), and 112 m (c). As to Figure 9, these depths of measurements are located within the upper cores (Figures 10a and 10b) and in the transition from the upper cores to the lower core (Figure 10c), where one at 112 m touches slightly the upper uppermost parts of the lower core. In a layer at depths from 16 m to 48 m, there are pronounced velocity maxima of 1.3–1.4 m/s in the left jet and 1.1–1.2 m/s in the right one (Figure 10a,b). The maximum velocity at a depth of 112 m (on the upper periphery of the lower core) is 1.3 m/s.

These three profiles detail the splitting structure of the two Stream's cores on the surface with their subsequent merging at a depth below 100 m (into the third core), which was reflected in a general form in the section in Figure 9. It is seen that below 50 m, this splitting into two jets quickly smoothed out, so that at depths below 100 m, the horizontal variations of velocity have a single maximum (Figure 10c). One can say that the core of the warm Stream has a Y-shaped cross-section.

Many reasons may cause such a 100 m deep slowdown in speed around 39.75°N. For instance, there are not uncommon complications of the Gulf Stream jet by sub-mesoscale currents occurring on lateral scales of 100 m–10 km and associated with density structures, filaments, eddies, topographic wakes, etc. [*Gula et al.*, 2014]. We also do not exclude an influence of the regional local topography on the ship route proposed in [*Frey et al.*, 2023]. However, we cannot expect a notable influence of the most significant topographic features: Cape Hatteras (at ~1400 km) and Newfoundland Bank (at ~1000 km), located too far from the core location.

3.2.4. Peripheral high-gradient zones

One can see in Figure 9 that all three cores of the Gulf Stream are bordered by transition regions. The narrowest of them, in which the most rapid decrease in velocity occurs, is the northern flank of lower core (on the northern side of the Gulf Stream). Within its limits one could expect high horizontal gradients of the velocities. The presence of significant vertical gradients of velocity could be expected in transition zones along the vertical from the three main cores to the areas of lower intensity flow: in the zone between the upper northern core and the lower one. We will see this below considering vertical profiles.

Examples of horizontal cross-flow profiles (Figure 10) and vertical profiles (Figure 11) confirmed these findings and facilitated the visualization and localization of high-gradient areas.

Horizontal shear of longitudinal velocity. One can see in Figure 10 that stable and high horizontal velocity gradients correspond to the northern peripheral sections of the flow at all three depths. To illustrate the existence of such zones in the Gulf Stream section we will show such an individual interval on the profiles.

In the considered depth range of horizontal profiles from 16 to 112 m, the strongest horizontal velocity change was found on the northern (left) periphery of the upper northern core at a depth of 48 m (Figure 10b). This is an area of steadily decreasing speed to the north between coordinates 39.95°N to 40.30°N with a length of ~ 40 km. It includes small local areas of even sharper variability. In Figure 10b they are limited by vertical black lines.

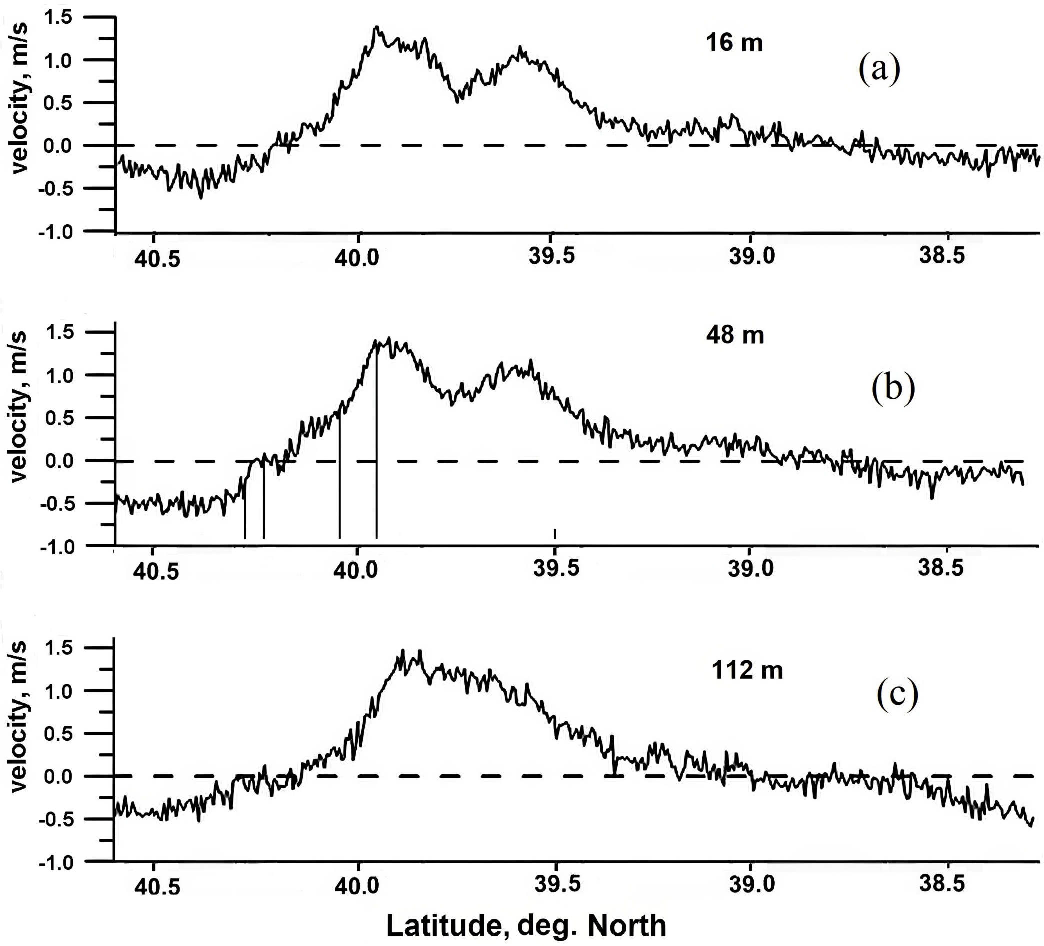

Figure 10. Characteristic variations in the longitudinal velocity (60°, east-northeast) of the Gulf Stream along the ship's route versus latitude at different depths in 2015. At depths of 16 m and 48 m, two current jets are seen, which merge deeper. Black vertical lines mark the intervals for assessing horizontal gradients.

Within the main 40 km section, the velocity changes by 1.6 m/s (from +1.2 m/s to −0.4 m/s). Change in velocity within the local 6-km section between 40.25°N and 40.30°N is 0.4 m/s and within the 12-km section in the range of 39.95°–40.05°N the velocity changes by 0.8 m/s.

From these data, the background mean velocity gradient $\mathrm{d}u/\mathrm{d}r$ (or the horizontal shear of velocity) at 40 km distance is approximately 0.4×10^{-4}/s where u is the longitudinal component of velocity, r is distance. Velocity gradient over smaller interval is ~0.7×10^{-4}/s for each of them. Slightly smaller horizontal shears are likely in the corresponding sections of the other two profiles, at depths of 16 and 112 m.

Such values correspond by the order of magnitude to the published mean horizontal shear of strong currents [*Frey et al.*, 2021]. With that, being of the same order as in the Malvinas Current [*Frey et al.*, 2021], they are several times higher than the horizontal shears at the onshore margins of the latter, which, to our opinion, may be explained by significantly sharper frontal zones of the Gulf Stream.

The given examples of numerical estimates indicate the reality of the occurrence of significant transverse horizontal shears of the longitudinal velocity on the left periphery of the Stream. The presence of strong horizontal shears leads to strong instability in the transition zone and also it indicates the high level of relative vorticity. The latter influences potential vorticity and its conservation that may control, in its turn, important patterns of circulation in the region.

3.2.5. Vertical profiles

Figure 11 shows typical vertical velocity profiles. The profile shown in Figure 11a, crosses the upper northern core and the left periphery of the lower core and has a section with a large vertical gradient of the horizontal velocity at depths from 120 m to 260 m. Over this 140 m interval, the velocity changes from 1.1 m/s to 0.3 m/s; this corresponds to a mean vertical gradient of 5.7×10^{-3}/s. The presence of strong vertical shear of longitudinal velocity means that the flow at the northern periphery of the lower high-speed core of the warm current may be locally unstable. At the same time, the presence of a strong vertical shear in this transition zone, together with the horizontal ones, may ensure continuous contact of the external cold countercurrent (from the Labrador) with the main jet of the warm current.

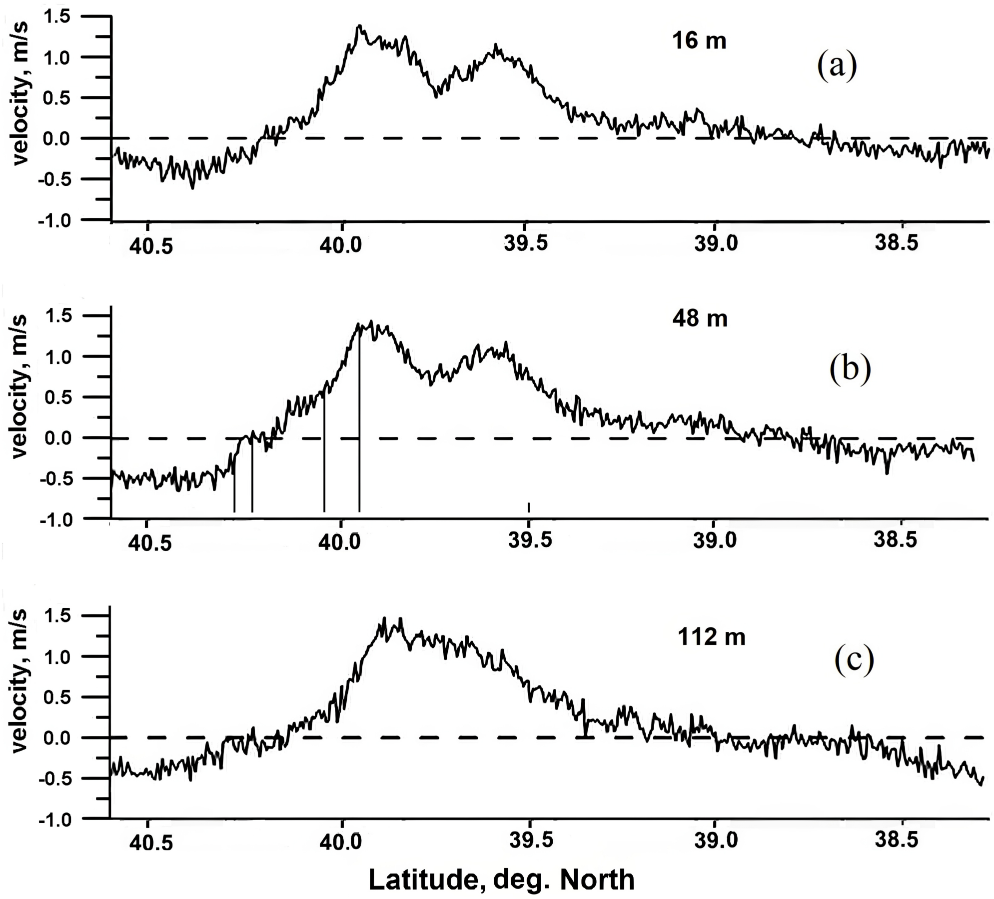

Figure 11. Vertical profiles of longitudinal velocity at three points of the section in 2015. Locations of profiles are shown in Figure 9: (a) 39.87°N; (b) 39.66°N; (c) 38.65°N. Gray bars mark the intervals for assessing vertical gradients.

Figure 11b shows velocity profile passing the north edge of the southern surface core and crossing southern part of the lower core. This profile is different from the peripheral profile in Figure 11a. The difference is that the vertical velocity gradients in the same interval are notably smaller, and the mean profile is convex. However, some high vertical shears (with the opposite sign) were found within smaller intervals, for example between 60 and 110 m, where velocity changes from 0.7 to 1 m/s that gives a mean vertical gradient of 6×10^{-3}/s. Even higher shears can be expected on profiles between two surface cores, in intervals where they intersect a transition zone at about 100 m deep, from low surface velocities to intense ones in the lower core. Strong local instability could be expected inside the area that is important for better understanding the splitting mechanism of the core of the Gulf Stream.

Figure 11c shows the velocity profile at a mark of 250 km crossing a small warm jet at depths from 150 m to 300 m, mentioned above. It can be assumed that this isolated formation is a result of local shear instability on the right periphery of the main current core, presumably due to instability and meandering of the current.

4. Summary

Information and a review of experimental researches in four cruises in the eastern part of the Gulf Stream are presented.

In 1989, based on the eddy-resolving survey including vertical CTD and current velocity profiling the motion of a meander, previously detected on the satellite image, was traced on a monthly scale. The meander was spreading across the test area to the southwest and carried cold water. During the same time, the Stream's core shifted to the north.

In 1990, detailed CTD-surveys in April–June in the region of the Gulf Stream delta traced changes in the Gulf Stream branching and eddy formation. During three months, the total transport of the Gulf Stream did not change strongly and remained within a range of 62–63 Sv, while the transports of each of the jets changed.

In 2014, a detail velocity structure of a transformed cyclonic eddy of elongated form carrying relatively cold water was identified in the velocity section. It penetrated at least to a depth of 700 m and had a complex internal structure with two cores of about 300 m deep.

In 2015, a detailed structure of the longitudinal velocity field revealed a strong core splitting into two to the surface. High velocity gradients leading to strong velocity shears are obvious in the northern vicinities of transition zone of the cores. These may ensure continuous contact of the external cold countercurrent (from the Labrador) with the main jet of the warm current.

Acknowledgments. This work was supported by the State Assignment of the Shirshov Institute of Oceanology (FMWE-2024-0017, ship measurements) and the Russian Science Foundation grant 21-77-20004 (analysis of measurement data).

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