LIMNOLOGY
and
OCEANOGRAPHY

Limnol. Oceanogr. 66, 2021, 3472–3488

doi: 10.1002/lno.11892

Recent warming and decadal variability of Gulf of Maine and Slope Water

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Abstract

The oceanographic conditions in the Gulf of Maine, Scotian Shelf, Slope Sea, and surroundings are determined by interplay of two major circulation systems—the Gulf Stream and Labrador Current. This study aims to better understand regional long-term climate trends caused by the Gulf Stream decadal variability. The in situ data analysis confirms a continuous slow warming within all three areas over the last five decades. It is shown that the warming accelerated in the recent 10 years coinciding with a strengthened northward incursion of warm water in the summer months. Such strong northward migration of warm water was not seen in the four preceding decades, making the current rapid warming different from previous ones. We argue that the recent decadal-scale warming is unique and may signal that the shift of the thermal regime in this region may be at least partially caused by a changed pattern of the Gulf Stream extension zone's long-term variability. We found that the Scotian Shelf and Slope Water region has recently been warming much faster than the Gulf of Maine, both in the subsurface (the upper ~ 50 m) and in deeper layers, indicating that the probable cause of the faster warming in the most recent decade is due to the regime change in the Gulf Stream extension region.

The Gulf of Maine, Scotian Shelf, and Slope Sea constitute a marginal sea, a shelf, and a slope water region controlled dynamically and thermodynamically by two most powerful currents of the Northwest Atlantic—the northeastwards flowing Gulf Stream and opposing Labrador Current. At Flemish Cap and east of the Tail of the Grand Banks, most of the water in the Labrador Current retroflects eastward (Loder et al. 1998). The rest continues southwestward partly over and around the Grand Banks and through the Gulf of St. Lawrence to the Scotian Shelf in the upper layers (above 200 m depth) and along the shelfbreak below that depth. This portion of the southwestward flow is a part of Northwest Atlantic Shelfbreak Current system (Fratantoni and Pickart 2007) between the west coast of Greenland and the Cape Hatteras. The Middle Atlantic Bight section of this currents system is also known as Shelfbreak Jet (e.g., Gawarkiewicz et al. 2018; Forsyth et al. 2020). Hereafter, part of the Shelfbreak Current system between the Grand Banks and the Great South Channel at the south border of the Gulf of Maine is referred to as the Shelfbreak Current. This current varies quite significantly both seasonally and on the longer time scale (Chen et al. 2018; Forsyth et al. 2020).

The cold offshore water in the southwest-bound Shelfbreak Current mixes with warmer water from the Gulf Stream to form the Slope Water. The Slope Water occupies the area between the Gulf Stream and the continental shelf west of the Tail of the Grand Banks (Peterson et al. 2017) and buffers the northern flank of the Gulf Stream and the cold water over the Scotian Shelf (Fig. 1). The intensity of the Labrador Current cold water and Gulf Stream-originated warm water mixing between the shelfbreak and the Gulf Stream main flow varies seasonally and interannually (e.g., Petrie and Drinkwater 1993). In the long run, it contributes, perhaps significantly, to the ocean climate change in this critical location and possibly further downstream of Gulf Stream, the Labrador Current retroflection, and the North Atlantic Current.

Gatien (1976) proposed that Slope Water is composed of two distinct sectors—the warm Slope Water, which is a well-mixed water mass between the surface and 400 m depth adjacent to Gulf Stream, and the cold Slope Water, identified as Labrador Slope Water. The boundary between those two sectors varies in sync with the Gulf Stream-Labrador Current interactions (Gatien 1976). A new naming convention for these water masses is the Atlantic Temperate Slope Water and the Labrador

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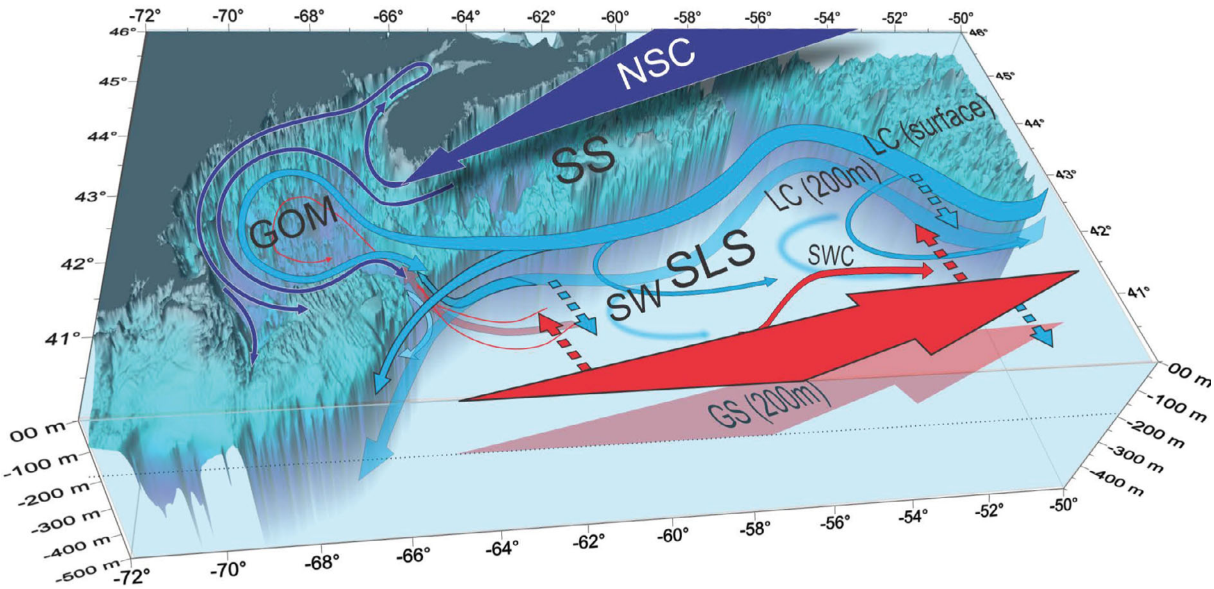

Fig 1. Simplified schematic view of the circulation in the Gulf of Maine (GOM) and its surroundings showing ocean currents at the sea surface and seasonal thermocline (~ below 100 m depth). Notable features include the Gulf Stream (GS), Nova Scotia Current (NSC), Labrador Current (LC), Slope Water (SW), Slope Water Current (SWC), Scotian Shelf (SS), and the Slope Sea (SLS). The GS path shifts to the north in summer and south in winter, shown by dashed red and blue arrows, respectively; see text for details.

Subarctic Slope Water (e.g., Greene et al. 2013). For simplicity, these two water masses are hereafter referred to as Atlantic Water and Labrador Water, respectively. The Nova Scotia Current borders the Atlantic Water and Labrador Water on the Scotian Shelf and the Slope Water Current as it is schematically shown in Fig. 1.

The entire system is primarily controlled by interannually varying position and dynamics of the Gulf Stream and Labrador Current. The alongshore intrusion of the Labrador Current competes with the Gulf Stream seasonally via the shelf-slope front (e.g., Drinkwater et al. 1994; Greene and Pershing 2003; Bisagni et al. 2006). The Gulf Stream-Labrador Current-Nova Scotia Current-Shelfbreak Current multipart composite governs the interaction between Atlantic Water and Labrador Water acting as a coupled system (Keigwin and Pickart 1999; Wanamaker et al. 2008). The complex interactions between Atlantic Water and Labrador Water develop a dynamical water mass system, sometimes called the Coupled Slope Water System (Pershing et al. 2001; Greene and Pershing 2003; Greene et al. 2013). It is further referred to as the "slope water system."

The Gulf Stream is thought to be undergoing substantial changes during the past decade. Recent studies indicate that there may be a slowing of the Gulf Stream (Caesar et al. 2018; Dong et al. 2019) and perhaps of the entire Atlantic Meridional Overturning Circulation (Caesar et al. 2021). Evidence of slowing reaches as far upstream as the Florida Current which has been found to be weakening steadily since the beginning of last century and especially during the past two decades (Piecuch 2020). Strong regime changes north of the Gulf Stream manifested in a jump-like increase in the number of Gulf Stream warm core rings, from an average of 18 warm core rings per year during 1980 to 1999 to 33 warm core rings per year during 2000–2017 in the area between 75 and 55°W (Gangopadhyay et al. 2019). These warm rings of the Gulf Stream can encroach on the Slope Sea and with an increase in the number of such rings possibly accelerating the warming north of the Gulf Stream over the past two decades.

There is little doubt that the entire region north of the Gulf Stream is warming. This is evident in the World Ocean Atlas 2018 (Boyer et al. 2018b) and in the Northwest Atlantic Regional Climatology (Seidov et al. 2016). The surface warming in the Gulf Stream, Gulf of Maine, and Slope Sea area is a complex process caused by the superposition of multiple factors involving atmospheric forcing, regional circulation change (e.g., including the Gulf Stream variability and increased warm core rings formation) and changes in radiative forcing (e.g., Chen et al. 2015; Gangopadhyay et al. 2019; Caesar et al. 2021), see also (Gangopadhyay et al. 2020). Importantly, it was argued that the Gulf of Maine has recently been warming at higher rates than before (Mills et al. 2013; Pershing et al. 2015; Greene 2016). There has been significant progress in diagnosing and explaining the increased warmth in the Gulf Stream-Slope Sea surroundings, but there are still many unknowns. One major unknown are the climate trajectories of the Scotian Shelf, Slope Water, Gulf Stream, and Gulf of Maine. These are complex and therefore warrant more studies into the long-term variability of this critical region.

Background and preliminary assessment

The Gulf of Maine's excessive warming is sometimes associated with the alterations of the Gulf Stream behavior, (e.g., Pershing et al. 2001; Mountain 2012; Thibodeau et al. 2018). Since the Gulf of Maine is relatively small compared to the slope water system, Labrador Current retroflection zone, and the surroundings of the Gulf Stream North Wall (further referred to as the North Wall or the Wall), slight variations in all or some of the latter, can induce substantial changes in thermohaline conditions of the gulf impacting its fisheries and ecosystem. The Gulf Stream effect may be direct, via occasionally extreme departures of the Gulf Stream path (Gawarkiewicz et al. 2012) or via seasonal northwest expansion of the Atlantic Water that may vary interannually. Therefore, to better understand the long-term oceanographic and ecosystem changes within the slope water system and gulf domains, it is imperative to know how those changes relate to the Gulf Stream variability on decadal and longer time scales.

Some authors suggested that the thermal regime of slope water system depends on the Labrador Water southwestward intrusion along the shelfbreak, (e.g., Pershing et al. 2001; Greene and Pershing 2003; Bisagni et al. 2006; Mountain 2012) et al. There have been attempts to relate the slope water system changes to major North Atlantic climatic indices such as the North Atlantic Oscillation, (e.g., Pershing et al. 2001; Greene and Pershing 2003). On a larger scale, the decadal variability of the Gulf Stream and North Atlantic Current have been associated with the Atlantic Multidecadal Oscillation, via the Gulf Stream and North Atlantic Current dynamics (e.g., Nye et al. 2014; Seidov et al. 2017; Nigam et al. 2018). Both indices are used widely in many Northwest Atlantic studies (see a review of the North Atlantic exploration in [Yashayaev et al. 2015]). However, the details of how those indices can explain and predict North Atlantic basin-scale and regional ocean climate dynamics remain not fully understood. For example, Gulf Stream north–south migration may stronger correlate with upper-ocean heat content anomalies and, to a lesser extent, with Atlantic Multidecadal Oscillation than with other climate indices like North Atlantic Oscillation, El Niño-Southern Oscillation, etc. (Seidov et al. 2019).

Northward shifts of the Gulf Stream path over the past five decades reached ~ 0.45° of latitude between 75 and 50°W and up to 2.6° of latitude in the Gulf Stream extension zone near the Grand Banks, between 50°W and 40°W, (Seidov et al. 2019). These Gulf Stream shifts can be a plausible cause in the long-term slope water system trends that may impact the Gulf of Maine thermal regime. The observed decadal scale warming of the Gulf of Maine (Pershing et al. 2001; Saba et al. 2016) may be linked, at least partially, to those changes. The northward shift of the Gulf Stream path may also be a part of larger-scale subtropical gyres expansion in both hemispheres (Wu et al. 2012), some of which may be attributed to anthropogenic impact (Saenko et al. 2005).

Another credible explanation of slope water system and Gulf of Maine warming connects it to the Atlantic Meridional Overturning Circulation (further referred to as the meridional overturning or simply overturning) weakening (Rahmstorf et al. 2015; Caesar et al. 2018; Thibodeau et al. 2018). High-resolution ocean models support the contention that there is a strong relationship between a weakening meridional overturning and a decrease of the Labrador Water progressing southwestward along the continental slope accompanied by a parallel increase of Atlantic Water presence attached to the Gulf Stream northern flank (Saba et al. 2016). Although the overturning weakening is allegedly coincident with the Gulf Stream path shifting northward, the relationship is not direct in the deeper subsurface layers. While the northward shift of the Gulf Stream path at the surface is confirmed by recent satellite observations (Aviso; https://www.aviso.altimetry.fr/en/applications/ocean.html), the annual mean position of the North Wall, defined as the 15°C isotherm at the 200 m depth has remained remarkably stable in its main stretch from Cape Hatteras to ~ 50°W over at least five decades since 1965 (Seidov et al. 2017, 2019). Moreover, (Rossby et al. 2019) have shown that the North Wall's position always remains very close to the velocity maximum—just about 20 km north of it. However, east of ~ 50°W the annual Gulf Stream paths deviate northward quite noticeably over the last ~ 50 years (Seidov et al. 2019), which may support the assertion of the Gulf Stream-induced changes of Slope Water in subsurface depths that has been revealed in models and data analyses (e.g., Pershing et al. 2001; Saba et al. 2016).

The seasonal variability of the North Wall position at ~ 200 m depth and deeper and thus of the Gulf Stream path is relatively small. In contrast, the near-sea surface position can experience a substantial seasonal variation on the decadal time scale. In other words, despite the stable year-round position of the North Wall preventing volumes of warm water from penetrating the Slope Water domain at and below 200 m, the seasonal amplitude of warm water northward incursion in the upper 50–100 m is significant. The decadal-scale variability of the warm summer water spread over the Slope Sea and Scotian Shelf domains can be critical for changes in slope water system seasonal dynamics on decadal and longer time scales. In support of this notion, our analysis revealed a prominent change of seasonal variability in the past ~ 15 years manifested in evident transformation of the near-surface Gulf Stream variability, causing substantial modification of the thermal regime in the Scotian Shelf and slope water system.

We analyzed all in situ seawater temperature data records in the region available for 1963–2017 period in the most recent release of the World Ocean Database 2018 (Boyer et al. 2018a). This data set allow examining the Atlantic Water expansion for five decades since 1965 as near-surface and subsurface thermal structure dynamics, formalized here as 15°C isotherms at 10 and 200 m depths, respectively. The positions of the 15°C isotherm at both depths were averaged yearly and over each of the five decades—1965–1974, 1975–1984, 1985–1994, 1995–2004, and 2005–2017; the last "decade" is 3 years longer than the other four decades to include all up-to-date data available in World Ocean Database 2018.

It should be strongly emphasized that the 15°C isotherm at 200 m is conventionally associated with the North Wall and is used as the Gulf Stream path definition (Fuglister and Voorhis 1965; Cornillon and Watts 1987; Sanchez-Franks and Zhang 2015), but the position of the 15°C isotherm at 10 m (reported in this study) *does not reflect the position of the Gulf Stream* near the sea surface. In fact, the variations in the Gulf Stream path's position remains relatively small for both annual and seasonal time periods on the decadal time scale ([Seidov et al. 2019]; see also the seasonal maps of Gulf Stream velocity at https://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html [Gyory et al. 2006]). The 15°C isotherm was selected, arbitrarily, to reflect the seasonal spread of warmth in the near surface layers. Any other isotherm, preferably depicting relatively warm water (e.g., 18°C or 20°C) could have served this same purpose. The near-surface Atlantic Water seasonal migration would follow the seasonal thermocline formation and decay and is impacted by regional circulation change in the Slope Sea, frequency of the Gulf Stream warm core rings formation, and seasonality of the radiative forcing. Having stated that, the selection of the 15°C isotherm at 10 m seems to be at least somewhat indicative of the long-term changes in the compound impact of those factors; see, for example, monthly and seasonal temperature maps in the Northwest Atlantic Regional Climatology (Seidov et al. 2016) for different decades.

As the Gulf Stream current vectors superimposed on the seasonal sea surface temperature (shown on the cited website) reveal, the most noticeable seasonal changes occur in summers. During the summer seasons the surface warm water to the north of Gulf Stream expands while the colder surface water of the Labrador Current retreats leading to warmer water taking over the Scotian Shelf in the thin near-surface layer.

The Gulf Stream system's surface and subsurface currents vary seasonally, giving way for Atlantic Water to swing northwestward in summer and retreat southeastward in winter. Figure 2 shows the Gulf Stream surface currents from https://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html (courtesy of Arthur Mariano, University of Miami); the velocities are computed using drifter data as described in (Laurindo et al. 2017). In winter seasons there is a pronounced inflow of cold water around Newfoundland carried by the Labrador Current's continuation. This water flows southwestward along the Scotia Shelf and shelfbreak and then recirculates in the Slope Sea as a part of the slope water system. Thus, the Labrador Water presence and the Labrador Current intrusion in the Slope Sea are reduced in summer and increased in winter (e.g., Pershing et al. 2001). In summer, the Labrador Water incursion in the Slope Sea is severely reduced. As a result, the Atlantic Water moves onshore in summer and retreats offshore in winter.

In this preliminary assessment, we argue that Gulf Stream variability in the extension zone (east of 50°W), both near the surface and in the subsurface, is the key to understanding the ocean climate change in the Gulf of Maine, Scotian Shelf, and slope water system. Although the $\sim 0.45°$ latitudinal shift of the Gulf Stream path appears to be small, this shift constitutes almost 20% of the Slope Water latitudinal size. This small yet noticeable northward shift of the North Wall main stretch over the last 50 years squeezes the slope water system area, increasing the proportion of the Gulf Stream warm water in the slope water system mix. The Gulf Stream path extension between 50 and 40°W demonstrates a wider path spread, with the decadal jet positions moving farther northward, up to 2.6° of latitude (Seidov et al. 2019). This displacement is geographically close to the Gulf Stream and Labrador Current collision area, where the Labrador Current partially retroflects toward the North Atlantic Current (e.g., Rossby 1996; Bersch 2002; Fratantoni and Mccartney 2010; Brickman et al. 2018). Therefore, the decadal-scale migration of the Gulf Stream path in the extension zone (50–40°W) may reduce the Labrador Water intrusion into the slope water system domain. Moreover, in summers the secondary northern branch of the Gulf Stream in the extension zone, sometimes called the Slope Water Jet (e.g., Fratantoni and Pickart 2007), intensifies significantly. Such an intensification can also reduce Labrador Water intrusion, curbing the cold water supply in GOM and its surroundings (see Fig. 2 and seasonal Gulf Stream maps https://oceancurrents.rsmas.miami.edu/atlantic/img_gosv_seasonal.php).

From both theoretical and practical viewpoints, it is essential to know if the regular multi-year cycle seen before the last decade will continue, with or without superimposed slow warming, as it has been happening in Northwest Atlantic for almost 60 years (Seidov et al. 2017). Besides, it is essential to find out if the subsurface (200 m and deeper) warming, if any, follows the near-surface tendencies, thus causing systematic year-long warming of the slope water system and subsequently of the Gulf of Maine.

Seidov et al. (2019) noted that for most years between 1965 and 2005, the annual Wall position was very coherent between 70 and 50°W and noticeably more variable in the Gulf Stream extension zone east of 50°W. In 1995–2012, individual annual Gulf Stream pathways east of 50°W began deviating toward the shelfbreak much farther than in earlier decades. Consequently, the slope water system regime associated with intensified Atlantic Water northward intrusion began shifting at the turn of the century.

Below 200 m, individual Gulf Stream pathways cannot veer too far to the north because the bottom topography at about 200 m depth prevents such movements. In contrast, the near-surface (above $\sim$ 100 m) warm water can spread over the entire Scotian Shelf and Slope Water area. To some extent,

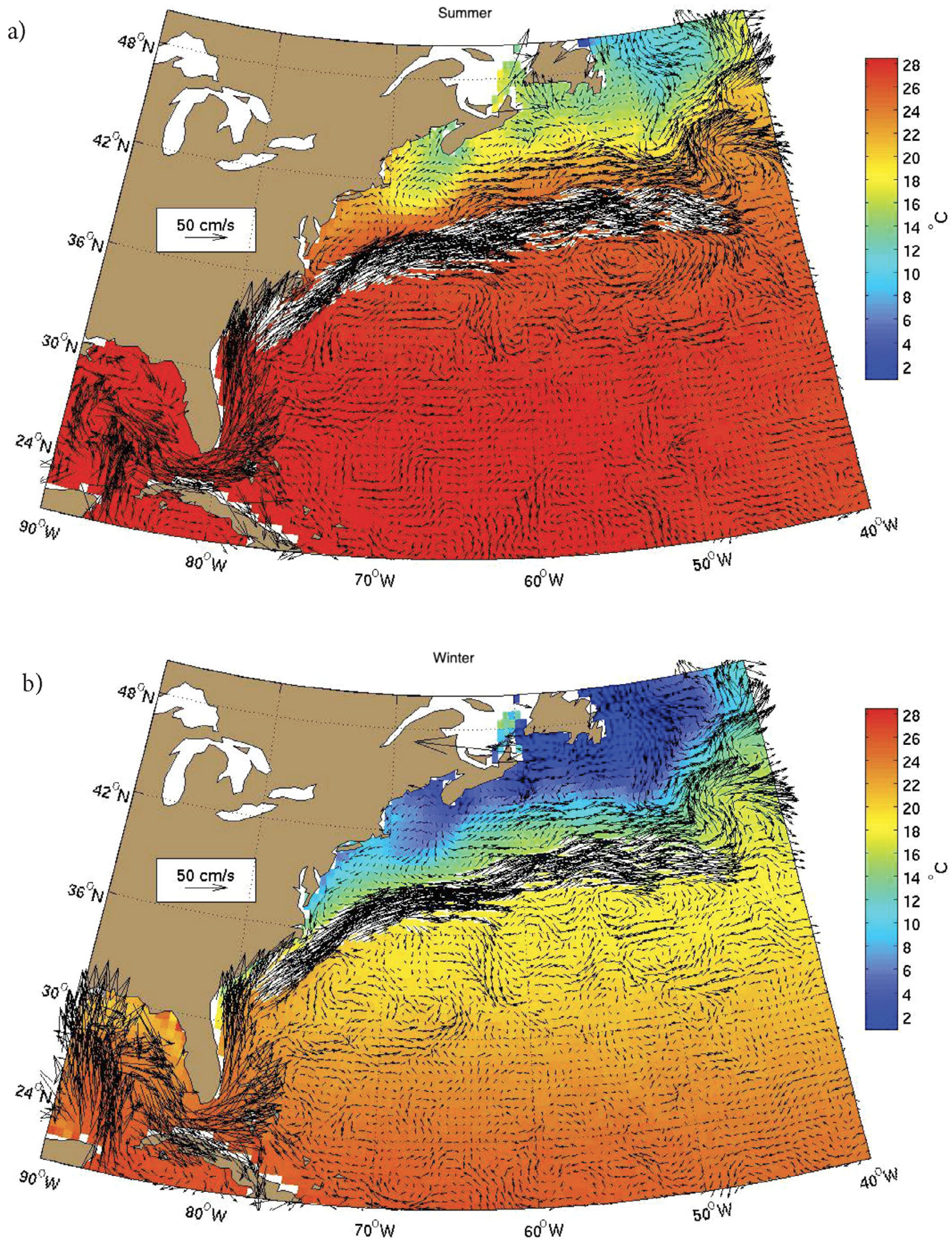

Fig 2. Surface velocities from drifters in the Gulf Stream region for (**a**) summer and (**b**) winter. The velocity vectors are superimposed on the sea surface temperature. The current maps are reproduced with permission from https://oceancurrents.rsmas.miami.edu/index.html (courtesy of Arthur Mariano of the University of Miami).

near-surface warm water intrusion into the shelf areas in summers may be perceived as the North Wall summer "tilting" in the near-surface depths allowing the Atlantic Water to spread inshore. This resemblance is, of course, only partial as the warming north of the Wall is a mix of seasonal surface heating, advection of widening near-surface Gulf Stream flow (see Fig. 2), and Ekman downward pumping of seasonally warming water. (See the AVISO Gulf Stream maps at https://www.aviso.altimetry.fr/en/applications/ocean.html and seasonal near-surface temperature maps at the NOAA Northwest Atlantic Regional Climatology website; [Seidov et al. 2016]).

Data and methods

We used the in situ seawater temperature profile data from the most recent version of the World Ocean Database published in 2018 and available at https://www.ncei.noaa.gov/products/world-ocean-database. The method of working with the World Ocean Database 2018 data involves processing all available seawater temperature profiles within the selected domain to reveal annual and decadal position of the 15°C isotherm at 10 and 200 m depths using the Ocean Data View software (Schlitzer 2020), with the year of 1965 used as the starting point based on data availability. The 2005–2017 "decade" is 3 years longer than other decades to include the most recent data available in World Ocean Database 2018. Ocean Data View software was also used for computing box-averaged temperature values within different domains and depth layers. The seasonal climate shift between the two 20-year climatologies is defined and computed as the differences between the temperature averages of 1995–2017 and 1965–1984. Maps and 3D figures were produced using Golden Software's Surfer and Voxler packages for spatial data analyses.

Results

We plotted the 15°C isotherm in the near-surface layers to examine decadal variability of its position. Figure 3a shows a map of decadal-mean annualized positions of the 15°C isotherm at 10 m depth calculated using in situ seawater temperature from World Ocean Database 2018. The map depicts five decadal positions of the 15°C isotherm superimposed over its 52-individual annual (1965–2017) positions. A similar chart of the 15°C isoline at 200 m (Fig. 3b), shows the annual North Wall positions for five decades and 52 years. The bold blue line represents the average of five decadal annual North Wall positions (inferred from the position of the isotherm 15°C at 200 m) in both Fig. 3a,b. Two rectangles in Fig. 3 display the areas of the Gulf of Maine and the Scotia Slope and Slope Water (marked as "SW"). Box-averaged temperatures were computed for those two domains to analyze time series at different depths layers (shown in Figs. 5–7). Hereafter, the Scotia Shelf and Slope Water is referred to as simply "slope water."

An analysis of annual (Fig. 3) and seasonal maps (Fig. 4) revealed that in winter (Fig. 4b), North Wall outcrops at the surface, and the Gulf Stream pathways at 200 and 10 m depths coincide very closely. It can be seen in Fig. 4b, that the winter regime in the slope water began to change since the decade of 1995–2004. During summers (Fig. 4a), the situation is quite different. There is northwestward spreading warm subsurface water with the maximum northward excursion of subsurface warmth inundating the Scotian Shelf and reaching the southeastern part of the Gulf of Maine. The annual map of the 15°C isotherm positions at 10 m depth in Fig. 3a reflects the substantial summer deviations depicted in Fig. 4a. In summers, and to some extent annually, in 1995–2004 and 2005–2017, the warm water extends northward much farther than in previous decades and spreads over the Gulf of St. Lawrence, thus departing dramatically from the summertime extent seen in the earlier three decades of 1965–1974, 1975–1984, and 1985–1994.

The northward summer spread of warm near-surface water is well-known (e.g., Rasmussen et al. 2005; Forsyth et al. 2015). We would not have given this fact any additional attention if not for an unusual and stunning increase of warm water excursions northward in the most recent decade of 2005–2017. That can be seen even in annual maps in 15°C isotherm at 10 m depth in Fig. 3a and even more so in the summer map in Fig. 4a. Examination of seasonal and monthly high-resolution maps of near-surface temperature in Northwest Atlantic region (available at https://www.ncei.noaa.gov/products/northwest-atlantic-regional-climatology) also supports this notion (Seidov et al. 2016).

The increased northward spread of warm subsurface water is an important point for further discussion because, as shown below, there is pronounced synchrony between these warm water excursions and the fast warming in the Scotian Shelf and Gulf of Maine. Indeed, the near-surface positions of the 15°C isotherm in the most recent decade of 2005–2017 (shown by dotted lines of the same color as the 2005–2017-decadal average) implies that these near-surface conditions cannot be explained by summer seasonal thermocline formation alone. The circulation changes leading to increase or reduction of the Labrador Current water entering the slope water region around the Grand Banks can contribute fundamentally to the thermohaline regime of this region and eventually of the Gulf of Maine (Petrie et al. 1996).

The complex nature of downstream warming in the slope water region implies that many factors can cause prolonged warming in the slope water and eventually in the Gulf of Maine. The interactions between the Gulf Stream and Labrador Current have the potential to contribute strongly to this warmth. Therefore, we believe our finding that the North Wall shifted northward in this region by 2.6° of latitude in the last decade (Seidov et al. 2019) points to this systemic change as the primary driver of the subsequent warming in the slope water region. This change can further induce warming in the Gulf of Maine by transporting warmer water across the Northeast Channel.

To explore the thermal history in the Gulf of Maine and slope water regions, we addressed the recent warming there by examining the time-series of box-averaged temperature in two domains (shown in Fig. 3) in six evenly spaced 50 m thick depth layers from the sea surface to 300 m depth. Figure 5 shows annual and pentadal (averaged over 5-year intervals)

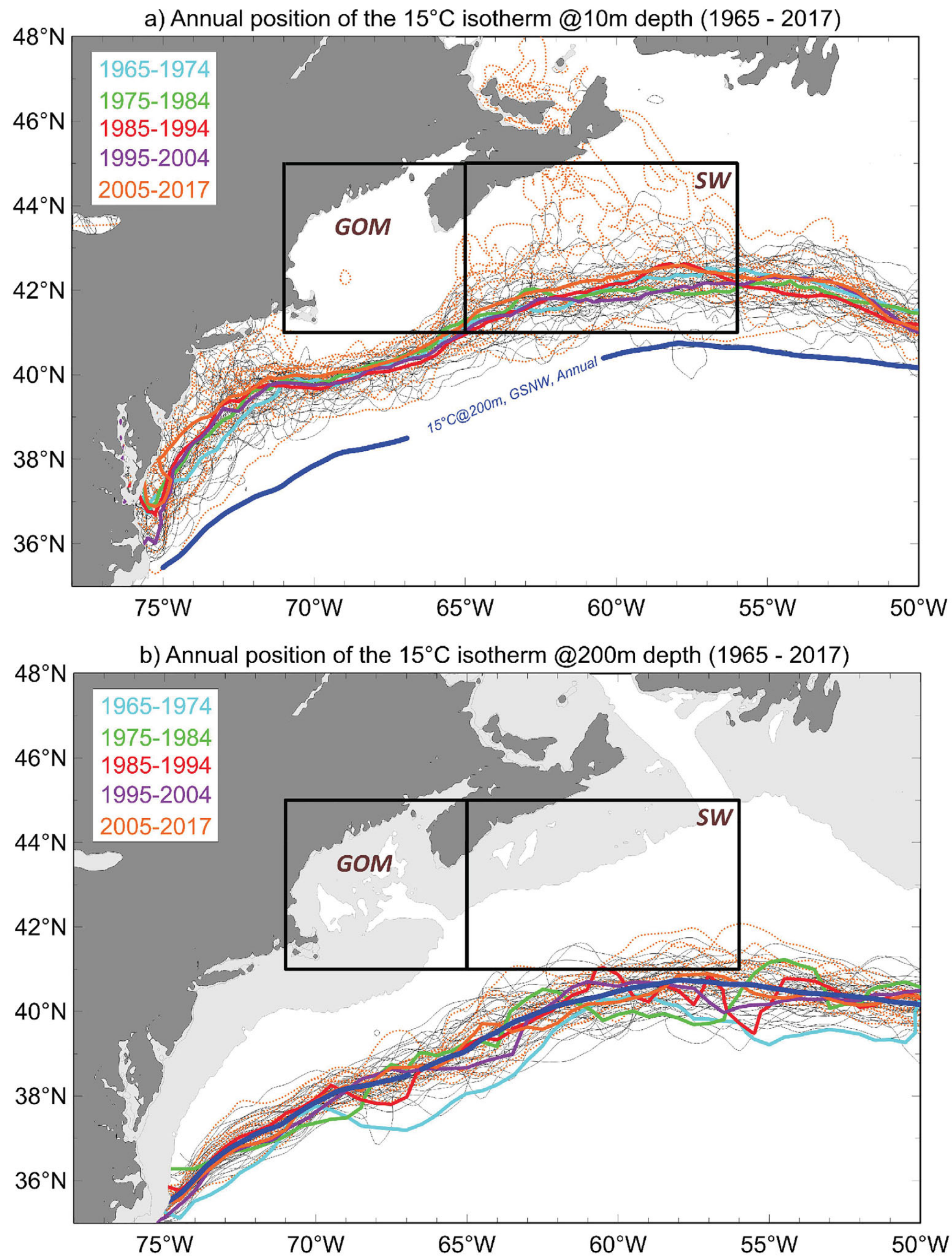

Fig 3. Annual positions of 15°C isotherm at (**a**) at 10 m and (**b**) at 200 m depth for the 1965–2017 period. Yearly (1965–2004)—thin gray lines, decadal—bold color lines and (2005–2017)—dotted lines—and 2005–2017 decadal average are shown by the same color. Mean (1965–2017) annual position of the Gulf Stream North Wall (15°C at 200 m) is shown by bold blue line. Rectangles are the areas where the Gulf of Maine and Slope Water box-averaged temperature was computed; see text for details.

averaged temperature in the Gulf of Maine (a) and the slope water (b) from 1963 to 2017. Yearly box-averaged temperatures shown by colored lines for all six layers. The red circles show the pentadal averages in the 0–50 m layer, and the gray diamonds show the pentadal averages in the 50–100 m layer at each pentad central years, that is, 1965, 1970, 1975, etc.

Sea surface water temperature in the Gulf of Maine has recently been rising faster than almost anywhere in the World Ocean (e.g., Mills et al. 2013). However, the Gulf of Maine's recent surface warming has not led to equally strong warmth in the upper 50 m layer judging by the in situ seawater temperature from World Ocean Database

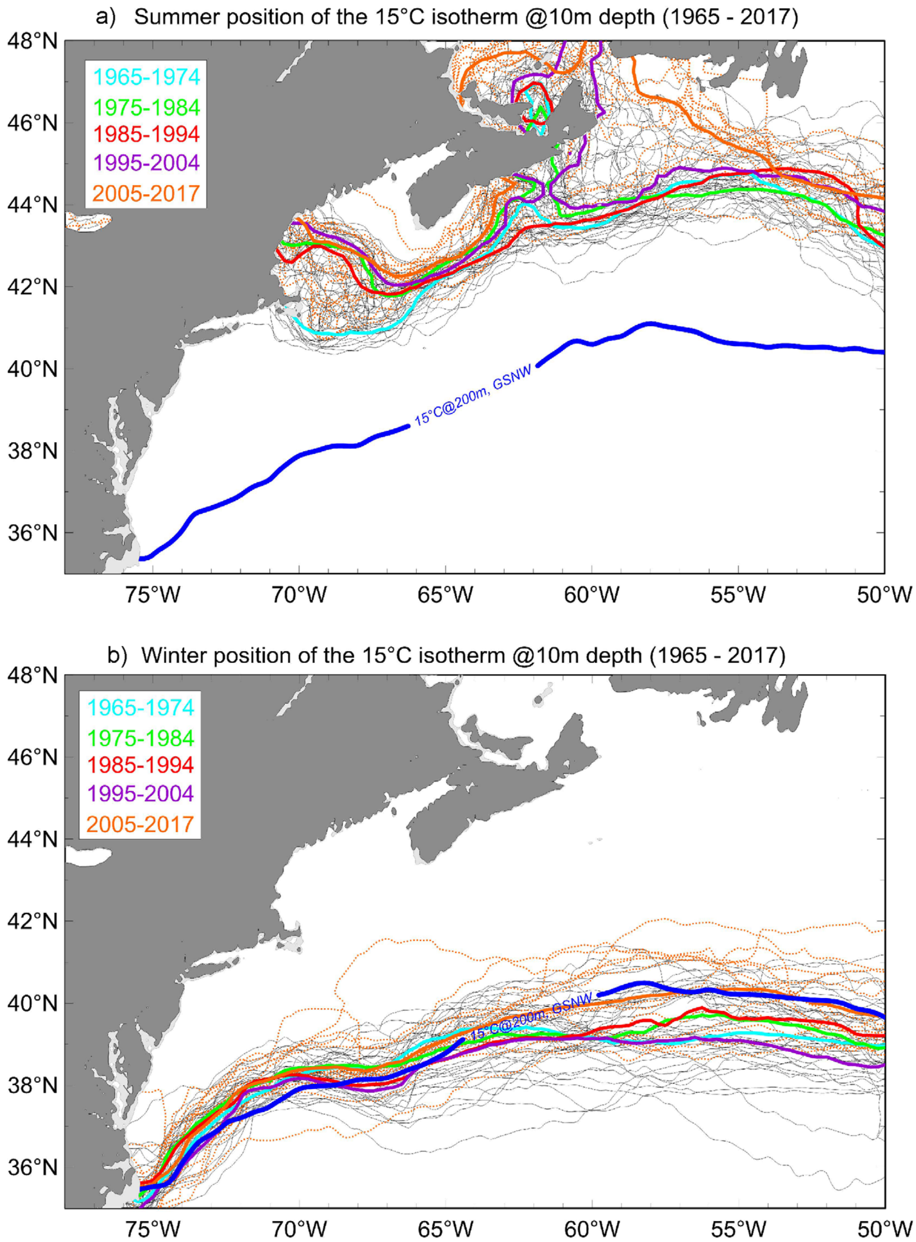

Fig 4. Seasonal positions of 15°C isotherm at 10 m depth in (**a**) summer and (**b**) winter for the 1965–2017 period. Yearly (1965–2004)—thin gray lines, decadal—bold color lines and (2005–2017)—dotted lines—and 2005–2017 decadal average are shown by the same color. Mean (1965–2017) annual position of the Gulf Stream North Wall (15°C at 200 m) is shown by bold blue line.

2018. Our analyses of the in situ historic data (Fig. 5a) shows that although the recent near-surface year-round gulf temperatures did rise noticeably, it did not rise much higher than during previous warm periods, for example, those in the mid-70s or 90s. In contrast, the slope water region warmed much quicker in the last 10 years, and the annually averaged temperature in the 0–50 m layer reached the highest ever recorded value of 14°C. The upper layer warming was accompanied by fast warming in the subsurface layer (50–100 m) reaching almost 9°C, though it is still slightly lower than around the mid-70s. All layers below 50 m in slope water reveal the similar pace of fast warming in the last 10 years.

The warming over the entire region since 1990 agrees with the assertion of quick warming in both the gulf and slope water. Nonetheless, the pentadal-mean temperature in the upper 100 m depth near 1985, for example, was almost as high as that around 2015. Warming in the Gulf of Maine area

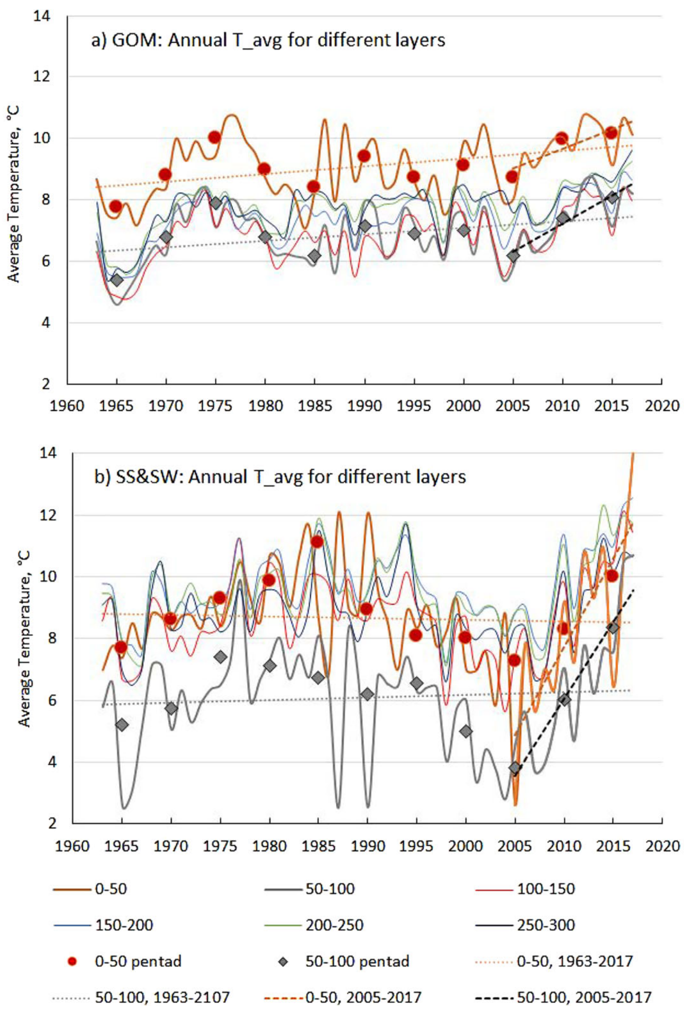

Fig 5. Time series of the annual temperature averaged over (**a**) the Gulf of Maine (GOM) area and (**b**) the Scotia Shelf and Slope Water (SS&SW) area (rectangles in Fig. 3). Lines show the yearly annual temperature in six layers; circles and diamonds indicate the pentadal (5-year averages) temperatures in the 0–50 m layer (red circles) and 50–100 m layer (gray diamonds) layers only. The dashed lines show the trends of temperature in 0–50 m (red dash lines) and 50–100 m (gray lines) for the entire series from 1963 to 2017 (54 years; thin dash lines) and the last 12 years from 2005 to 2017 (bold dash lines).

in 2005–2015 was almost as fast as in 1965–1975, and the warming in the slope water area is happening even faster in the last 10 years.

The near-surface annual pentadal temperatures in the Gulf of Maine rose since 2005 by less than ~ 0.2°C/year (Fig. 5a), a little more than 0.2°C/year in summer (Fig. 6a), and <0.1°C/year in winter (Fig. 6b). The deeper subsurface pentadal temperature variations in the Gulf of Maine looks different from that in the near-surface layer.

The slope water temperature in all layers has risen steeply since 2005 and continues to rise both in summer and winter. In the last decade, pentadal near-surface temperature in both the Gulf of Maine and slope water shows similar summer tendencies. The gulf temperature shows a sloping rise after 2005, both seasonally and annually, which agrees well with (Pershing et al. 2015).

The slope water warming is quite significant and much steeper than in the Gulf of Maine. Since 2005, the annual temperature in slope water increased by ~ 4.5°C, the summer temperature raised by approximately 3.8°C, and the winter temperature increased by almost 5°C in practically all layers. Overall, warming in slope water is much steeper than in the gulf.

Temperature in the surface and bottom layers in the Gulf of Maine is indeed changing asynchronously, while temperature in layers between those two ones varies more coherently (Figs. 5, 6). The asynchrony between the top and bottom layers may reflect that there are different oceanographic forcings in the surface and bottom layers: the Gulf of Maine's surface layer is influenced by cool water flowing along the Scotian Shelf. The near-bottom layer temperature depends on the inflow of warmer Atlantic Water through the Northeast Channel. The upper layer also interacts with the atmosphere and is impacted by river runoffs. The internal layers, on the other hand, depend more on the circulation and vertical mixing with the top and bottom layers. Overall, both the Gulf of Maine and slope water are getting warmer, but slope water is warming faster than Gulf of Maine at all depths.

Averaged over the upper 300 m, the summers, winters, and year-round temperature in the Gulf of Maine (Fig. 7a) and slope water (Fig. 7b) shows significant warming throughout the time record in both regions. However, in the recent decade, slope water's warming is much steeper than that in the gulf. The trends of vertically averaged temperature in the two domains illustrate the accelerated warming in 2005–2017, especially in the slope water (Table 1). The slope water and Gulf of Maine were warming at a comparable rate for the extended period from 1963 to 2017. However, after 2005, the warming in the slope water has accelerated much steeper than in the gulf. Astonishingly, the slope water was warming almost four times faster between 2005 and 2017. In the Gulf of Maine, the linear trend from 1965 to 2017 was about 0.3°C/decade, like reported by (Chen et al. 2020), while between 2005 and 2017, it increased to more than 1.2°C/decade. The temperature in slope water also increased steadily, with the overall warming there even lesser than in the gulf in earlier decades. However, between 2005 and 2017, the warming rates skyrocketed to almost 4°C per decade.

To illustrate the long-term ocean climate shift in the gulf and slope water, we computed 3-D plots of the temperature anomalies in the region calculated by subtracting the climate of 1965–1984 from 1995 to 2017. Figure 8a shows an annual climate shift over the selected ~ 50-year period (the 1985–1994 is excluded from the comparison). Figure 8b displays the annual temperature anomalies at three sections across Slope Water and the Scotian Shelf. Two sections in Fig. 8b are across the Scotian Shelf toward the Gulf Stream and one across the middle of gulf

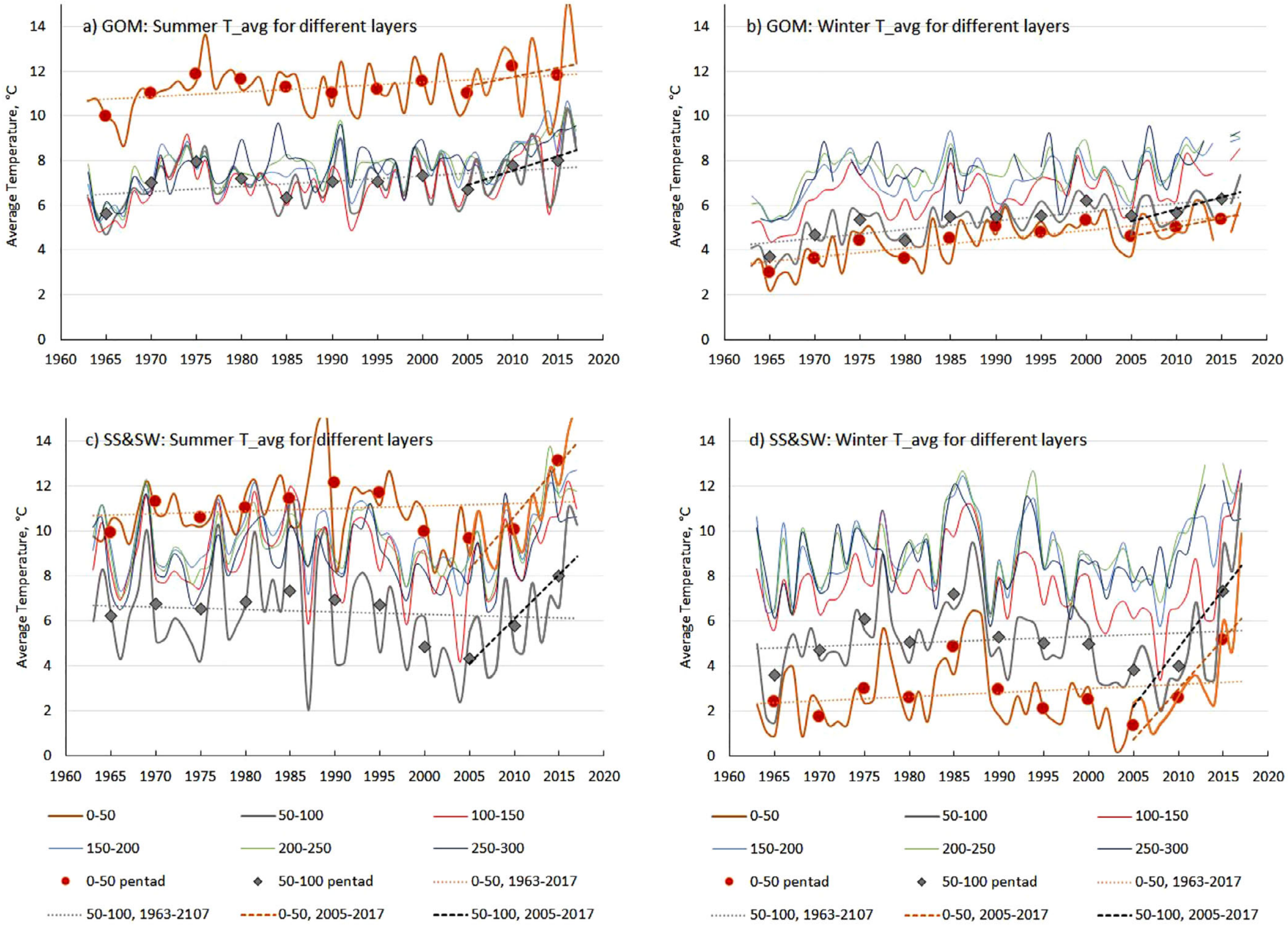

Fig 6. Summer and winter temperature in the Gulf of Maine and Scotia Shelf and Slope Water regions in (**a**) summer, (**b**) winter, and in the Scotia Shelf and Slope Water region: (**c**) summer, (**d**) winter. Lines show the yearly annual temperature in six layers; circles and diamonds indicate the pentadal (5-year averages) temperatures in the 0–50 m layer (red circles) and 50–100 m layer (gray diamonds) layers only. The dashed lines show the trends of temperature in 0–50 m (red dash lines) and 50–100 m (gray lines) for the entire series from 1963 to 2017 (54 years; thin dash lines) and the last 12 years from 2005 to 2017 (bold dash lines).

through the Northeast Channel and over the Slope Water area, reaching the annual position of the Wall at 200 m depth. Here we use the "climate shift" term referring to the difference between two 20-year temperature averages. This term "climate" of 20-year average is slightly different from the more broadly accepted definition of climate as a 30-year average, as in (Seidov et al. 2017), but somewhat shorter time it is more appropriate, in our view, for smaller and shallower areas.

According to Fig. 8a, most of the annual warming (up to 1.8°C) occurs along the shelfbreak and over the slope, which agrees well with (Chen et al. 2020). Warming of almost 1°C is seen inside the Gulf of Maine close to the bottom (green shading). The decadal data coverage in this region is quite dense and can be viewed at https://www.ncei.noaa.gov/access/world-ocean-atlas-2018f/.

The seasonal climate shift between the two 20-year climatologies is presented in Fig. 9 for winter (a), spring (b), summer (c), and fall (d). The most vigorous climate shift in the Gulf of Maine area occurs in winter, with warming about 0.5°C at the Northeast Channel over the 50 years. In the near-surface layers, the most significant climate shift is in the Gulf Stream extension zone south of Newfoundland in the summer, as expected from the surface warm water migration (Fig. 4). The most robust warming in winter is seen in the Northeast Channel, where the warmer mixture of the Slope Water and Atlantic Water enters the gulf. This water ultimately mixes upward entraining in the upper layer, in agreement with a general understanding of how Gulf of Maine near-surface layers can be warmed in winter (e.g., Ramp et al. 1985).

Discussion and conclusions

This study aims to analyze how the changes in the Gulf Stream decadal inter-annual and inter-seasonal variability can

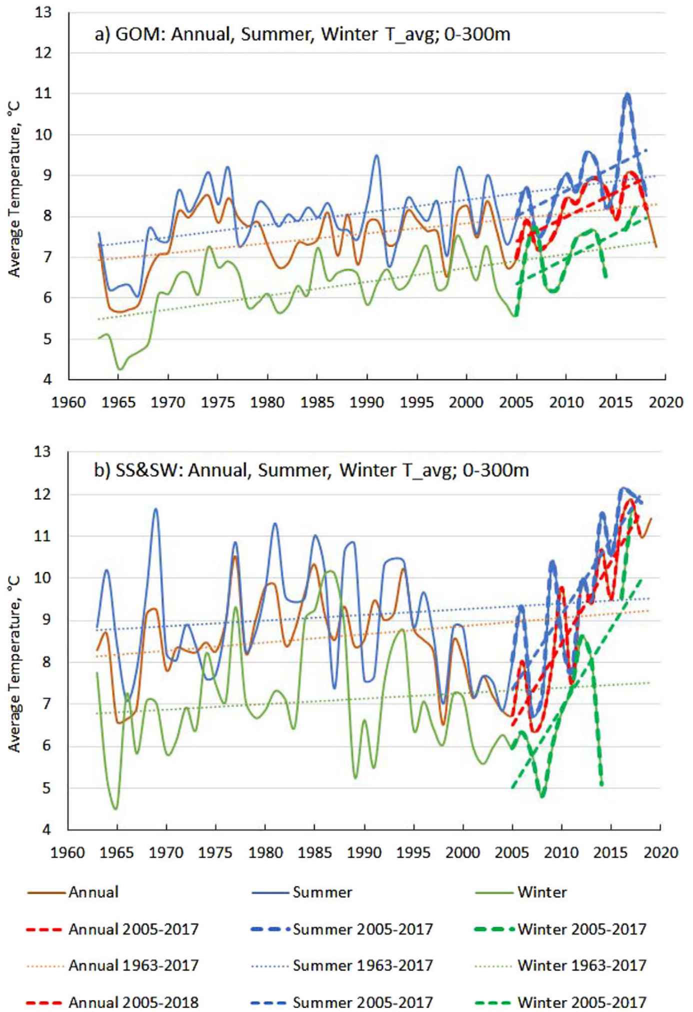

Fig 7. Annual, summer, and winter temperatures averaged within 0–300 m layer in (**a**) the Gulf of Maine and (**b**) in the Scotia Shelf and Slope Water regions. The trends values with errors are shown in Table 1. The gaps in the lines mean that there are no data for the entire year.

Table 1. Temperature trends (°C/decade) in the Gulf of Maine and the Scotia Shelf and Slope Water area (averaged from the sea surface to 300m)

Years	1963–2017	2005–2017
Gulf of Maine		
Annual	0.23 ± 0.013	1.20 ± 0.359
Summer	0.29 ± 0.015	1.22 ± 0.578
Winter	0.32 ± 0.012	1.22 ± 0.548
Scotian Shelf and Slope Water		
Annual	0.20 ± 0.229	4.21 ± 0.770
Summer	0.14 ± 0.267	3.84 ± 0.963
Winter	0.13 ± 0.274	4.11 ± 1.193

affect the ocean climate in and around slope water system and in the Gulf of Maine. We did not explore the causation-response connections between this regional ocean climate and external climate factors. Moreover, we did not investigate any correlation between the slope water system/Gulf of Maine changes and North Atlantic and/or North Pacific basin-scale climate indices, like the North Atlantic Oscillation, Atlantic Multidecadal Oscillation, El Niño-Southern Oscillation, etc. In a broader view of Northwest Atlantic climate change, these aspects have already been addressed recently (Seidov et al. 2017; Seidov et al. 2019). There are many research efforts directed explicitly at finding such relationships, especially between the North Atlantic Oscillation and the long-term climatic change in the Northwest Atlantic in general and in the Gulf of Maine and slope water system regions (e.g., Bersch 2002; Greene and Pershing 2003; Pershing et al. 2001). Our study differs from those extensive efforts. The sole goal here was to explore how the significant changes in the inter-annual and inter-seasonal behavior of the Gulf Stream are reflected in long-term ocean climate change in and around the slope water system and the Gulf of Maine on a decadal time scale. Therefore, this is by nature a phenomenological study of ongoing ocean climate change by using in situ historical seawater temperature data, and we discuss our results from that angle only.

Available field observations accumulated in World Ocean Database 2018 confirm the overall long-term warming in slope water and the gulf regions. Notably, the slope water area undergoing faster recent warming with an upward curve and the Gulf of Maine experiencing less severe recent warming primarily caused by the Scotian Shelf influence in the subsurface and by the SW impact in bottom layers. The warming in these regions agrees with all previous study on climate trends in the Gulf of Maine and its surroundings. The new findings here are that the Gulf Stream behavior in its extension zone, east of 50°W, has significantly changed in the period of 2005–2017, and that the rates of warming in the slope water are substantially higher than in Gulf of Maine. The overall and localized changes in the gulf and slope water are manifested in a substantial expansion of near-surface warm water toward the Scotian Shelf and the Tail of Great Banks in summers. The warm water, which is a mix of seasonal warming and the wider northward spread of Gulf Stream warm water, soared in 2005–2017, reaching the northern corner of the Scotian Shelf and the Gulf of St. Lawrence. The expansion of the warmer water may itself contribute to the warming of the Scotian Shelf (seen in Figs. 8, 9). It also may coincide with stronger retroflection of the Labrador Current and thus even lesser Labrador Water incursion into the slope water system area all year round; the winter Labrador Water flow is anyhow strongly reduced (Pershing et al. 2001; Greene et al. 2013). Cutting off or reducing the Labrador Current flow around the Great Banks can further limit Labrador Water incursion along the shelf-break, promoting further warming of the slope water mix.

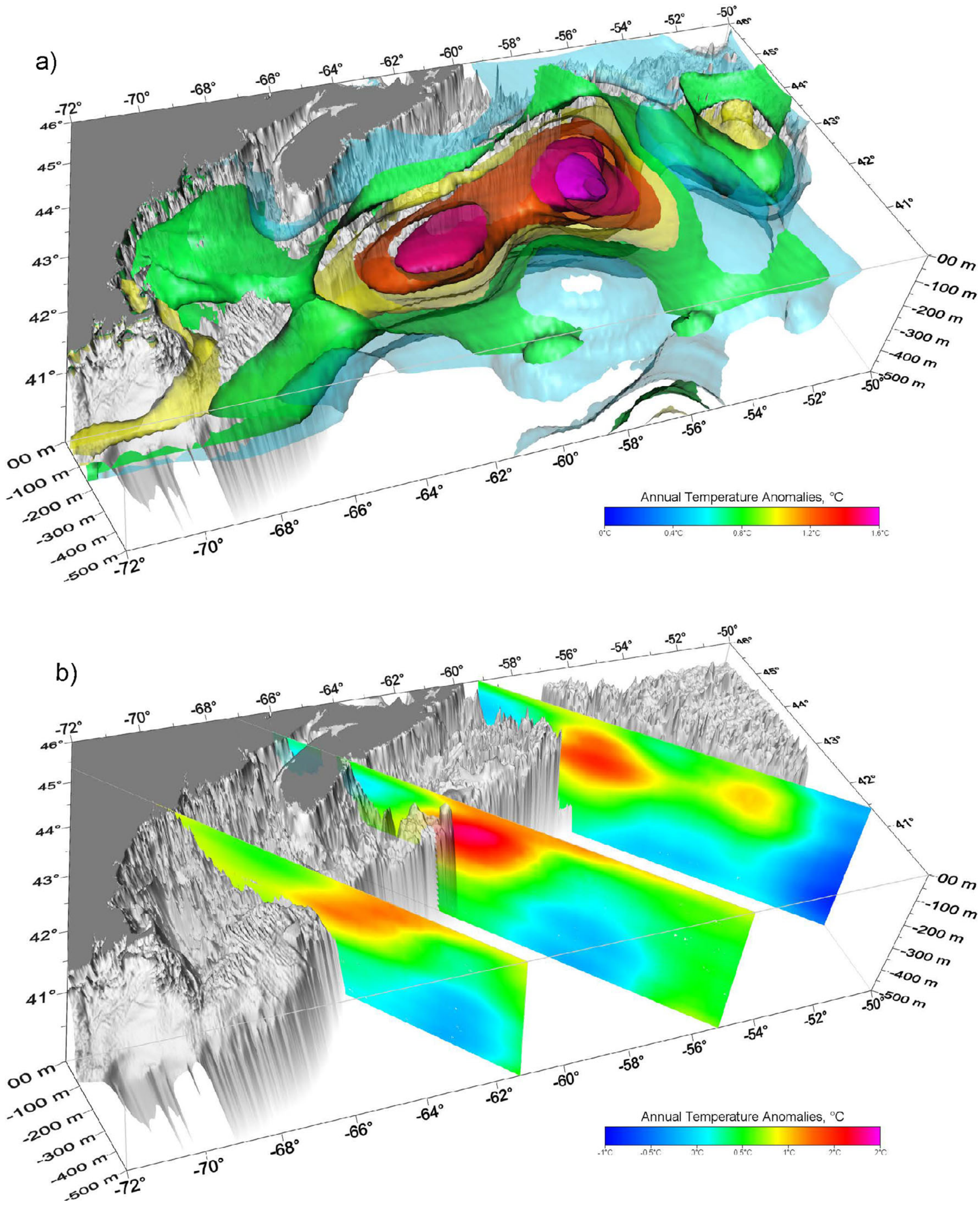

Fig 8. Annual temperature differences (ocean climate shift; see text) between the averages: 1995–2017, and 1965–1984; (**a**) 3D annual temperature anomalies and (**b**) annual temperature differences at three sections—South of the Laurentian Channel outflow, across the middle of the Scotia Shelf and Slope Water area, and in the middle of the Gulf of Maine.

Brickman et al. (2018) suggested that the warm events of 2012, 2014, and 2015 in the subsurface waters over the Scotian Shelf could be caused by interactions between the Gulf Stream and the Labrador Current south of Newfoundland. Based on their modeling results, they argue that there can be a situation where a perturbation of the Gulf Stream flow near the Tail of the Great Banks may push the warm (and saltier) water of the Gulf Stream against the cold (and fresher) water of the Labrador Current, effectively shutting off its flow around the Great Banks. The mechanism of transporting the

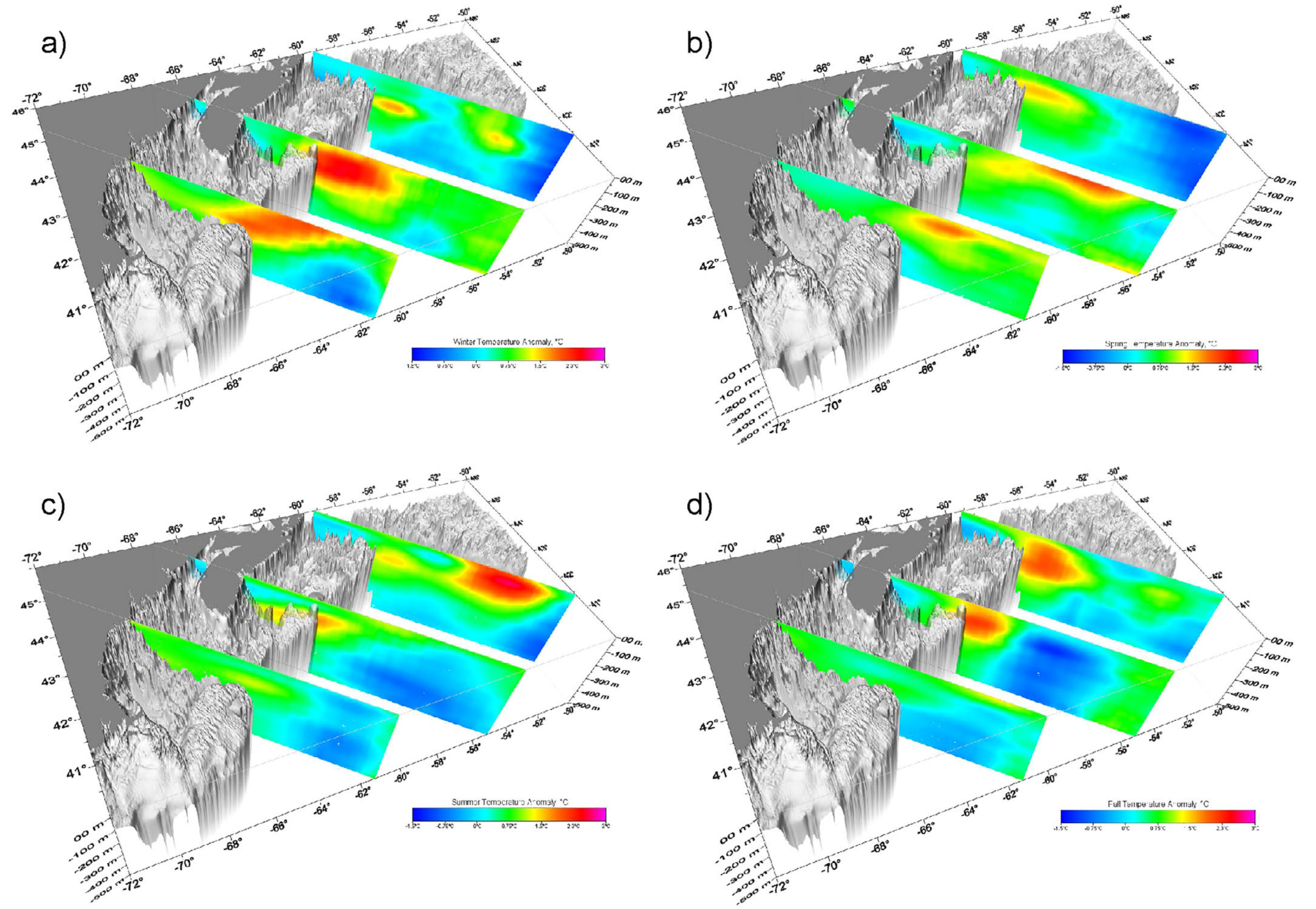

Fig 9. Seasonal temperature differences (ocean climate shift; see text) between the averages: 1995–2017, and 1965–1984; (**a**) winter, (**b**) spring, (**c**) summer, and (**d**) fall. The sections are south of the Laurentian Channel outflow, across the middle of the Scotia Shelf and Slope Water area, and in the middle of the Gulf of Maine.

warm water along the shelf break is then supposedly through warm eddies generated by the Gulf Stream and Labrador Current interactions around the Great Banks.

The differences in warming rates in the near-surface and deeper layers can be explained by how the thermal structure of those layers are maintained year-round. In the near-surface layer, air-sea thermal and dynamic interactions superimposed on the surface currents are responsible for intense surface heating in summer and cooling in winter. The thermohaline state of subsurface water below $\sim$ 100 m is less dependent on thermal air-sea interaction than the near-surface layer, which is mostly driven by Ekman pumping and turbulent mixing, while deeper layers are more firmly controlled by the regional ocean circulation reflecting the dynamic balance between the warm Atlantic Water and cold Labrador Water. Although previous studies provide a detailed picture of slope water system structure and dynamics (Pershing et al. 2001; Conversi et al. 2015), it has not yet been clearly shown on how a change of thermal structures can be connected to decadal and longer Gulf Stream variability.

The Gulf of Maine's deep layers warming is regulated by the inflow of warmer water through the Northeast Channel. We argue that all regional climate shifts point to the Gulf Stream's shoreward expansion in the shallow subsurface layers. This incursion occurs in all seasons but is most pronounced in summer. Moreover, the North Wall or the Gulf Stream path, defined as 15°C isotherm at 200 m, has shifted northward by over 2.6° of latitude in area east of 50°W. This shift of the North Wall may be the primary cause of increased blockage of Labrador Water around the Tail of the Great Banks, thus curtailing the amount of cold water branching at the Labrador Current retroflection.

The explanations of the subsequent warming of the slope water along the shelfbreak may differ. One reason for faster warming in selected years, for example, 2012, 2014, and 2015, is that warm eddies generated in the Gulf Stream and Labrador Current collision zone south of Newfoundland caused warming downstream along the shelfbreak (Brickman et al. 2018). However, we also see systematic warming in this region for the entire period of 2005–2017. Therefore, we believe that the North Wall northward shift east of 50°W in this period was the more potent and permanently acting cause that may contribute to the overall warming in this region.

Summer climate in the slope water northeastern corner became much warmer in 1995–2017 relative to 1965–1984 than the winters' climate for the same periods (Fig. 9a,c). Figure 4a gives a clue as to why it may happen. In the summers of 1995–2004, and especially in 2005–2017, the warm surface water of the Gulf Stream origin extends much further north than in 1965–1984. However, such change impacts only the northeastern part of the slope water and the Gulf of St. Lawrence. It is reflected in Fig. 9c showing decadal scale warming in the upper layers in that northern area. In contrast, the winters' anomalies differ more in the slope water system rather than on the Scotian Shelf (Fig. 9a). In all seasons, the decadal temperature changes in gulf's bottom layers are caused by warmer water inflowing through the Northeast Channel, which is in agreement with (Fratantoni and Pickart 2007).

Figure 8a implies that the slope water region warmed annually more than Gulf of Maine. The overall decadal climatic change is centered in the Slope Sea and thus is most probably tied to the northward Gulf Stream path shift of $\sim 0.45°$ of latitude in the main stretch and 2.6° in the Gulf Stream extension zone east of 50°W in the last decade, as reported in (Seidov et al. 2019). This Gulf Stream shift could effectively squeeze the Slope Waters area and decrease propagation of the cold Labrador Current water southwestward along the shelfbreak, thus causing relatively faster slope water warming in the last decade, as shown in Figs. 6–8.

The climate trajectories of the Gulf of Maine and slope water were already slightly different on the stretch of 50 years but started to diverge strongly in the last decade. Indeed, the $\sim$ 50-year temperature trend in the gulf is only slightly steeper than in the slope water region. However, the trends in these regions in the last decade show radically quicker warming in the slope water area, almost four times faster than in the Gulf of Maine (Table 1).

Regarding the fast warming of the slope water in the last decade relative to similar rapid warming in previous decades, we believe that fast warmings before 2005 cannot be linked to the Gulf Stream variability as clearly as the most recent warming. It is true that the previous warming events in the region were not much weaker than the most recent one (Figs. 5 and 6). For example, (Petrie et al. 1996) and (Loder et al. 2001) reported a very steep temperature rise between the cold years of the 1960s to the warmer years of the 1970s, with about 3°C increase in the subsurface and bottom temperature over a decade. However, as it was mentioned throughout the text, the recent warming coincides with a northward shift of the North Wall in the last decade of 2005–2017 by about 0.45° of latitude west of 50°W and up to 2.6° east of 50°W. The northward shift of the Wall west of 50°W squeezes the Slope Water offshore thus increasing relative warm water content, while the significant northward shift of the Wall east of 50°W may cause circulation change in the Labrador Current retroflection zone consequently cutting off or substantially reducing Labrador Water incursion into slope water area. Most probably, squeezing the Slope Water area, reducing the Labrador Current inflow in the slope water, and warm eddies propagating the warmth from the Tail of the Great Banks southwestward along the shelfbreak, e.g. (Brickman et al. 2018) are all synergistically working together and thus possibly enhancing each other. To explore the causation-response connections and relation of the ocean climate trajectory in this region with the major climate indices is far beyond our primary goal of descriptive analysis of this trajectory and would require a different kind of extended research, perhaps with a combined observation-modeling approach.

The 3-D climate shift, temperature time series, and cross-regional sections of the climate shift all indicate the regime change. However, they do not favor or disfavor any conclusion on how persistent these trends are and how the climate trajectory in this part of the Northwest Atlantic may evolve about the next decade or longer.

In general, without multifaceted analysis of the in situ data, remote imaging of the sea surface height dynamics, and the results of high-resolution ocean and climate modeling, the complete picture of the climate trajectory in any region of the World Ocean and especially in the area of such complexity as the Gulf Stream, Gulf of Maine, Scotia Shelf, and Slope Sea will remain incomplete. Another aspect of the local changes is their linkage to the global ocean climate changes, especially the meridional overturning slowing and related transformation in the Gulf Stream surroundings (e.g., Caesar et al. 2021). Some recent results of high-resolution climate modeling confirm enhanced warming in the North Atlantic Ocean caused by increased atmospheric CO_2 (Saba et al. 2016). This study shows that upper-ocean ($\sim$ 0–300 m layer) of the Northwest Atlantic Shelf warms at a rate nearly three times faster than the global average under the warming climate scenario of increased atmospheric CO_2. These simulations reveal a retreat of the Labrador Current and a northerly shift of the Gulf Stream in the warmer climate. Moreover, that study argued that their model results agree with the possible relationship between a weakening of the overturning and an increase in the proportion of warm water entering the Northwest Atlantic Shelf, which includes the Scotian Shelf and the gulf surroundings (Saba et al. 2016). The high-resolution modeling of the coupled ocean–atmosphere is critical for in-depth understanding of the ocean climate trajectories both at global and local scales. Our results are in good qualitative agreement with this study and with a more recent analysis of the meridional overturning climate trajectory (Caesar et al. 2021).

To elaborate on the previous statement, we emphasize that the in situ data analysis shows a persistent, albeit slow, multidecadal warming trend in the Gulf of Maine and surrounding areas. This analysis also indicates that in the last decade, the warming in this region, especially in the slope water system, intensified at a faster rate than ever before. Likewise, the decade of 2005–2017 has undergone an unprecedented northward excursion of warm near-surface Gulf Stream water in summer. These results are consistent with both modeling and climate-data analyses. However, there is yet no clear sign that this behavior will either persist, further accelerate, or noticeably diminish in the next decade and beyond. Figures 5–7 show that the steep uprise of temperature in the past warming did not persist long enough to become warming runaways. On the other hand, there is one important indication that the current situation may be different and can potentially become a warming runaway. The last decade witnessed an "abnormal" behavior of the Gulf Stream, which did not occur during previous ~ 50 years. This abnormality is clearly seen after 2005 in near-surface layers in summer and below 150–200 m depth year-round, which is coincident with fast warming in the gulf and slope water. The question of whether the abnormal Gulf Stream dynamics and the steep recent warming will persist, perhaps forming a positive feedback loop, and thus causing a warming runaway, needs to be addressed in a more comprehensive study employing oceanographic analysis combined with numerical forecast.

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Acknowledgments

We want to thank the scientists, technicians, data centers staff, and data managers for their contributions to the IOC/IODE, ICSU/World Data System, and NOAA/NCEI Ocean Archive System, which provided a foundation of in situ oceanographic data for this study. We are thankful to Sydney Levitus (retired, formerly of NOAA/NCEI) for his pioneering work on the World Ocean Climatology that initiated all subsequent efforts in building World Ocean Database and all ocean climatologies founded on this database. We are grateful to Arthur Mariano of the University of Miami for granting permission for reproducing the maps of surface currents and providing high-resolution graphics. We also thank our colleagues at NOAA/NCEI for many years of data processing and constructing the World Ocean Database and World Ocean Atlas and especially to Tim Boyer for his leadership role in the World Ocean Database project. We are grateful to James Reagan of NOAA/NCEI who helped to improve the text. We are very thankful to two anonymous reviewers and an Associate Editor of Limnology and Oceanography, for their useful and insightful comments and suggestions. This study was partially supported by NOAA NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies—CISESS) at the University of Maryland/ESSIC. Further support was provided by NOAA's Climate Program Office's Ocean Observing and Monitoring Division. The data and maps described in this paper are publicly available at https://www.ncei.noaa.gov/products/world-ocean-database and https://oceancurrents.rsmas.miami.edu/index.html. The views, opinions, and findings in this report are those of the authors and should not be construed as an official NOAA or US Government position, policy, or decision.

Conflict of Interest

None declared.

Submitted 25 January 2021
Revised 26 June 2021
Accepted 28 June 2021

Associate editor: Maitane Olabarrieta