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Labrador Slope Water connects the subarctic with the Gulf Stream

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28 July 2021A L New^{1,*} , D A Smeed¹ , A Czaja² , A T Blaker¹ , J V Mecking¹ , J P Mathews² 
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E-mail: A.New@noc.ac.uk**Keywords:** Labrador Slope Water, Slope Sea, Gulf Stream, Atlantic Meridional Overturning Circulation, climate variabilitySupplementary material for this article is available [online](#)Original content from
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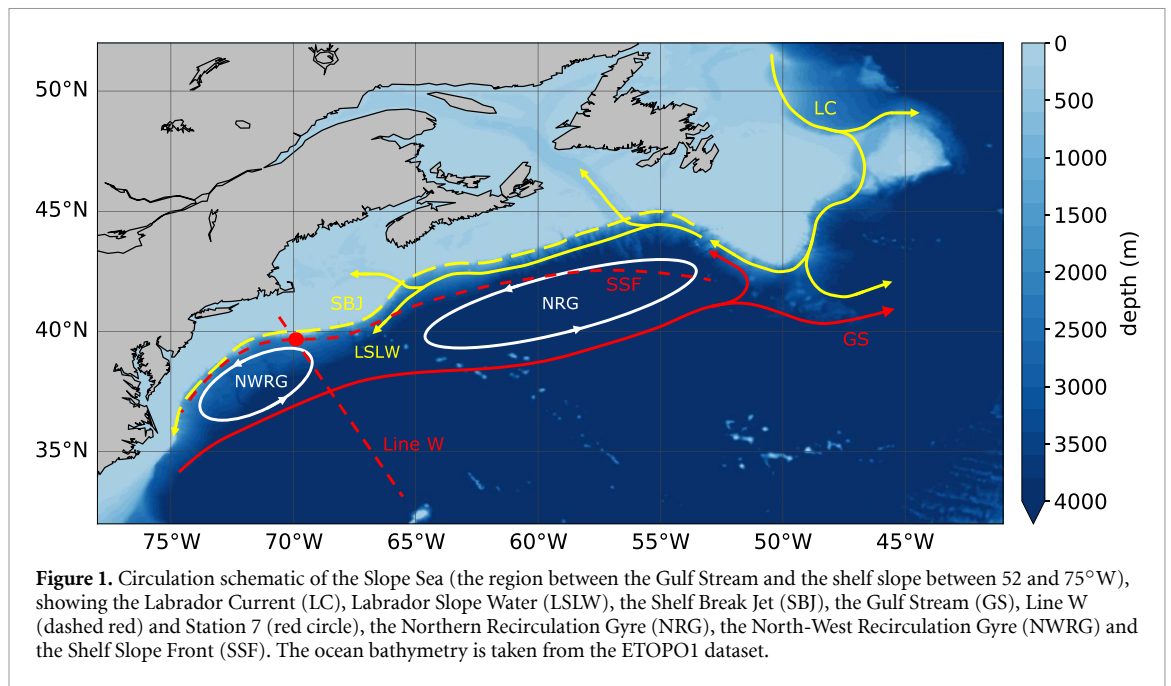
Labrador Slope Water (LSLW) is a relatively fresh and cool water mass that originates from the Labrador Current in the subarctic and is known to occur in the Eastern Slope Sea on the US-Canadian shelf-slope north of the Gulf Stream. It has potential densities of $27.4\text{--}27.65\text{ kg m}^{-3}$. Using ocean observations, we show here that the LSLW penetrates as a boundary current deeply into the Western Slope Sea (west of 66°W) as a salinity minimum between 400 and 600 m, bringing it into close proximity with the Gulf Stream. The LSLW at Line W (near 69°W) also spreads across, and brings fresher and thicker waters to, the Slope Sea north of the Gulf Stream. A high-resolution ocean model simulation shows that the spreading of the LSLW occurs throughout the entire Slope Sea through the extrusion of fine-scale filaments from the boundary current following interaction with Gulf Stream meanders and eddies. At Line W, the LSLW is also found to be fresher and thicker between 2003 and 2008, when the Atlantic Meridional Overturning Circulation (AMOC) at 26°N is higher (by 3 Sv), and the Shelf Slope Front is further south (by 0.7°), compared to AMOC low conditions in 2009–2014. The thicker LSLW causes lighter isopycnals to rise over the shelf slope, and through increasing the lateral density gradient contributes an additional 1.3 Sv to the Gulf Stream transport. These changes to the LSLW and the Shelf Slope Front are likely to result from an enhanced flow of the Labrador Current into the Slope Sea, caused by changes in the wind stress in the subpolar gyre. The transport of the LSLW (as opposed to the deeper Labrador Sea Water) thereby offers a potential new mechanism for decadal variability in the Atlantic climate system, through connecting changes in the subarctic with subsequent variability in the Gulf Stream and AMOC.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) carries warm, salty near-surface waters northwards, a major component of this being the Gulf Stream, and cooler, fresher deeper waters southwards, particularly in the Deep Western Boundary Current (DWBC), the whole being a key component of the climate system (e.g. Smeed *et al* 2018). As such, it is critical to better understand the mechanisms that regulate its variability.

The Slope Sea (figure 1) is found between the Gulf Stream and the shelf-slope west of the Tail of

the Grand Banks (TGB). The upper waters of the Eastern Slope Sea ($52\text{--}66^\circ\text{W}$) consist of Warm Slope Water in the upper 300 m immediately north of the Gulf Stream and overlying North Atlantic Central Water, and the fresher Labrador Slope Water (LSLW) near the shelf slope (Gatien 1976, Fratantoni and Pickart 2007). The LSLW has a core potential density (referenced to the surface, σ_0 , used throughout the present study) near 27.5 kg m^{-3} , and at 65°W is centred between 400 and 800 m, below the even fresher Coastal Water in the upper 50–100 m. The Coastal Water extends from the shelf into the Slope Sea, and the boundary between it and the Warm Slope



Water denotes the Shelf-Slope Front (Peterson *et al* 2017). The Warm Slope Water flows eastwards with the Gulf Stream, while the LSLW moves westward along the slope (Gatien 1976). This circulation may be viewed as a component of the Northern Recirculation Gyre (Hogg *et al* 1986), a barotropic cyclonic cell in the Eastern Slope Sea. A pronounced cyclonic cell is also found in the Western Slope Sea (66–75°W), which we here call the North-West Recirculation Gyre (Csanady and Hamilton 1988, Andres *et al* 2020).

The LSLW derives its (cold, fresh) core properties from the Labrador Current in the subarctic region of the Labrador Sea. The Labrador Current system has an inshore branch exiting the Hudson Strait (which flows over the Grand Banks and continues as the Nova Scotia Current, Rossby 1999, Townsend *et al* 2015) and a further core (the LC) on the upper Labrador shelf-slope, comprising waters from the Davis Strait and (slightly more saline) the West Greenland Current (Florindo-López *et al* 2020). The LC flows southwards and partially rounds the TGB into the Slope Sea (figure 1), where it continues as the Shelf Break Jet, or Labrador Current Extension, in the upper 200 m, through the entire Western Slope Sea (Flagg *et al* 2006, Fratantoni and Pickart 2007). The inflowing LC water also mixes with the (warmer and more saline) North Atlantic Central Water and forms the origins of the LSLW in the Slope Sea (Gatien 1976, Petrie and Drinkwater 1993). The LSLW is thereby distinct from the deeper Labrador Sea Water (LSW), which instead forms through open ocean convection in the subpolar gyre (McCartney and Talley 1982).

Below the LSLW in the Slope Sea, the DWBC carries the LSW (with neutral densities greater than 27.8 kg m^{-3} , equivalent to σ_0 greater than 27.68 kg m^{-3}) and deeper waters westwards (e.g.

Talley and McCartney 1982). Indeed, Csanady and Hamilton (1988) describe the circulation of the deeper waters in the Slope Sea (below 500 m and colder than 6°C) as a southwestward flow as far as the Gulf Stream, labelling this as Labrador Basin Water. Through reference to Richardson (1977), McCartney and Talley (1982), and Talley and McCartney (1982), it is clear that this is essentially the LSW. However, Richardson (1977) shows a section at Cape Hatteras in which there is a minimum in the salinity anomaly (when compared with mean western North Atlantic conditions) on the slopes between 400 and 1000 m which could indicate the presence of the LSLW here as well as the LSW, although this was not made explicit. Finally, the DWBC has traditionally been thought of as a continuous boundary current from the subpolar gyre, and the main conduit for the AMOC southward return flow (Watts 1991, Joyce *et al* 2005, Gary *et al* 2011, Peña-Molino *et al* 2011). However, recent float and tracer studies (Bower *et al* 2009, 2011, Smith *et al* 2016) and modelling investigations (Gary *et al* 2011) have challenged this view, showing instead the importance of an interior route through the Newfoundland Basin for these waters.

Freshening, cooling and an increased prevalence of LSLW in the Eastern Slope Sea would be expected to result from an enhanced flow of the LC into the Slope Sea (Petrie and Drinkwater 1993). This in turn may result from a high AMOC, which could be associated with increased DWBC transport and vortex stretching near the TGB, leading to a strengthening and expansion of the Northern Recirculation Gyre and a more southerly Gulf Stream in the Eastern Slope Sea (Zhang and Vallis 2007). This may then lead to freshening of the LSLW in the bottom waters

of the Laurentian Channel, the Scotian Shelf and the Gulf of Maine (Saba *et al* 2016, Thibodeau *et al* 2018) and higher levels of nutrients and oxygen in the near surface waters (Sanchez-Franks and Zhang 2015, Claret *et al* 2018). Alternatively, larger inflows of the LC may result from a southward shift of wind stress patterns in the subpolar gyre, again resulting in cooling and freshening in the Eastern Slope Sea (Peterson *et al* 2017, Holliday *et al* 2020). An increasing proportion of LSLW in the Gulf of Maine may also result from decreases in either the Nova Scotia Current (Townsend *et al* 2015) or a shift from a positive to a negative phase of the North Atlantic Oscillation (NAO, Mountain 2012). This latter relationship is supported by Marsh (2000), who forced a 1° ocean model with extreme negative NAO conditions (in which the Icelandic Low was typically further to the southwest), resulting in the subpolar gyre expanding to the south, which in turn allowed an enhanced flow of Labrador Current waters westwards from the Grand Banks, and cooling in the Eastern Slope Sea.

Consequently, while the focus of the above studies has been on the Eastern Slope Sea, the presence of the LSLW in the Western Slope Sea has so far been largely undocumented. We therefore examine here the penetration of the LSLW into the Western Slope Sea, how its characteristics change between recent AMOC high and low periods, and its impact on the Gulf Stream.

2. Methods and data

We use the EN4.2.1 dataset, which provides monthly gridded objective analyses of available ocean observations at 1° resolution (Good *et al* 2013). Profiles with density inversions which are thought to be spurious and related to anomalously cold water at 657 m are removed from our analysis. Furthermore, EN4 profiles are derived through averaging on constant depth levels, and are subject to biases similar to those reported by Lozier *et al* (1994) in the Levitus climatology (Levitus 1982). These biases are largest in frontal regions where the isopycnals slope steeply such as the Gulf Stream, and result in water which is too warm and saline on intermediate-depth isopycnals. However, while EN4 cannot therefore be used for isopycnal analysis in the Gulf Stream core, it may be employed to examine the mean structure of the LSLW along the shelf slope where the isopycnals are relatively flat. These issues are described more fully in the supplementary material (available online at stacks.iop.org/ERL/16/084019/mmedia).

We also use the Line W hydrographic observations near 69°W (e.g. Joyce *et al* 2005). The Line passes through the Western Slope Sea, extending from Cape Cod towards Bermuda (figure 1), and provides full-depth high-quality hydrographic observations at fixed station positions between 1994 and 2014. Here, we employ water mass analysis, commonly used in oceanography, that is, examination of

the relationship of the temperature (T) and salinity (S) of various water masses. Water masses form with different temperature and salinity in different parts of the ocean surface through interaction with atmospheric fluxes. These water masses are then drawn down into the ocean interior, recirculating over large distances. Here, since mixing is generally low, they tend to maintain their T/S properties quite well as they recirculate. Therefore, they can be easily distinguished in diagrams plotting their temperature against their salinity, usually by either minima or maxima in one or other of these properties.

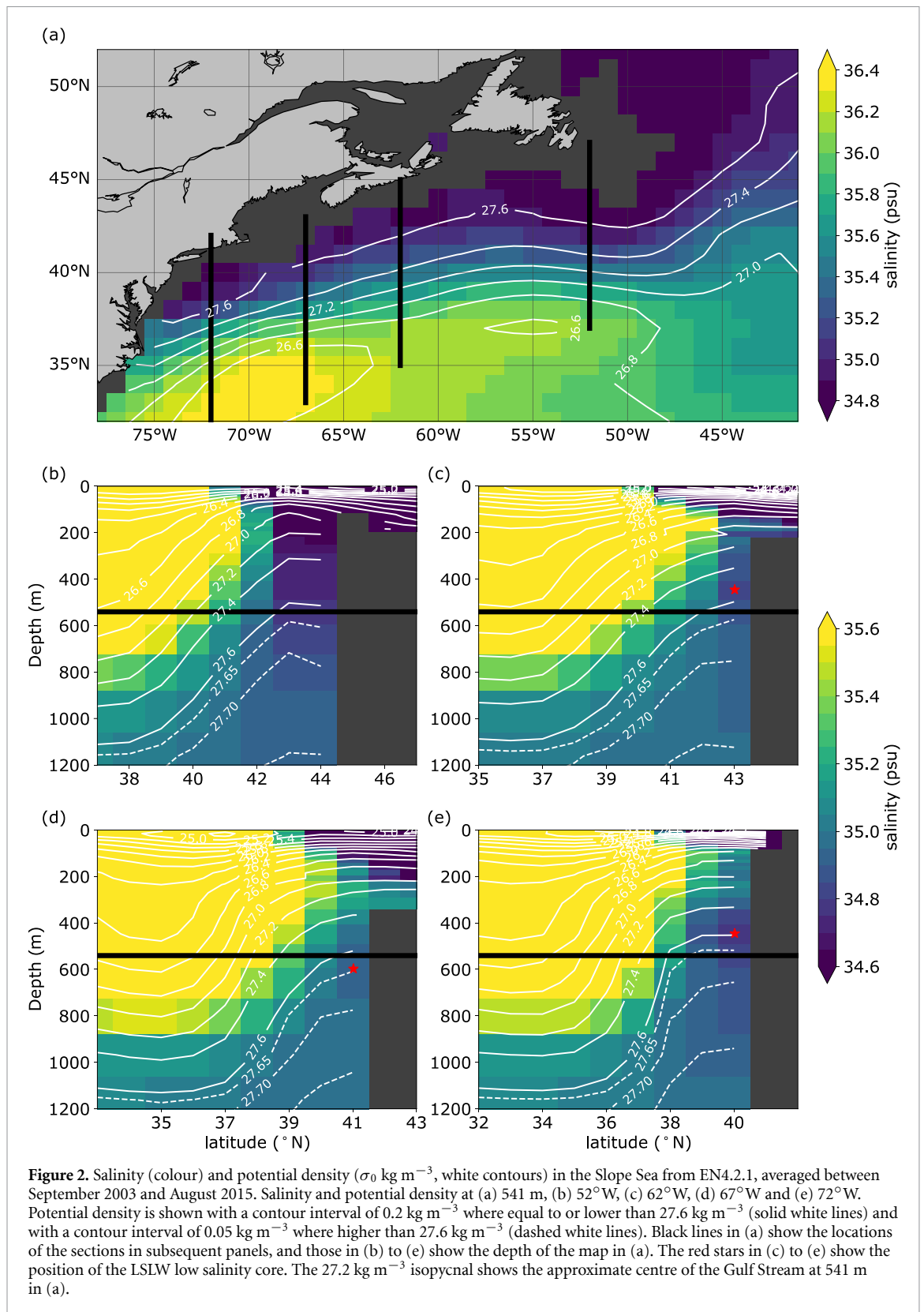
We also undertake analysis of the ERA5 monthly-averaged wind stress fields (Hersbach *et al* 2019), which provides an updated version of the ERA-interim fields, and with increased horizontal resolution (0.25° rather than approximately 0.75°).

Finally, we employ a global simulation with the NEMO (v3.2) ocean model (Madec 2008). With a horizontal resolution of $1/12^\circ$ and 75 levels in the vertical, the model resolves the details of the flow in the Slope Sea. Realistic bottom topography is interpolated from ETOPO2 (U.S. Department of Commerce 2006) and surface forcing is provided by DFS4.1 (Brodeau *et al* 2010). The simulation starts from rest and January climatological initial conditions for temperature and salinity, which are provided by the World Ocean Atlas 2005 (Antonov *et al* 2006, Locarnini *et al* 2006). This simulation shows a good representation of features that are important for this study, such as the subpolar gyre and the Gulf Stream (Marzocchi *et al* 2015).

3. Westward penetration

The mean intermediate-depth water column salinity structure in EN4.2.1 is now examined between September 2003 and August 2015 (a whole number of years to remove any seasonal bias). Figure 2(a) shows the salinity at 541 m, this being close to the depth of the core of the LSLW. The fresh LSLW (with salinity below 35.2 and density near 27.6 kg m^{-3}) extends as a boundary current around the TGB and into the Western Slope Sea as far as Cape Hatteras. It also spreads southwards as far as the centre of the Gulf Stream over the entire Slope Sea (e.g. the fresher waters extending southwards to the 27.2 kg m^{-3} isopycnal).

At 52°W , the LC appears as the broad (2° wide) fresh region nearest the slope and extending to 600 m with salinities below 34.9 and densities less than 27.65 kg m^{-3} (figure 2(b)). This structure is similar to that at 46°N before the LC has rounded the TGB (though extending only to 300 m there) and at 57°W near the Laurentian Channel (not shown). Further west, the LSLW at 62°W (figure 2(c)) appears as a distinct low salinity core between 400 and 600 m above the shelf slope (marked by the red star at 43°N), and with densities of $27.4\text{--}27.65 \text{ kg m}^{-3}$, but

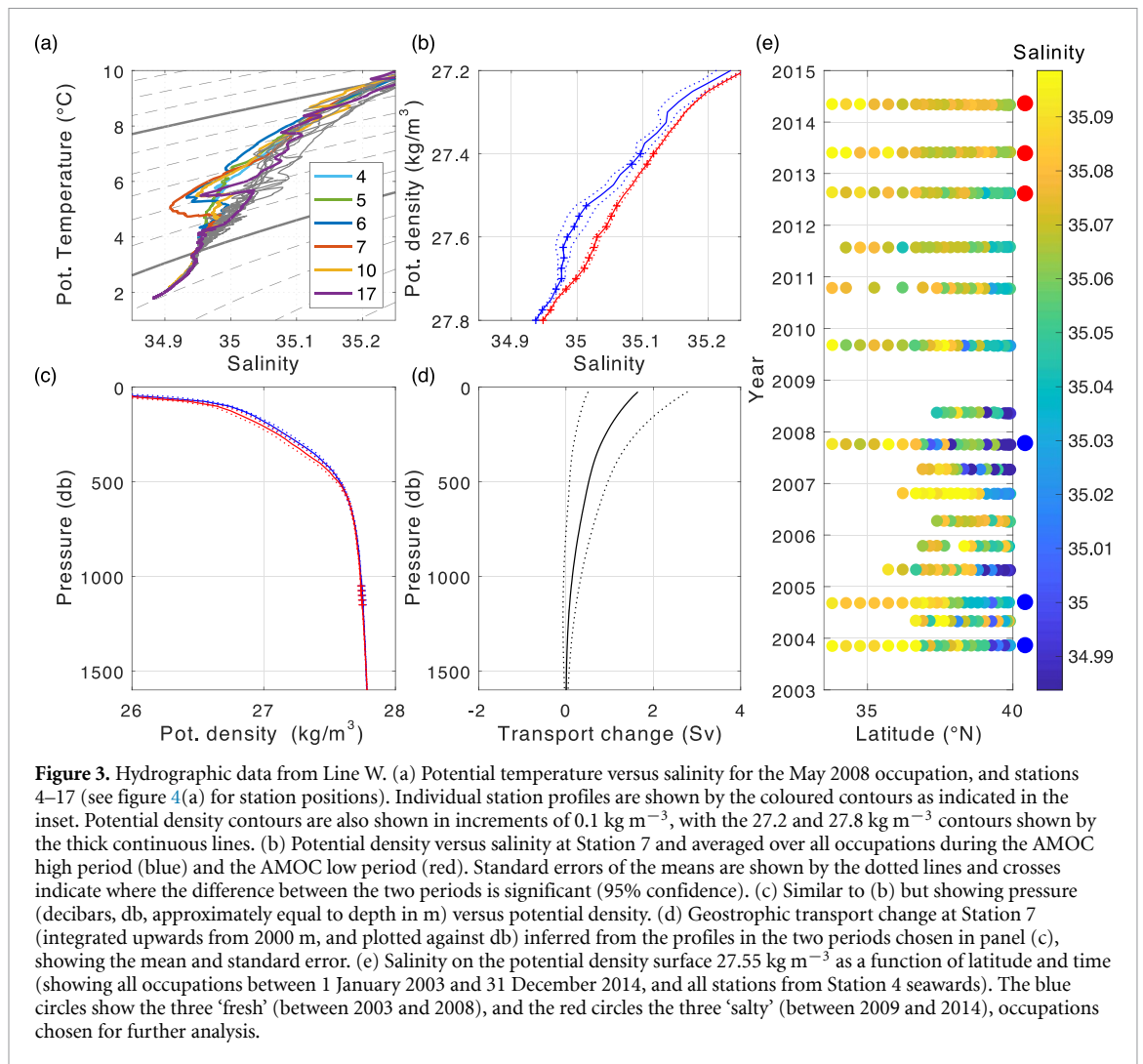


is here only 1° wide. The Warm Slope Water is indicated by the yellow colours immediately to the south in the upper 300–400 m, and the Coastal Water by the freshest waters in the upper 100 m above the shelf and slope. The structure is similar at 67 and 72°W (figures 2(d) and (e)), with an easily identifiable LSLW salinity minimum, clearly showing that the

LSLW has penetrated deeply into the Western Slope Sea.

4. Variability and links to the AMOC

We now discuss the Line W observations between September 2003 and August 2014. By analogy with



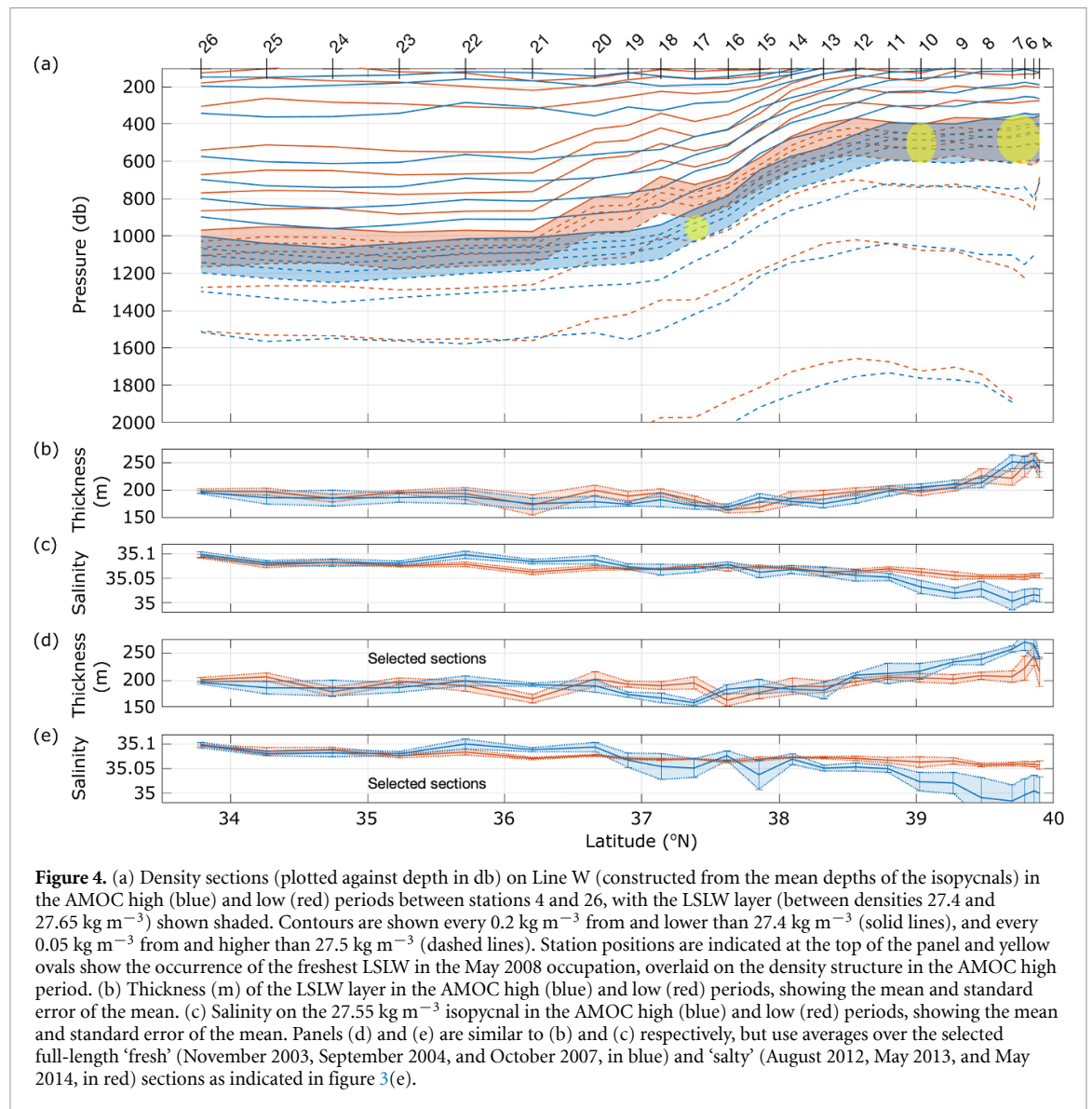
Smeed *et al* (2018), who reported a reduction in the AMOC of about 3 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) as measured by the RAPID array at 26°N from 2008, we refer to September 2003–August 2008 as the AMOC high period, and to September 2008–August 2014 as the AMOC low, these being complete numbers of years to reduce seasonal biases. With reference to figure 3(e), which shows when the occupations occur, we consider these periods to represent 2003–2008 and 2009–2014 respectively.

Figure 3(a) presents the Temperature/Salinity curves from stations 4–17 (which extend seaward from the shelf break with increasing station number, see figure 4(a) for the May 2008 survey). The LSLW is the salinity minima between temperatures of 4.5°C and 7°C and densities of 27.4 and 27.65 kg m^{-3} . This occurs in stations 4–7 on the upper slopes, being most pronounced at station 7, where the water depth is about 2000 m. It is then absent in stations 8 and 9 but, surprisingly, re-appears at both stations 10 and 17 but not at the intervening stations. At station 17, the LSLW penetrates deeply (to near 1000 m, see figure 4(a)) and occurs underneath and southwards

of the centre of the Gulf Stream. The LSLW therefore appears primarily as a boundary current (supported by Toole *et al* 2011) with a core at station 7, but also occurs intermittently across the entire North-West Recirculation Gyre.

Figure 3(b) shows the mean salinity at station 7 during the AMOC high and low periods. The LSLW salinity minimum is only found in occupations during the AMOC high period (though not in every occupation), but is not found at all during the AMOC low period. This results in the low salinity bulge near 27.55 kg m^{-3} in the AMOC high period, which is absent in the AMOC low. We therefore define the LSLW to be centred on the 27.55 kg m^{-3} isopycnal, but to occupy densities between 27.4 and 27.65 kg m^{-3} (which also avoids overlap with the LSW).

This LSLW is also thicker at station 7 in the AMOC high period (see figure 4) and this results in the uplift of all isopycnals above the LSLW core, figure 3(c). The geostrophic transport calculated between the density profiles in the AMOC high and low periods will be the same as the transport difference between each profile and some arbitrary profile

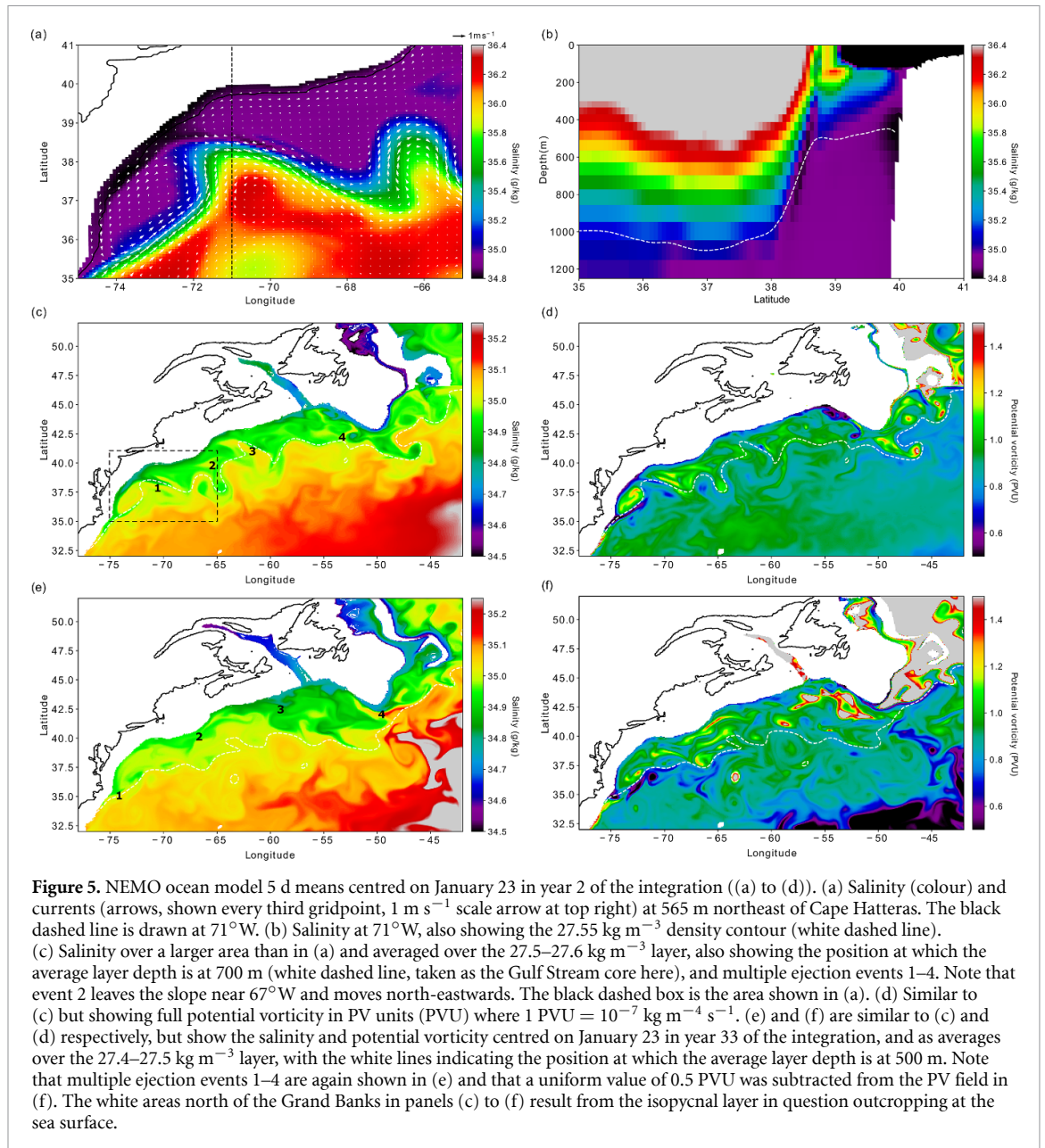


on the southern side of the Gulf Stream, and so will give the transport change across the Gulf Stream due to the changes at station 7. The result of this calculation, integrated upwards from 2000 m, figure 3(d), shows that this contributes an increase of 1.3 Sv in Gulf Stream transport (i.e the change above 600 m), nearly half of the AMOC change reported by Smeed *et al* (2018) at 26°N. While the role of the DWBC waters cannot be entirely discounted, note that the transport change below 600 m is relatively small.

Figure 3(e) shows the salinity on the 27.55 kg m⁻³ isopycnal for every occupation in our time window. The LSLW is generally fresher north of the Gulf Stream core (near 37.7°N, figure 4), and is freshest nearest the shelf (39–40°N). There is also a striking change from 2008, between fresher varieties during the AMOC high period and more saline varieties during the AMOC low. During the AMOC high there are actually two shorter periods of particularly fresh LSLW, with a more saline variety around 2006. The influx of the freshest LSLW to the Western

Slope Sea therefore occurs episodically. After 2009, the LSLW shows a gradual salinification up until 2013–2014, indicating a slowly reducing input of the fresher waters from the northeast. Also, in most of the occupations, the freshest LSLW occurs intermittently across the North-West Recirculation Gyre, as already noted for May 2008.

Figure 4 shows the mean density structure for the AMOC high and low periods. The downward slope of the isopycnals between 38.5 and 36.5°N shows the Gulf Stream core, and the LSLW layer is shown shaded, together with the locations of the freshest occurrences in May 2008. The LSLW layer descends from 400 to 600 m on the northern side of the Gulf Stream, to 1000–1200 m on its southern side. It is always thickest near the slope and decreases in thickness to 38°N, after which it does not vary greatly, figure 4(b). At station 7, the LSLW increases from 220 m thickness at AMOC low, to 250 m at AMOC high, and this forces all the lighter isopycnals to shallow similarly (figures 4(a) and 3(c)). During



the AMOC high, the LSLW is also markedly fresher from the slope to 38.5°N , with diminishing effect across the gyre, figure 4(c). This, together with the decreasing thickness across the gyre, is indicative (in the mean) of a source of thick and fresh LSLW on the upper slopes, and spreading across the entire Slope Sea. A plausible explanation for this and the intermittency of the LSLW in individual occupations is LSLW filaments being drawn out of the boundary current by Gulf Stream meanders or eddies and then mixed isopycnally within the gyre.

Figures 4(d) and (e) are similar to figures 4(b) and (c) but now show averages over three fresh full-length occupations in the AMOC high period, and three full-length saline occupations in the AMOC low (see the blue and red circles, respectively, in figure 3(e)). The effects previously described are increased dramatically with the fresh sections being markedly fresher and

thicker between 39 and 40°N than the mean of the AMOC high period. This correlation is investigated further in the supplementary material.

5. Ejection of filaments

In the NEMO simulation, the LSLW, present in the initial state, flows southwestwards along the slope towards Cape Hatteras and quickly forms filaments which are pulled out into the Slope Sea. Figure 5(a) shows one such event in the Western Slope Sea at the start of the second year of integration at 565 m. An extrusion has formed between 73 and 69°W near 38.5°N (see the black shades) through interaction with a Gulf Stream meander which has an eastward flow. Figure 5(b) at 71°W shows that the filament extends deeply to 1000 m as it meets the Gulf Stream core at 38.5°N . The two are interacting strongly, with

the filament providing fresh and dense water into the system, and being associated with the steep rise in the 27.55 kg m^{-3} isopycnal. The similarity with the irregular occurrences of the LSLW at Line W suggests these filaments are a plausible mechanism to explain the observations.

In the supplementary material, a sequence of events centred on that shown in figure 5(a) is examined. There we see how ‘upward/downward’ dipoles are co-located with northward/southward (or ‘coldward/warmward’) motion in the meanders, as highlighted in previous studies with simpler models (e.g. Gill 1982, Flierl and Davis 1993). An idealised model is also described which suggests that these dipoles are solidly rooted in quasi-geostrophic dynamics. The ejection event here is thus interpreted as the southeastward and downward entrainment of a fresh slope-origin water mass in the ‘warmward’ sector of a Gulf Stream meander. The deep extent of this motion is striking, with the filament descending (see figure S3(b)) into and under the Gulf Stream, reflecting the similar occurrence at Line W in figure 4(a).

Figure 5(c) presents salinity on the LSLW density surface (averaged over the $27.5\text{--}27.6 \text{ kg m}^{-3}$ layer) over a wider area. The LC is the fresh boundary current extending around the TGB, and providing the source for the LSLW as it continues through the entire Slope Sea (with generally increasing salinity). We identify four concurrent ejection events, all transporting fresh LSLW away from the slope, and caused by interaction of Gulf Stream meanders or eddies with the boundary current as in figure 5(a) (which is event number 1 here). These extrusions reduce the salinity of the entire Slope Sea as far as the Gulf Stream (dashed white line). Figure 5(d) shows the full potential vorticity (PV) for this layer. (PV is essentially inverse layer thickness, modified by the inclusion of all the relative vorticity terms relevant in NEMO, see White *et al* 2005, and in the absence of mixing this is conserved following the circulation). The LSLW on the slope is a region of generally low PV (being somewhat thicker here) and the extrusions carry this low PV water into the interior of the Slope Sea, acting to reduce the PV there, as well as its salinity. The region of low PV on the western side of the TGB could indicate a possible source of the LSLW in the Slope Sea (through mixing either with topography, or with Gulf Stream eddies which in NEMO propagate northwestwards here, as indicated in figure 1). A further low PV region penetrates to Cape Hatteras and retroflects to the northeast, possibly affecting Gulf Stream separation. These features require further investigation.

To contrast model differences between AMOC high and low states, figures 5(e) and (f) are similar to panels (c) and (d) but show the situation in January of year 33 (the final year) of the integration rather than in year 2, when the AMOC (at 26.5°N) has reduced from 13.2 Sv (in January of year 2) to 7.4 Sv. The LSLW is still found as a salinity minimum on the

shelf slopes in the Slope Sea, but with a core on a slightly lighter density surface, 27.45 kg m^{-3} rather than 27.55 kg m^{-3} , so that figures 5(e) and (f) are representative of this change. The LSLW still appears as a low salinity, low PV boundary current extending to, and retroflecting at, Cape Hatteras, and filaments of the LSLW, comprising this low salinity, low PV water, are still apparent (marked as 1–4) being drawn out from the boundary current, though perhaps marginally less well pronounced than in year 2. This may be because the Gulf Stream meanders (indicated by the white dashed lines) are further from the slopes at this time. We also remark that while a full investigation is beyond the scope of the present study, a comparison of these two snapshots does show fresher and thicker (lower PV) LSLW in the Western Slope Sea when the AMOC is higher (especially noting that a uniform value of 0.5 PVU has been subtracted in panel (f)), in agreement with the observational results above.

6. Summary and discussion

LSLW (of densities $27.4\text{--}27.65 \text{ kg m}^{-3}$) has its origins on the Labrador shelf in the subarctic, and in the Slope Sea is an intermediate depth water mass above the LSW. We have shown that the LSLW penetrates deeply into the Western Slope Sea as a boundary current where it is characterised by a salinity minimum between 400 and 600 m on the slopes, and where it interacts strongly with the Gulf Stream. The LSLW is relatively thick and fresh during the recent AMOC high period (2003–08), compared with the following AMOC low period (2009–14). This thickening lifts up the isopycnals in the upper 600 m on the slope, and increases the density gradient across the Gulf Stream, contributing an additional 1.3 Sv to its transport. The LSLW is also drawn out from the boundary current in extrusions, caused by Gulf Stream meanders or eddies, bringing fresher and lower PV water to the whole Slope Sea in this density layer.

Our study has focussed on the impacts of the LSLW in the Western Slope Sea. However, it is clear that periods of thicker LSLW propagate along the shelf-slope and must first transit the Eastern Slope Sea. Given that there is no additional source of the LSLW along this pathway, we would expect the impact of the LSLW on the Gulf Stream transport and AMOC here to be just as large as in the Western Slope Sea, and possibly even larger given that the continued mixing away from the boundary in the filaments as the LSLW travels southwestwards would tend to lessen the LSLW thickening with distance travelled, and hence its impact on the AMOC. However, as there are no observations similar to Line W in the Eastern Slope Sea, we are unable to investigate this aspect further here.

It has long been known that the Gulf Stream position is affected by the (winter) NAO, the prin-

cial mode of atmospheric variability in the North Atlantic) index, with a high NAO being associated with a northerly position of the Gulf Stream, with a lag of either 2 years (Taylor and Stephens 1998) or occurring simultaneously (Joyce *et al* 2000). In particular, the Icelandic Low component of the NAO is likely to have a dominant influence over the position of the Gulf Stream, in contrast to the Azores High, suggesting variability in the transport of waters from the Labrador region into the Slope Sea provides the important control over the Gulf Stream position (Sanchez-Franks *et al* 2016). The connection between the NAO and the Gulf Stream is apparent in figure 4, in that the Gulf Stream at Line W is further north during 2003–2008 than during 2009–2014 (the 26.6 kg m^{-3} isopycnal at 200 m, close to the 15°C isotherm, moving from 38.4 to 38.0°N between these periods), together with the observation that the NAO is neutral during the former period and negative during the latter (Robson *et al* 2018). We also note in figure 4 the increased thickening between the density surfaces 26.2 – 26.6 kg m^{-3} between 34 and 36.5°N during the AMOC high, implying lower PV in the Subtropical Mode Water when the Gulf Stream is further north. Although this is counter to the finding of Joyce *et al* (2000), their result describes the PV changes near Bermuda (33°N) and at 300 m depth.

The realisation that the NAO and Gulf Stream position co-vary led Joyce *et al* (2000) to propose a mechanism for decadal climate variability in the North Atlantic. When the NAO is high, the winds in the subpolar gyre are strong, leading to enhanced cooling and open ocean convection in the Labrador Sea. This produces an enhanced southward flow of the LSW which is entrained into the DWBC and transported along the slopes to the Gulf Stream separation region. Here, the two currents interact, with the DWBC passing below the Gulf Stream, but with the additional LSW pushing the Gulf Stream into a more southerly position. This southward movement would, through changes in the sea-surface temperature and air-sea fluxes, then cause a reduction in the NAO (as these are observed to co-vary), resulting in a lessening of LSW production and a reversal of the cycle. This was shown by Joyce *et al* (2000) to lead to cycles on the decadal timescale.

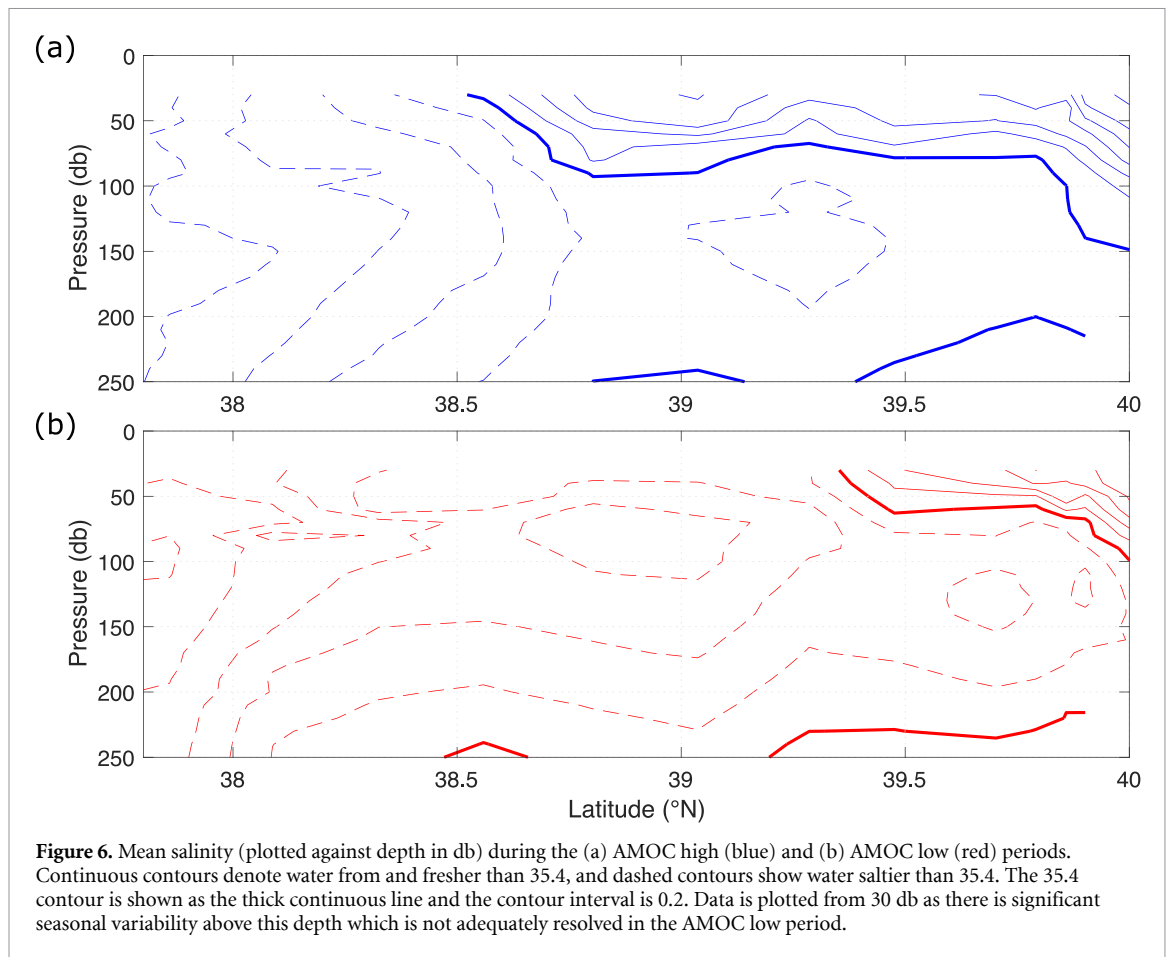
Other mechanisms affecting decadal variability have been proposed which involve changes in the Gulf Stream transport rather than its position. Robson *et al* (2014) proposed that increases in the LSW density would propagate along the western boundary and act to increase the east-west density gradient across the Gulf Stream, increasing its transport and the AMOC. The subsequent increased northward heat transport would warm the subpolar gyre, causing a reduction of the LSW density and a reversal of the cycle. Similarly, Menary *et al* (2015) described several modelling studies which involved variations in the LSW leading to deep anomalies propagating along the

western boundary, and then to subsequent changes in the northward ocean circulation and heat transport, leading finally to changes in the Labrador Sea and a reversal of the cycle. In these studies, a positive feedback was also often found to occur between the NAO and the sea-surface temperatures in the subpolar gyre which amplified the mode. Depending on the model studied, cycles arose with timescales of between 10 and 50 years.

We now address the question as to whether the LSLW could play a similar role in decadal cycling in the North Atlantic as outlined above for the deeper LSW, remembering that observations do not strongly support such a role for the LSW. Firstly, we remark that we have established here a strong presence of the LSLW throughout the Slope Sea. Secondly, temperature-salinity analysis (Petrie and Drinkwater 1993) clearly shows that the LSLW derives its cold, fresh properties from the Labrador Current on the Labrador and Newfoundland Shelves. There is therefore a direct observational connection for the LSLW between these two regions (supported by the model results in figure 5).

Peterson *et al* (2017) then suggest that a stronger flow of LC water westwards from the TGB is caused by a southward shift of the Zero Wind stress Curl Line (ZWCL) near 40°W (and 40°N), whereas the Gulf Stream position is instead related to wind stress changes linked to the NAO further to the north-east. They also invoke such an enhanced LC inflow to explain a cooling event in the upper 650 m on the Nova Scotia shelf and slope between 2004 and 2009, and relate this to a more southerly position of the Shelf Slope Front rather than to any shift in the Gulf Stream. Figure 6 shows that the Shelf Slope Front in our study, denoted by the offshore boundary of the fresh Coastal Water in the upper layer (with salinity below 35.4), is indeed further southwards (and extends more deeply) when the LSLW is fresher between 2003 and 2008 than during 2009–14. This both supports the conclusion of Peterson *et al* (2017), and shows that the Shelf Slope Front is further south at the same time as the LSLW is fresher. Indeed, Peña-Molino and Joyce (2008) find that fresher and cooler water occur in phase, together with enhanced south-westward flow, in the upper 1000–1500 m over the slopes at Line W during 2003–2006. We conclude that enhanced inflows of LC water into the Slope Sea would simultaneously feed both the Shelf Break Jet and thereby enhanced volumes of Coastal Water spilling southwards into the Shelf Slope Front, and the LSLW, causing them both to experience cooling and freshening concurrently.

Similarly, Holliday *et al* (2020) propose a wind-stress induced alternation between freshening events west of the TGB, and in the eastern North Atlantic, depending on whether the LC is steered more strongly to the southwest or to the east at the Grand Banks. They analyse wind stress patterns from the



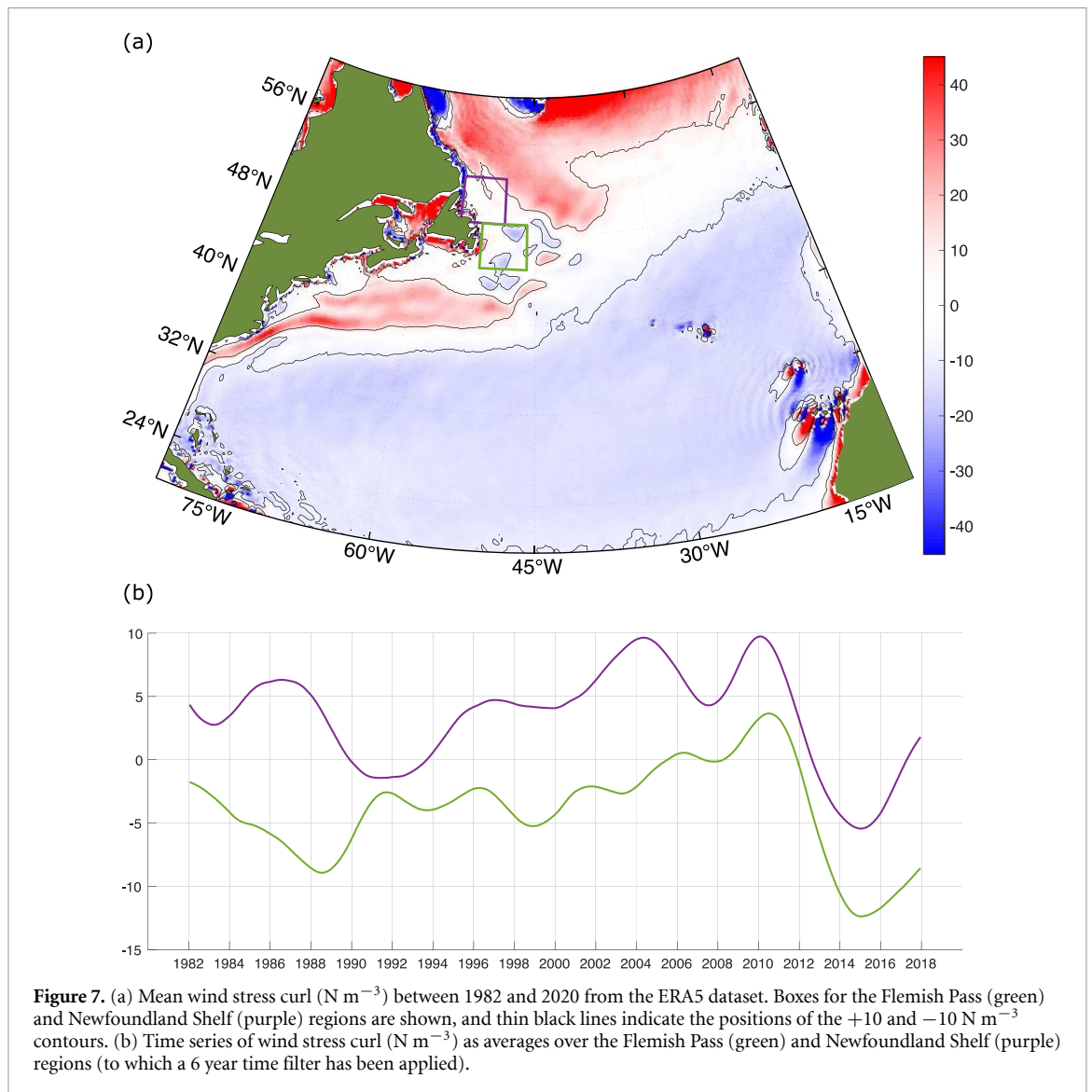
ERA-interim dataset, and show a switch from positive to negative wind stress curl in the Newfoundland shelf region (just north of the Grand Banks) from about 2012, associated with a northward shift of the ZWCL here, leading to a greater transport of LC waters off the shelf (due to enhanced Ekman transport) and into the northeast Atlantic. At the same time, there is correspondingly less LC water flowing into the Slope Sea, leading to an increased (upper layer) salinity there.

The key aspect in both Peterson *et al* (2017) and Holliday *et al* (2020) therefore seems to be whether the ZWCL is northwards or southwards of the Grand Banks region. We examine this further in figure 7. Figure 7(a) shows the mean wind stress curl between 1982 and 2020 in the ERA5 dataset, with a generally positive region in the subpolar gyre (north of about 48°N), and a negative region further south. Figure 7(b) then shows wind stress curl time-series in two key regions near the Grand Banks, these being directly over the Flemish Pass (the channel between the Flemish Cap and the Grand Banks through which the LC flows), and on the Newfoundland shelf just to the north. Between 2002 and 2010, the mean curl over the Newfoundland region is positive, but this then reduces rapidly between 2010 and 2012, becoming negative between 2012 and 2018. In the Flemish Pass region, the wind curl is close to zero in the former period, and strongly negative in the latter. It is

clear that the ZWCL has moved north between these two regions, between 2010 and 2012, with a region of negative curl extending further northwards along the Newfoundland shelf. From the above studies, this would be expected to reduce or terminate the flow of the fresh LC water into the Slope Sea between these times.

Consistent with these ideas (since ocean currents tend to follow the ZWCL line e.g. Marshall *et al* 2001), Gonçalves Neto *et al* (2021) find north-south shifts of the Gulf Stream near the TGB between 2008 and 2010, with a final northward shift occurring by 2011–2012, and that such northward shifts are accompanied by warming on the Scotian Shelf and Slope about a year later. They argue that the northward shift of the Gulf Stream acts to reduce the inflow of the LC waters into the Slope Sea, so causing the observed warming. They also show that the LSLW at the TGB becomes saltier and warmer at about the same time. In addition, a reduced inflow of the LSLW into the Slope Sea from about 2010 is consistent with Andres *et al* (2020) who show that the North-West and Northern Recirculation Gyres are stronger and better connected during 2004–08 than during 2010–14.

In terms of propagation timescales, Peterson *et al* (2017) obtain maximum correlations between the year-to-year changes in the Shelf Slope Front position and the wind curl (near 40°W) using a lag of



8 months. This is consistent with the 4–6 month timescale found by Peña-Molino and Joyce (2008) for sea-surface temperature anomalies to propagate from 60 to 75°W in the Slope Sea, and with an examination of the model in section 5, which shows that LSLW anomalies would take 9–12 months to travel from the Newfoundland Shelf to the Gulf Stream separation region. Furthermore, Gonçalves Neto *et al* (2021) found that the propagation of surface velocity anomalies from the TGB to 67°W takes about 10 months.

Finally, we remark that the expected reduction or termination of the flow of the fresh LC water into the Slope Sea from about 2010–2012 and the likely timescale of 10–12 months for changes to propagate between the Newfoundland Shelf and the Slope Sea, are completely consistent with the freshest LSLW at Line W (figure 3) occurring between 2003 and 2009, with the subsequent gradual salinification between 2010 and 2012, and with the most saline varieties occurring in 2013–2014 (indicating a possible cessation of the LSLW inflows then).

We therefore propose the LSLW transport as a new mechanism for connecting changes on the Labrador and Newfoundland Shelves in the subarctic with the Gulf Stream, and that such a connection is favoured when the ZWCL near the Grand Banks is sufficiently far southwards. This would allow an enhanced flow of the LC into the Slope Sea, leading to thicker and fresher LSLW, and an increased Gulf Stream transport and AMOC, about 10–12 months later. Further analysis of our model results also shows the Gulf Stream being pushed southwards into a good separation position just eastwards of Cape Hatteras when sufficient quantities of the LSLW reach this point. The increased flows of the LSLW could therefore result in either or both an increased Gulf Stream transport or a more southerly Gulf Stream position, and thereby take part in mechanisms similar to those proposed by either Joyce *et al* (2000), Robson *et al* (2014) or Menary *et al* (2015), but which rely instead on the deeper LSW. A full investigation of these ideas will be undertaken as a separate study in a very high-resolution climate model

with an ocean resolution similar to that used here (7.5 km), capable of resolving the processes involved (the models in the studies above using ocean resolutions of at best 25 km, insufficient to resolve such processes).

In summary, the LSLW, deriving its properties from the Labrador Current, itself influenced by flows from the Arctic through the Davis Strait, could therefore provide a new and alternative pathway (supported by observations) for connecting the subarctic with the Gulf Stream, and offer a potential new mechanism for decadal variability. It is now more important than ever to better understand such pathways and mechanisms, since enhanced future outflows of freshwater from the Arctic (particularly through the Canadian Arctic Archipelago into the Davis Strait) are likely to further freshen the Labrador Current and reduce the AMOC (Gervais *et al* 2018).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://scienceweb.who.edu/linew/index.php>.

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