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A multi-decadal meridional displacement of the Subpolar Front in the Newfoundland Basin

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Abstract

Observations since the 1950s show a multi-decadal cycle of a meridional displacement of the Subpolar Front (SPF) in the Newfoundland Basin (NFB) in the North Atlantic. The SPF displacement is associated with corresponding variations in the path of the North Atlantic Current. We use the ocean general circulation model MPIOM with enhanced horizontal and vertical resolutions and forced with NCEP/NCAR reanalysis data to study the relation of the SPF displacement to Labrador Sea Water (LSW) volume, atmospheric forcing and intensities of the Subpolar Gyre (SPG) and Meridional Overturning Circulation (MOC). The simulations indicate that the SPF displacement is associated with a circulation anomaly between the SPG and the subtropical gyre (STG), an inter-gyre gyre with a multi-decadal time scale. Contributions of wind stress curl (WSC) and LSW volume changes to the inter-gyre gyre are similar between 35 and 55° N (excluding the western boundary current). An anticyclonic inter-gyre gyre is related to negative WSC and LSW anomalies and to a SPF north of its climatological position, indicating an expanding STG. A cyclonic inter-gyre gyre is related to positive WSC and LSW anomalies and a SPF south of its climatological position, indicating an expanding SPG. Therefore, the mean latitudinal position of the SPF in the NFB could be an indicator of the amount of LSW in the inter-gyre region. Spreading of LSW anomalies intensifies the MOC, suggesting our SPF index as predictor of the MOC intensity at multi-decadal time scales. The meridional displacement of the SPF has a pronounced influence on the meridional heat transport, both on its gyre and overturning components.

1 Introduction

The Subpolar Front (SPF) separates the cold and less saline waters of the Subpolar Gyre (SPG) from the subtropical waters. It is associated with the North Atlantic Current (NAC), which transports warm and saline waters from the subtropics to the subpolar region. The SPG is a region of strong interaction between ocean and atmosphere that includes the formation of Labrador Sea Water (LSW) in the Labrador Sea. Mixing of LSW with dense Nordic Seas overflows forms North Atlantic Deep Water (NADW), feeding the lower branch of the Atlantic Meridional Overturning Circulation (MOC). Additionally, increased production of LSW intensifies the SPG strength and, therefore, an index of SPG variations could be used to monitor the overturning circulation in the subtropics (Böning et al., 2006).

At the decadal and longer time scales, the variability of the SPG has been found to be mainly driven by buoyancy fluxes modulated by the North Atlantic Oscillation (NAO; Eden and Jung, 2001): Changes from periods of lower to higher NAO index are associated with stronger westerlies and increase of latent and sensible heat fluxes from the ocean to the atmosphere over the SPG in winter (Cayan, 1992). This cooling intensifies the deep convection, forming LSW, and increasing the volume of intermediate water in the gyre's interior. Owing to these density changes, acceleration of the baroclinic component of the SPG has been observed one to two years after a switch to positive NAO (Curry and McCartney, 2001). Lagging the change to positive NAO by three years, the change of density structure of the SPG has been simulated to intensify also its barotropic component, due to coupling of the baroclinic structure and the barotropic mode (Eden and Willebrand, 2001). In agreement with these notions, Häkkinen and Rhines (2004) state that weakening of the SPG in the 1990s is not attributable to wind stress curl (WSC) changes but to decreasing buoyancy fluxes in the subpolar region.

While there is a rough agreement about the mechanisms ruling the SPG intensity, there is still ambiguity about the influence of these mechanisms on the SPG geometry, i.e., on displacements of the Subpolar Front. In response to a decreasing NAO, the isoline of zero WSC displaces southward, yielding a cyclonic circulation anomaly between the SPG and subtropical gyre (STG): an inter-gyre gyre (Marshall et al., 2001). Eden and Greatbatch, 2003 agree on the influence of the WSC on the formation of the inter-gyre gyre and state that it dominates the variability at interannual time scales. This circulation anomaly advects more cold subpolar water into the subtropical region

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in the Newfoundland Basin (NFB), displacing the SPF southwards, and more warm subtropical water into the subpolar region in the Eastern North Atlantic, displacing the SPF north-westwards (Eden and Willebrand, 2001). Consistently, Bersch et al. (1999) observed a westward displacement of the SPF in the Eastern North Atlantic during the 1990s as the NAO decreased. The impact of this front displacement on the volume transport of subtropical waters at the interannual to inter-decadal time scales has been discussed by Hátún et al. (2005). In the Western North Atlantic, a southward shift of the SPF at 55° W was observed between 1976 and 1977 when the NAO index dropped (McCartney et al., 1980). Displacements of the Gulf Stream axis between 50 and 70° W have been found to be in phase with the NAO (Joyce et al., 2000) or to follow it by 11 to 18 months (Frankignoul et al., 2001). Bersch (2002) observed a similar south-eastward displacement of the SPF in the NFB, 1.5 years after the drop of the NAO index during the 1990s.

SPF displacements at longer time scales, their causes and their impact on the meridional heat transport (MHT) have, so far, not been investigated in detail. The present study tries to fill this gap focusing on the multi-decadal variability in the subpolar region of the North Atlantic by using an extended database of hydrographic observations and ocean model simulations. This paper is structured as follows: In Sect. 2 we present the observational data and in Sect. 3 the model simulations and analysis methods. The simulated and observed multi-decadal SPF displacements during the last six decades are presented in Sect. 4. In Sect. 5.1 we contrast LSW spreading and changes of WSC to explain the multi-decadal SPF displacement in the NFB. In the following we discuss the relation between the meridional position of the SPF in the NFB and LSW volume (Sect. 5.2), MOC intensity (Sect. 5.3) and MHT (Sect. 5.4). In Sect. 6 we present a summary and the conclusions.

2 Observations

The observational data set from the CliSAP (Integrated Climate System Analysis and Prediction) data center used in this study consists of about 800 000 hydrographic stations with water samples and/or CTD measurements between 1950 and 2006 in the region of 30 to 70° N and 85° W to 10° E. Data sources are WOD05 (World Ocean Database 2005; Boyer et al., 2006), HydroBase2 (Curry, 2002), ICES (International Council for the Exploration of the Sea), WOCE (World Ocean Circulation Experiment), CLIVAR (Climate Variability and Predictability Programme), and others. Additionally, about 30 000 float profiles from the Argo project between 1998 and 2006 were used.

The temperature and salinity data were inspected for erroneous data, then selected at 82 pressure levels and averaged for each year in 1° × 1° geographical boxes. Each box time series was then filtered with a 3-year running mean, yielding 55 3-year intervals between 1950 and 2006, which increases the spatial data density in each interval. For this study, the data at 500 m depth, where the seasonal signal is relatively small, were selected and objectively interpolated horizontally for each 3-year interval. The observations were finally detrended and filtered with a Lanczos filter with a cut-off period of 25 years to extract the multi-decadal signal, which is dominant in the subpolar region.

3 Model simulations and analysis methods

The model used in the present study is the ocean general circulation model MPIOM of the Max Planck Institute for Meteorology (Marsland et al., 2003). It is a primitive equation model with hydrostatic and Boussinesq approximations, Arakawa-C grid, z-coordinate, free surface, bottom boundary layer scheme and embedded sea-ice dynamics and thermodynamics. The model has been used in a number of previous studies (Haak et al., 2003; Jungclaus et al., 2006; Olsen et al., 2008; Zhu and Jungclaus, 2008).

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The applied model set-up features quasi-homogenous horizontal resolution of 0.4° and 80 vertical layers. We start the model with climatology conditions from Levitus (1994) and spin it up for 700 years, using a climatological annual composite of sea surface fluxes and wind stress (OMIP; Röske, 2010) and surface salinity restoring of 35 days. Thereafter, we force the ocean using NCEP/NCAR data (Kalnay et al., 1996) from 1948 to 2008 subsequently for three times. Short wave radiation of the NCEP data are scaled by a factor of 0.89 (Haak et al., 2003). The last cycle of these simulations is discussed in this paper.

We interpolate simulated salinity, temperature, and stream function onto a 1° × 1° regular grid and average them to annual means. To analyse these data, the usual approach of characterizing oceanic and atmospheric variables with indices is followed: we define an index for the intensity of the SPG with the mean barotropic stream function between 45 and 65° N and 20 to 60° W. We multiply this index by minus one to obtain a strong SPG related to a positive index and a weak SPG to a negative index.

We define the intensity of the MOC in the subpolar region as the strength of the zonally integrated stream function at 47° N and 1400 m depth. A similar index for the MOC has been chosen by Eden and Willebrand (2001) (52° N and 1500 m) and by Eden and Greatbatch (2003) (47.9° N and 1270 m).

For every time step, we define the SPF at 500 m depth as the region with the magnitude of the horizontal density gradient larger than its space mean plus 1/4 of its standard deviation. Only data between 30 to 50° W and 35 to 55° N are considered. Varying the size of this box in meridional direction gave similar results. We call the mean latitude of the SPF the SPF index. Increase of the SPF index indicates a general northward displacement of the SPF in the NFB, decrease of the index indicates southward displacement.

We study the atmospheric forcing with the NAO index which is calculated as the principal component time series of the leading EOF of sea level pressure anomalies over the Atlantic sector (20 to 80° N and 90° W to 40° E) from December to March (Hurrell, 1995; data provided by the Climate Analysis Section of the National Center for

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Atmospheric Research, Boulder, USA).

To define LSW in the model we study first the salinity minimum with Θ/S-diagrams and vertical sections of salinity. From these plots, several isopycnals above and below the salinity minimum are chosen and tracked during the last NCEP experiment. We choose as LSW bounds the isopycnals closest to the salinity minimum but that diverge during winter in the Labrador basin (potential density anomalies $\sigma_0 = 27.60\,\mathrm{kg\,m^{-3}}$ and $\sigma_2 = 36.96\,\mathrm{kg\,m^{-3}}$).

As the observations, we detrend and then filter the indices and the spatially interpolated model data with a Lanczos filter and a cut-off period of 25 years. The variance of the yearly averaged indices explained by the filtered indices is 39% for the MOC, 51% for the SPG and 54% for the SPF. All anomalies shown in the figures are referred to the 1950–2006 mean.

3.1 Model evaluation

The global ocean model features an eddy-permitting resolution of 0.4° that allows for a good representation of topographic features, such as the Florida Strait and the Greenland-Scotland Ridge with its overflow conduits. However, resolution issues remain in the proper representation of Mediterranean Overflow Water (MOW), which is too warm and too salty in the model. Another persisting deficit is a too zonally-oriented NAC. Notwithstanding these deficiencies, MPIOM is able to reproduce correctly the mean state of the Subpolar North Atlantic, as shown by comparing model output with CliSAP data, as well as with previous studies: The time-average simulated SPG spans from 44 to 65° N and reaches maximum annual strength of about 30 Sv ($1\,\mathrm{Sv} = 1\,\mathrm{Sverdrup} = 10^6\,\mathrm{m^3\,s^{-1}}$). This value is inside the range of previous estimates from observations, from 27 to 34 Sv (Clarke, 1984; Bersch, 1995; Bacon, 1997). Vertical sections of salinity feature a well defined salinity minimum related to LSW (not shown), yet shallower than the climatological depth from observations. The mean zonal stream function shows that the MOC strength at 26° N and 1000 m depth is approximately 12.8 Sv, which is weaker than the observed estimates of 18.7 ± 5.6 Sv

(Cunningham et al., 2007) or 18.5 ± 4.9 Sv (Kanzow et al., 2010). However, our MOC intensity is not particularly weak in comparison to other models: From the seven models compared by Griffies et al. (2009), only two show a stronger MOC than MPIOM.

Further comparison of the model output with previous studies and with CliSAP observations indicates that the model represents the interannual and decadal variability of the SPG reasonably good: e.g., for the stratification of the SPG (Bersch et al., 2007, for the potential energy anomaly (PEA); Curry and McCartney, 2001; Kieke et al., 2007; upper left panel in Fig. 1), and for the simulated Sea Surface Height (SSH) (Hátún et al., 2005; upper middle panel in Fig. 1). The choice of the isopycnals defining LSW (Sect. 3) is supported by a comparison of annual means of our modelled LSW thickness and observations from Curry et al. (1998) (upper right panel in Fig. 1). LSW thickness has been calculated in the region of maximum winter convection (which is not necessarily the same in model and observations). Modelled salinity at 500 m depth in the subpolar region (averaged between 60 and 10° W and between 45 and 65° N) matches the CliSAP observations well (lower left panel in Fig. 1). Our modelled mean meridional position of the SPF in the NFB is roughly in phase with the observed one, even though it differs in amplitude sometimes like in 1965 or 1978 (lower middle panel in Fig. 1). The intensity of the MOC (lower right panel in Fig. 1) is in good agreement with the MOC index of Frankignoul et al. (2009). Sea ice concentration and extension (not shown) match observations of the British Meteorological Office (Rayner et al., 2003).

Finally, the overall relations between SPG, STG, MOC and NAO are in agreement with previous studies: SPG and STG intensities are nearly in phase (Curry and McCartney, 2001). A few years after a change to positive NAO, SPG (Eden and Willebrand, 2001) and MOC (Eden and Greatbatch, 2003; Brauch and Gerdes, 2005; Böning et al., 2006) intensify, indicating that both are nearly in phase (Frankignoul et al., 2009).

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4 Results

Figure 2 shows the low-pass filtered observed (panel a) and modelled (panel b) salinity anomalies at 500 m depth for selected years, which are representative for the upper layer of the SPG. Temperature anomalies are not shown here since they are strongly correlated to salinity anomalies. The evolution of the salinity anomalies in the simulation and observations from the 1960s to 2000s is the following: there is an almost full cycle from anomalously high salinity in the entire SPG region in the 1960s to much fresher conditions in the 1970s and 1980s and back to more saline conditions in the 1990s. More regionally, in the NFB, a negative salinity anomaly during the 1950s and 1960s, centred near 45° N and 40° W becomes positive from the middle 1970s on to become negative again in the middle 1990s. Thus, salinity in the subpolar region evolves out of phase to the one in the NFB.

The general agreement between simulation and observations is reasonable but there are obvious differences in certain regions. E.g., the discrepancies in the Iceland and West European Basins (upper right panels in Fig. 2a, b) can be related to the too zonal NAC in the model. The resemblance between observed and modelled salinity in the NFB and the western SPG region is reasonably good. Therefore, we concentrate in this study on the SPF displacement in the NFB.

To study the time evolution of the anomalies, we show in Fig. 3 the indices for NAO and our modelled oceanic variables. A complete multi-decadal cycle of the indices is observed during the 60 year experiment: The NAO (panel a) decreases to its minimum in 1965, increases to its maximum in 1993 and finally decreases to the end of the record. The MOC (panel b) is anomalously slow until 1968, when it starts to increase to its maximum in 1989, to slow down to the end of the record. The SPG intensity (panel c) decreases to its minimum in 1974, increases to its maximum in 1993 and then decreases again to the end of the record. The SPF in the NFB (panel d) is south of its mean latitude during the 1950s and 1960s as it shifts northwards to its maximum latitude in 1981 (before NAO, MOC and SPG maxima). Then, the front displaces southwards to its minimum latitude in 2005.

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These salinity and temperature changes in the subpolar region are associated with MHT changes. The temporal evolution of the total MHT is characterized by pronounced variations with the largest amplitudes in the SPF region (Fig. 4a). Generally, negative anomalies prevail during the 1970s and early 1980s and positive anomalies can be seen through the 1950s and for the 1990s and the 2000s for all latitude bands. The slope of the isolines indicates southward propagation of anomalies north of the SPF and northward propagation south of the SPF. A decomposition of the MHT into gyre and overturning components (Fig. 4b, c) reveals that these propagations result mainly from the gyre MHT. Overturning MHT anomalies occur most pronounced directly at the SPF. South of 40° N, overturning and gyre MHT anomalies seem to contribute with similar amounts to the total MHT variations, while the gyre MHT anomalies dominate the total MHT variations north of the SPF.

5 Discussion

The salinity changes in the NFB (Fig. 2) correspond to a multi-decadal displacement of the SPF: positive temperature and salinity anomalies arise due to advection of warm salty subtropical water as the SPF shifts northwards, while negative anomalies arise due to cold fresh subpolar water as the SPF shifts southwards. Figures 2 and 3d show a complete multi-decadal cycle of the SPF displacement in the NFB: the front displaces northwards from its southernmost position at the beginning of the experiment, passing its mean latitudinal position around 1967 and reaching maximum northward position in 1981 as the salinity in the NFB increases to a maximum. Then, the SPF retracts southwards to its mean latitudinal position as the salinity anomaly in the NFB reduces to zero. The front keeps displacing southwards until reaching its most southward position in 2005 as the salinity reduces to a minimum. The cycle length of the SPF meridional oscillation is on the order of 50 years.

In the following subsections we discuss possible causes for this multi-decadal SPF displacement and its relation to SPG, LSW, MOC and MHT in the Subpolar North Atlantic.

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5.1 Causes of the SPF displacement

The multi-decadal displacement of the SPF and, thus, the NAC are associated with anomalies of the barotropic stream function (Fig. 5). A SPF south of its climatological position (i.e., before 1967 and after 1995; Fig. 3d) is characterized by a cyclonic anomaly overlying the SPF, while a SPF north of its climatological position (between 1967 and 1995) is characterized by an anticyclonic anomaly. This circulation anomaly is similar to the inter-gyre gyre proposed by Marshall et al. (2001) and discussed by Eden and Greatbatch (2003) and, therefore, we will also use the term inter-gyre gyre here. Additionally, we note that our circulation anomalies propagate from the north towards the south. Analyzing local trends between snapshots of Fig. 5 (not shown) indicate that the northward displacement of the SPF is related to an increasing anticyclonic inter-gyre circulation indicating a northward expansion of the STG in this region, while the southward displacement of the front occurs during periods of increasing cyclonic inter-gyre circulation, indicating a southward expansion of the SPG. The maximum northward position of the SPF occurs when the rate of change of the multi-decadal inter-gyre gyre is at minimum.

We turn now our attention to the mechanisms driving these circulation changes. Häkkinen and Rhines (2004) compare the dynamic consequences of buoyancy forcing and barotropic and baroclinic response to local WSC changes and state that an increase of SSH in the subpolar region during the second half of the 1990s parallels the warming in the central SPG as a result of the relaxation of the water column after shut-down of intense winter convection in the previous years. Similarly, Eden and Jung (2001) have shown with sensitivity experiments that the multi-decadal variability of the SPG would be driven by heat fluxes rather than by changes of WSC. On the other hand, Bersch et al. (1999), Frankignoul et al. (2001) and Bersch (2002) have suggested changes of WSC modulated by the NAO at interannual time scales as cause for the SPF displacement during the 1990s. In the specific case of the Eastern North Atlantic, the front displacement has been attributed to a WSC-generated inter-gyre gyre

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by Eden and Willebrand (2001) and Herbaut and Houssais (2009). At the decadal time scale, Häkkinen et al. (2011) stress also the importance of WSC changes on the SPF shift in the Eastern North Atlantic. Therefore, the two main candidates responsible for the circulation changes of Fig. 5 are WSC and heat-flux changes, the latter being reflected by changes in convection and amount of LSW.

To study the influence of possible multi-decadal changes of WSC on the SPF displacement, we zonally integrate the WSC of the NCEP data to obtain its contribution to the barotropic stream function (Sverdrup, 1947). We call this contribution the "WSC component" of the circulation. The residual between the WSC contribution and the total barotropic stream function represents the contribution by the hydrographic changes driven by buoyancy fluxes, which, at this multi-decadal time scale, would mainly be related to LSW changes (more about this in Sect. 5.2 below). We call this residual circulation the "LSW component" of the circulation.

Figures 6 and 7 show the circulation anomalies of the WSC and the LSW components, respectively. Comparison of these figures shows large differences north of 55° N, where the circulation components are of opposite sign. South of 35° N, the circulation components have also different sign during the 1960s. We exclude the western boundary region from the discussion because the Sverdrup relation is not appropriate there. In the inter-gyre region the two circulation components are more similar (with differences of less than 1 Sv), with cyclonic inter-gyre anomalies during the 1960s and anticyclonic anomalies from the 1970s to the 1990s. This suggests that WSC changes coincide with heat flux changes at the multi-decadal time scale and that both circulation components contribute similarly to the multi-decadal inter-gyre gyre and, therefore, to the displacement of the SPF.

Differences between the two circulation components appear during certain periods of time near the SPF, suggesting a temporally larger impact of one or the other circulation component. For instance, the cyclonic inter-gyre gyre in the 1960s seems to be dominated by WSC. A similar case can be seen in the 1990s: the WSC component is related to a cyclonic inter-gyre gyre from 1996 on (Fig. 6), while the LSW component

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only from 2001 on (Fig. 7). This suggests a larger influence of WSC than of LSW on the southward displacement of the SPF during the 1990s.

Despite the temporal differences, the *overall* multi-decadal meridional displacement of the SPF in the NFB can be seen as the result of both LSW and WSC changes of similar magnitudes, emphasizing the importance of long-term variations of WSC on the dynamics of the multi-decadal variability of the SPG. In fact, the multi-decadal variations of the WSC (not shown) are only one order of magnitude smaller than the long-term mean WSC, yielding thus a transport anomalies of similar magnitude compared to the transport anomalies due to LSW changes (a few Sv). This notion is different to results of Eden and Jung (2001), who stress mainly the importance of heat fluxes on the multi-decadal variability of the SPG, but similar to Häkkinen et al. (2011), who state that the shift of the SPF in the Eastern North Atlantic is due to multi-decadal WSC changes.

5.2 The SPF position as indicator for LSW volume changes

LSW anomalies in the frontal region contribute to the multi-decadal inter-gyre gyre and, thus, the SPF displacement. A negative anomaly of LSW thickness is beginning to develop in the Labrador Basin in the 1960s (Fig. 8) when the NAO is growing negative (Fig. 3a) and convection is anomalously weak. This negative LSW thickness anomaly displaces from north-west to south-east, spreading along the SPF and further into the STG and SPG interiors, following a path similar to the one diagnosed for positive anomalies by Sy et al. (1997).

A negative LSW anomaly in the inter-gyre region is related to an anticyclonic inter-gyre gyre and to a SPF north of its climatological position as in the 1970s and 1980s, while a positive LSW anomaly is related to a cyclonic inter-gyre gyre and a SPF south of its climatological position as in the second half of the 1990s and 2000s. The LSW thickness in the frontal region is at minimum roughly in 1981 when the SPF index is at maximum. A close relationship between LSW and SPF in the NFB is also indicated by observations in the 1990s and early 2000s (Bersch et al., 2007). Therefore, the mean latitudinal position of the SPF in the NFB (SPF index; Fig. 3d) could be used as an indicator of the amount of LSW in this basin on a multi-decadal time scale.

5.3 The SPF position as an indicator for the MOC intensity

Comparison of the MOC index (Fig. 3b) with Fig. 8 shows that the negative LSW thickness anomaly in the western subpolar region up to 1976 is related to an anomalously weak MOC, while the positive LSW thickness anomaly after 1976 is related to an anomalously strong MOC. This is in agreement with LSW volume changing the zonal density gradient and, in turn, the MOC intensity (Eden and Greatbatch, 2003; Böning et al., 2006).

We study these variations of the MOC intensity in the North Atlantic analyzing circulation anomalies of the MOC stream function (Fig. 9): the MOC is divided by the SPF in two regimes, with the regime in the subpolar region showing larger variability. A similar MOC anomaly spanning comparable latitudes and depths inside the subpolar region is found by Eden and Greatbatch (2003) and by Gulev et al. (2003), while multi-decadal gyre-specific changes of the MOC have been simulated by Lozier et al. (2010). The MOC in the subpolar region is at maximum in 1986 as also indicated by our MOC index at 47° N, while the MOC intensity-changes in the subtropics are delayed approximately by five years, with maximum in 1991. Following Eden and Greatbatch (2003) and Böning et al. (2006), anomalies in the MOC would propagate from the SPF region towards the south following changes of the zonal density gradient due to spreading of LSW anomalies. Our time period between the intensification of the MOC at the frontal region and in the subtropics is in agreement with Eden and Greatbatch (2003), who simulated an intensification of the MOC in the subtropics 4 years after the MOC maximum at the frontal region.

The relation between MOC, LSW and SPF in the NFB suggests the SPF index as an indicator of intensity changes of the MOC in the subtropics with a lead time of roughly 10 years: The southward displacement of the SPF after 1981 indicates the arrival of a positive LSW anomaly in the NFB (Fig. 8, central panel), which then intensifies the

MOC in the subtropics to its maximum in 1991 (Fig. 9, lower left panel) as it flows with the DWBC. The SPF index, obtained from satellite altimetry or hydrographic measurements, can be used as complementary or alternative to the SPG intensity index (Fig. 3c), DWBC transport at 53° N (Böning et al., 2006), or subpolar SST (Latif et al., 2004).

5.4 SPF displacement and MHT

The gyre MHT anomalies (Fig. 4b) propagating southwards from ca. 55° N to the frontal region are a consequence of the southward propagation of circulation anomalies (Fig. 5). The overturning MHT anomalies (Fig. 4c) propagating southwards from the frontal region until 34° N (Sect. 4) are in agreement with the southward propagation of circulation anomalies of the MOC due to the flow of LSW with the DWBC. The overturning MHT at the front's latitude is roughly simultaneous with the SPF index (Fig. 3d): negative values until the 1970s, maximum value in the 1980s and negative again from the middle 1990s. This is consistent with warm subtropical water displacing northwards in the NFB. Part of the additional heat in the frontal region seems to propagate northwards with the overturning circulation to 62° N in a period of 15 years. Eden and Willebrand (2001) simulate an increase of MHT at the frontal region at decadal time scales, due to enhanced gyre and overturning circulations. Eden and Greatbatch (2003) state that their MHT increases with positive NAO is mainly due to an MOC circulation anomaly in the Subpolar North Atlantic. They argue that this MHT anomaly changes the sign of the SST dipole in the ocean and, thus, is responsible for the negative feedback with the atmosphere. However, the time evolution and magnitude of our total MHT (Fig. 4a) matches the gyre MHT (Fig. 4b) rather than the overturning MHT (Fig. 4c), suggesting that the contribution of the MOC to the total MHT anomalies in the subpolar region (excluding the frontal region) is minor at the multi-decadal time scale. This is the consequence of subpolar waters flowing southwards with a strengthened SPG.

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SPF displacement, horizontal circulation changes and MHT anomalies are intrinsically related. As an interesting example of this, changes of overturning MHT partially cancel with changes of gyre MHT in the frontal region: the reduction of gyre MHT near the SPF (Fig. 4b) due to the anti-cyclonic inter-gyre anomaly in the mid-1980s (Fig. 5) is compensated by the related northward displacement of the SPF (Fig. 4c). The resulting total MHT anomaly at the frontal region is almost zero at this time (Fig. 4a); similar compensations happened in the 1950s and the 2000s.

However, the importance of horizontal circulation changes for the MHT anomalies revealed by our model could be exaggerated. For instance, our gyre MHT in the subpolar region is considerably larger compared to model simulations by Gulev et al. (2003), while overturning and gyre MHT components are similar south of the SPF. If our gyre MHT in the SPG region is overestimated, this could be a consequence of the too zonal NAC in our model and/or simulated MOW being warmer and saltier than in the observations, which makes the modelled zonal temperature differences in the subpolar region significantly larger than the real ones.

6 Summary and conclusions

A novel data set (CliSAP data center) spanning 57 years of hydrographic observations in the North Atlantic evidences salinity anomalies related to a multi-decadal meridional displacement of the SPF in the NFB (Fig. 2a). While interannual displacements of the front in the Western North Atlantic have been documented, the main contribution of the present study is the observation and modelling of a complete multi-decadal displacement cycle of the front.

Model results with MPIOM show that the SPF and associated NAC displacement is reflected by changes of a multi-decadal inter-gyre gyre, i.e., a circulation anomaly between the SPG and STG (Fig. 5). An anticyclonic inter-gyre gyre is related to a SPF north of its climatological position, indicating a northward expansion of the STG, while a cyclonic inter-gyre gyre is related to a SPF south of its climatological position,

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indicating a southward expansion of the SPG. The contributions of WSC (Fig. 6) and LSW (Fig. 7) changes to the variations of the barotropic stream function are of similar magnitude in the inter-gyre region (between of 35 and 55° N). A negative LSW thickness anomaly is thus related to a SPF north of its climatological position, while a positive LSW thickness anomaly is related to a SPF south of its climatological position. Therefore, the mean latitudinal position of the SPF in the NFB (SPF index) could be an indicator of the amount of LSW in the inter-gyre region. An anticyclonic WSC anomaly shifts the SPF northward, while a cyclonic anomaly leads to southward displacement.

The MOC is divided by the SPF in two regimes, with the subpolar regime having larger variability. The MOC intensifies as LSW flows with the DWBC into the NFB and beyond the SPF, increasing the zonal density gradient. The MOC has a maximum in the subpolar region five years after the SPF reaches its northernmost position, while, in the subtropical region, it lags by about 10 years. Therefore, the SPF index can be used as an index to predict the intensity of the MOC in the subpolar and subtropical regions at multi-decadal time scale.

Between 30 and 60° N, the shift of the SPF is associated with the strongest signals in the gyre and overturning MHTs. The temperature anomalies linked to the SPF displacement in the NFB are (partially) associated with opposite effects of gyre and overturning MHT (Fig. 4): while the gyre MHT decreases with an anticyclonic intergyre gyre (i.e., reduction of the cyclonic circulation north of the SPF), the overturning MHT increases due to the intrinsically related northward displacement of the front. In the subpolar region, MHT changes are dominated by the gyre component at the multi-decadal time scale. This study emphasizes that SPG strength and shape are the dominant factors for the MHT and thus ocean climate changes in the subpolar region of the North Atlantic.

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Multi-decadal displacement of the Subpolar Front

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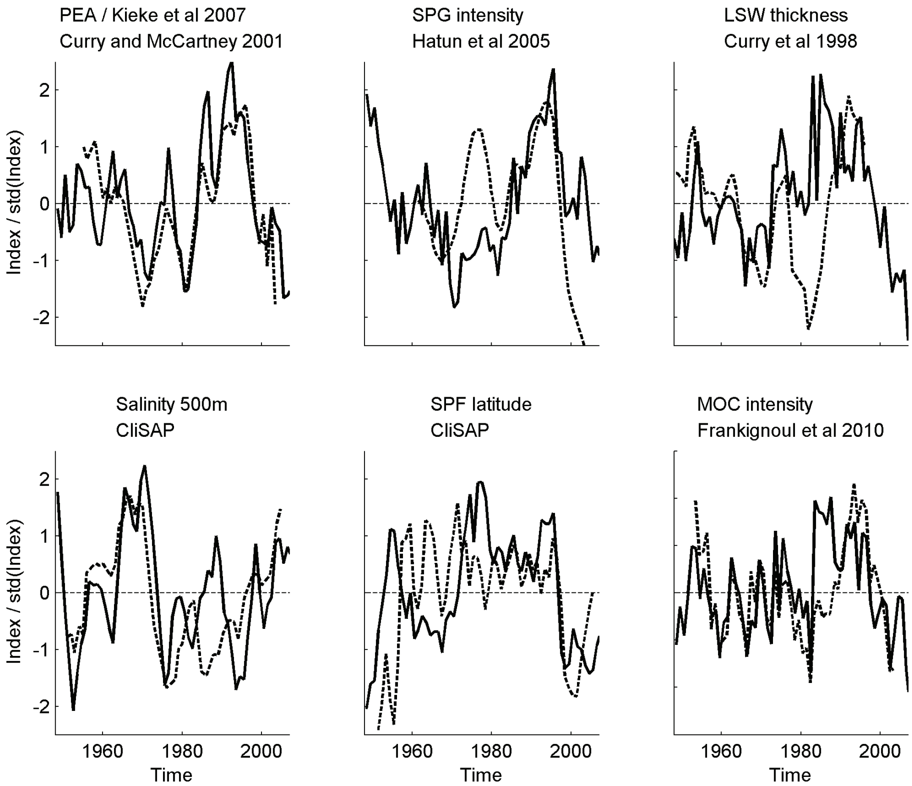

Fig. 1. Comparison between our simulated (solid lines) and observed or previously simulated (dashed lines) indices derived from annual data of PEA (upper left panel), gyre intensity index (upper middle panel), LSW thickness in its formation area (upper right panel), mean salinity at 500 m depth in the subpolar region (lower left panel), mean latitudinal position of the SPF in the NFB (lower middle panel) and MOC intensity (lower right panel).

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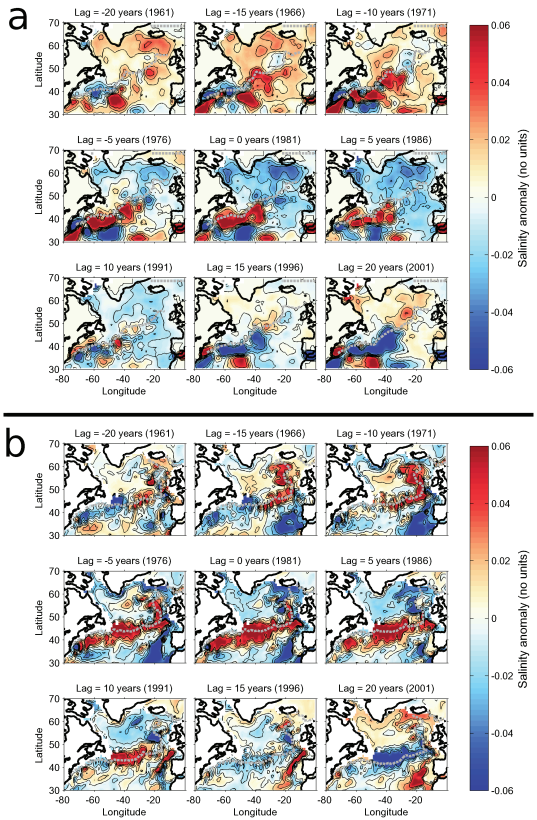

Fig. 2. Low-pass filtered observed **(a)** and simulated **(b)** salinity anomalies (referred to the 1950–2006 mean) at 500 m depth for various time lags around 1981 (central panel in each figure), the year in which the SPF in the NFB reaches maximum northern latitude. The observations have been filtered spatially with a boxcar window (5° in the zonal direction and 3° in the meridional one). The colour bars indicate the magnitude of the anomalies. The grey dashed curves show the position of the SPF for each year.

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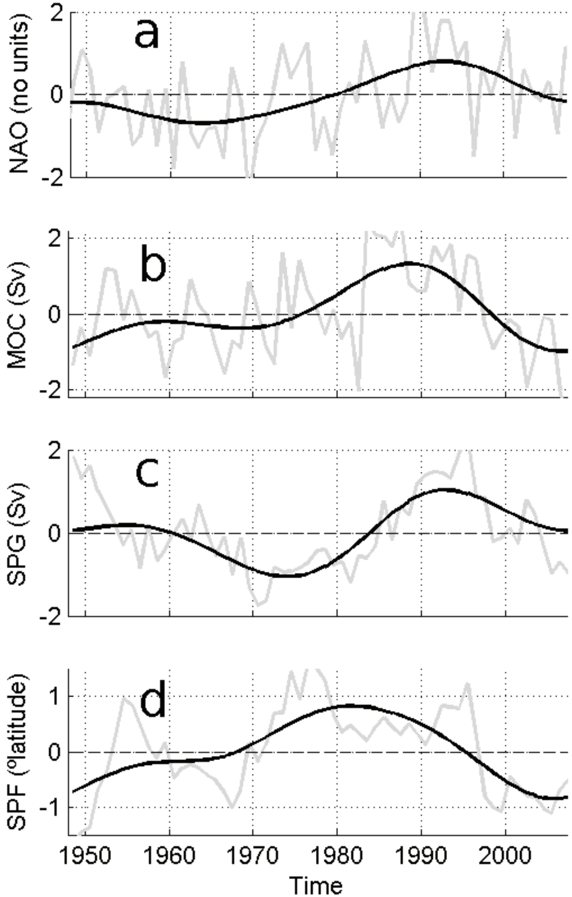

Fig. 3. Annual averaged (grey curves) and low-pass filtered (black curves) indices used in the present study: NAO (panel **a**; no units), MOC intensity at 47° N (panel **b**; Sv), SPG intensity (panel **c**; Sv) and mean latitude of the SPF in the NFB (panel **d**; degrees of latitude).

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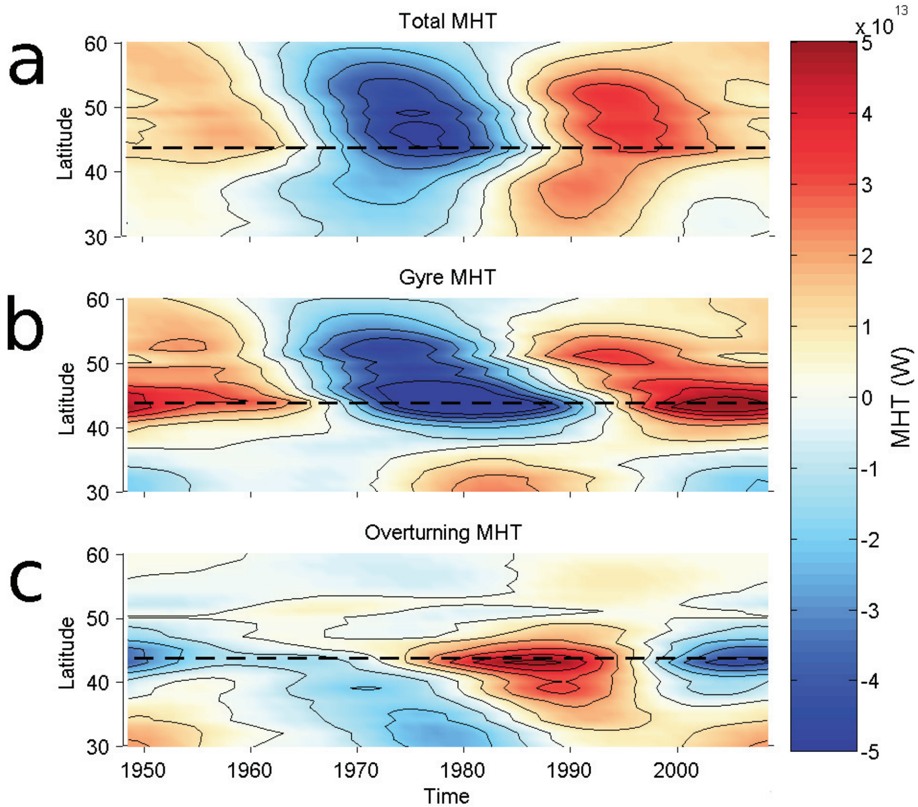

Fig. 4. Hovmöller diagrams of anomalous total **(a)**, gyre **(b)** and overturning **(c)** MHT (watts) against latitude. The mean latitude of the SPF in the NFB (44° N) is shown with a dashed line in all the panels. Red indicates northward heat transport, blue southwards. A colour bar shows the magnitude of the MHT anomalies.

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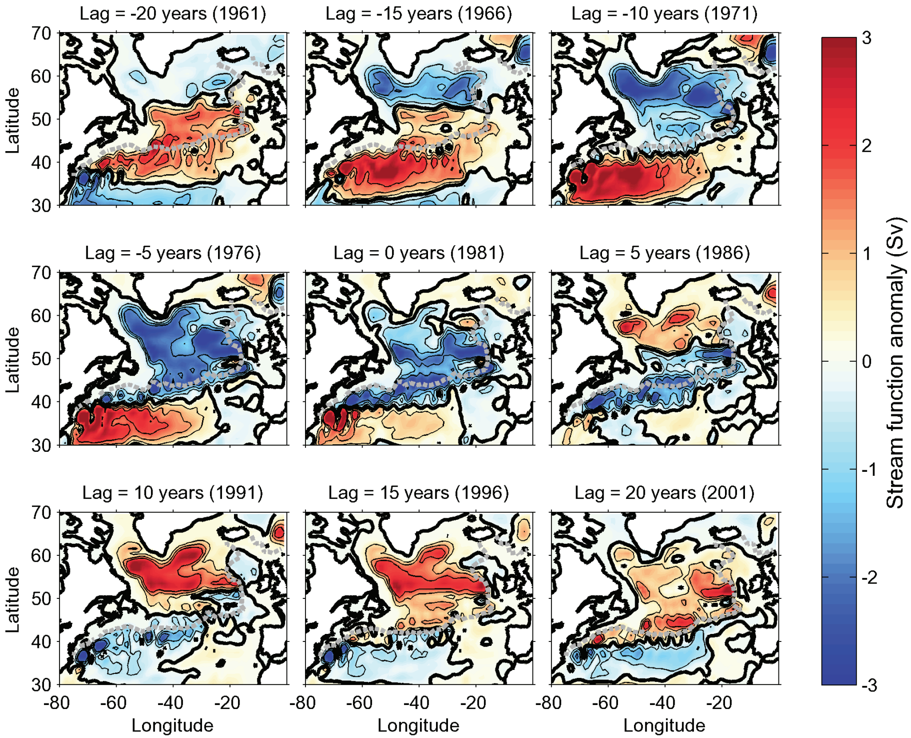

Fig. 5. As Fig. 2, but for barotropic stream function anomalies (Sv). Positive anomalies (red) are cyclonic and negative anomalies (blue) are anticyclonic.

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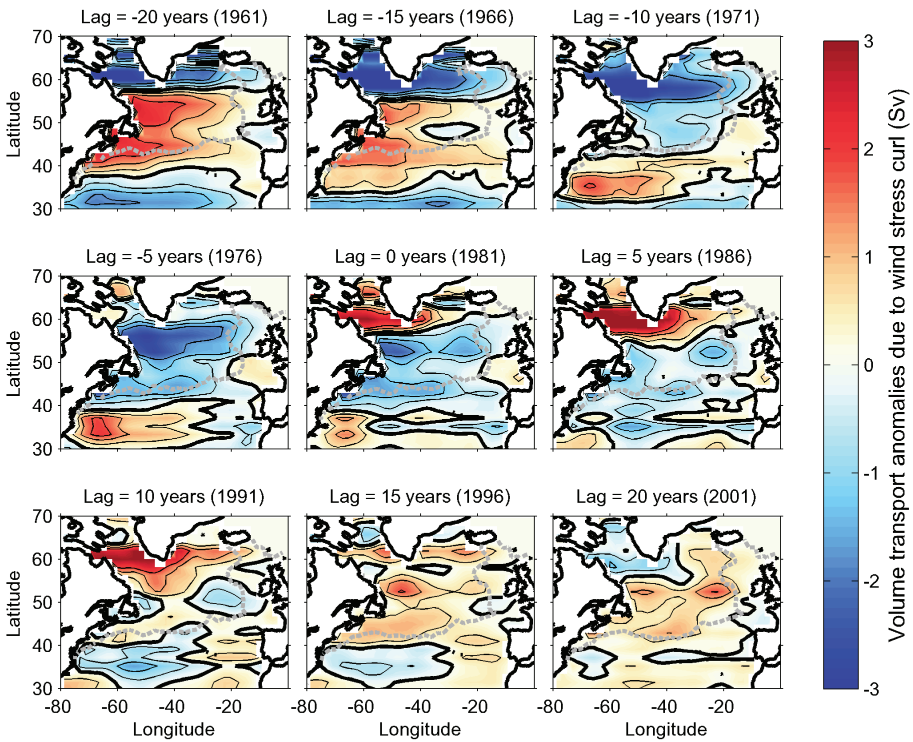

Fig. 6. As Fig. 5 but for the anomalies of the WSC component of the barotropic stream function (Sv).

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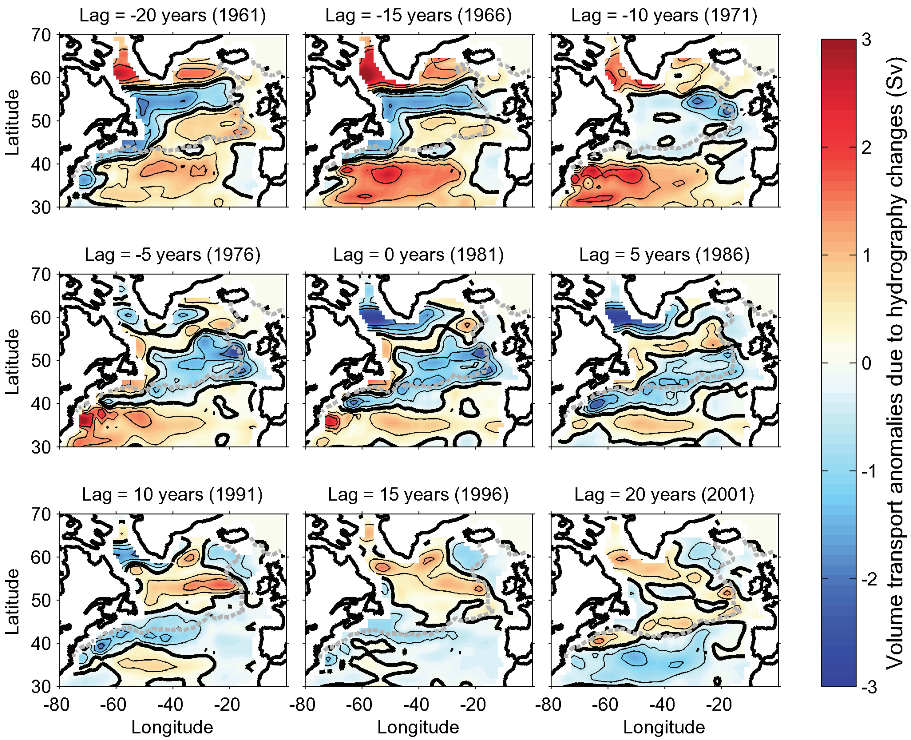

Fig. 7. As Fig. 5 but for the anomalies of the LSW component of the barotropic stream function (Sv). The data have been spatially filtered with a boxcar window with 5° in the zonal direction and 3° in the meridional one (like Fig. 2a) to allow a better comparison with the WSC component (Fig. 6) because the MPIOM grid has larger resolution than the NCEP grid.

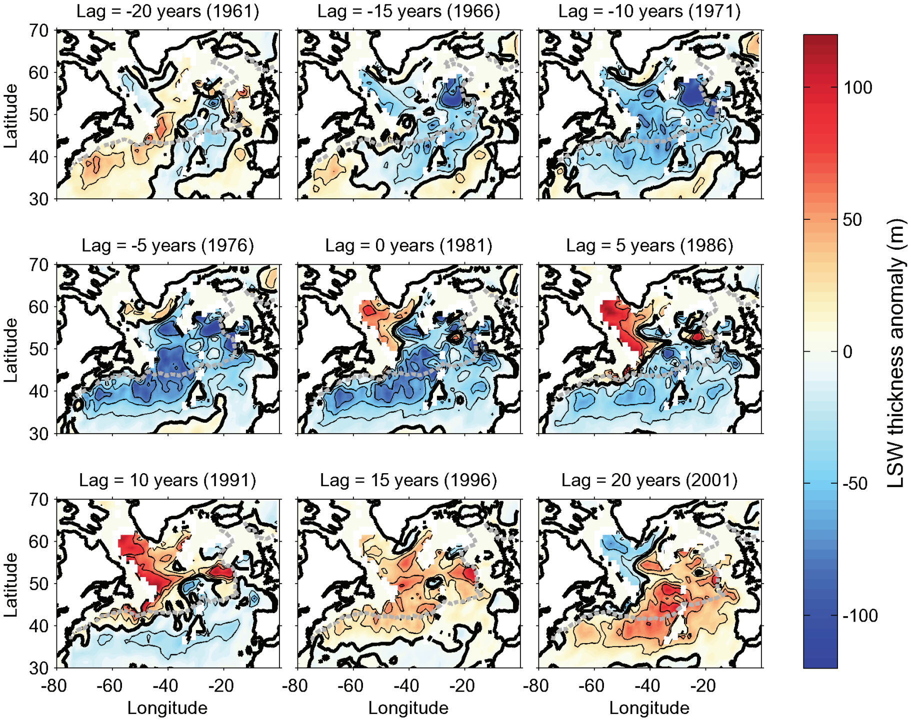

Fig. 8. As Fig. 2 but for LSW thickness anomaly (m).

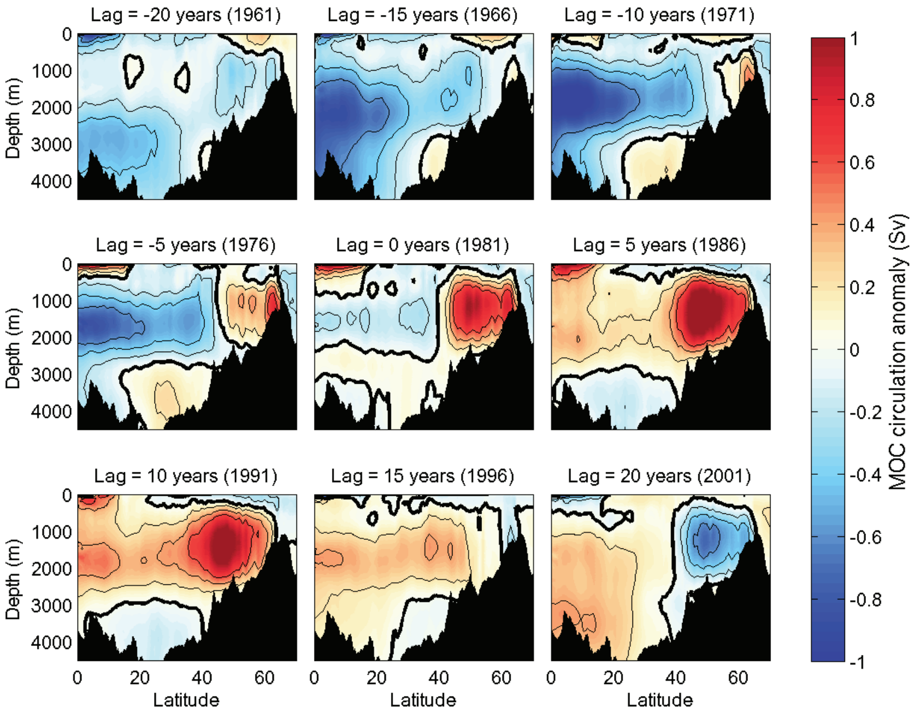

Fig. 9. Circulation anomaly of the MOC stream function (Sv). Positive anomalies (red) are clockwise and negative anomalies (blue) are anticlockwise.

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