Shifting surface currents in the northern North Atlantic Ocean

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Analysis of surface drifter tracks in the North Atlantic Ocean from the time period 1990 to 2006 provides the first evidence that the Gulf Stream waters can have direct pathways to the Nordic Seas. Prior to 2000, the drifters entering the channels leading to the Nordic Seas originated in the western and central subpolar region. Since 2001 several paths from the western subtropics have been present in the drifter tracks leading to the Rockall Trough through which the most saline North Atlantic Waters pass to the Nordic Seas. Eddy kinetic energy from altimetry shows also the increased energy along the same paths as the drifters. These near surface changes have taken effect while the altimetry shows a continual weakening of the subpolar gyre. These findings highlight the changes in the vertical structure of the northern North Atlantic Ocean, its dynamics and exchanges with the higher latitudes, and show how pathways of the thermohaline circulation can open up and maintain or increase its intensity even as the basin-wide circulation spins down.

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Inflows to the Nordic seas from the main North Atlantic pass through three routes: through the Rockall Trough to the Faroe-Shetland Channel, through the Iceland basin over the Iceland-Faroe Ridge and via the Irminger Current passing west of Iceland. We focus on the first two routes, which carry most of the volume flux into the Nordic Seas. There are indications that the water masses in these channels change over time, as suggested by the most recent observations from the 1990s and early 2000s (Hatun et al 2005; Pollard et al 2004). During the same period other findings of major climatic fluctuations have reported such as the significant decrease of deep convection in the Labrador Sea (Dickson et al 1996, 2002), the westward movement of the subarctic front in the eastern subpolar gyre (Bersch, 2002) and the weakening of the subpolar gyre associated with increased sea surface height (Hakkinen and Rhines (2004)).

Over the years there has been considerable debate about the source for the waters flowing to the Nordic Seas and whether and how these waters relate to the North Atlantic Current (NAC) (e.g. reviews by Rossby, (1996) and McCartney and Mauritzen (2001)). The Faroe-Shetland Channel flow carries the most saline waters northward, which has raised the question how these waters gain such a high salinity content and whether the high salinity is attributable to mixing with the Mediterranean waters. Pollard et al. (2004) has called the saline waters masses in Rockall Trough (Hatton Bank) as Eastern North Atlantic Water with origins in the eastern subtropics (where some branches of the NAC terminate). A differing view is proposed by McCartney and Mauritzen (2001) who attribute the source to be the NAC water masses from farther west which have gained salinity by mixing with the Mediterranean Overflow Waters before entering Rockall Trough. The determination of the source waters is further complicated by the fact that the Rockall Trough water masses undergo significant long term changes in its temperature and salinity characteristics (Holliday et al. 2000).

The surface water pathways can be followed by surface drifters, which have been deployed since the 1980s in the North Atlantic Ocean. Using the Lagrangian approach Reverdin et al (2003) and Brambilla and Talley (2006) show that surprisingly few subtropical surface drifters are diverted to the subpolar gyre since the large scale surface drifter program started 1989 and before 2002. A rather different view of the surface currents is provided by the Eulerian average of surface drifter fields which shows the surface waters from the western Atlantic crossing the Mid-Atlantic Ridge (MAR) and continuing towards north to the Iceland Basin and the Rockall Trough (Krauss, 1986; Brugge, 1995; Fratantoni, 2001). Hence the pathways of warm and saline subtropical water reaching the Nordic Seas and feeding the overflows are not clearly known.

In this work we show that these pathways can change with time and we also provide supporting evidence from altimetry. Analysis of surface drifter tracks in the North Atlantic Ocean from the time period 1990 to 2006 provides the first evidence that the Gulf Stream waters can have direct pathways to the Nordic Seas. Prior to 2000, the drifters entering the channels leading to the Nordic Seas originated in the western and central subpolar region. Since 2001 several paths from the western subtropics have been present in the drifter tracks leading to the Rockall Trough through which the most saline North Atlantic Waters pass to the Nordic Seas. Eddy kinetic energy from altimetry shows also the increased energy along the same paths as the drifters since 2000. These near surface changes have taken effect while the altimetry shows a continual weakening of the subpolar gyre. These findings highlight the changes in the vertical structure of the northern North Atlantic Ocean, its dynamics and exchanges with the higher latitudes, and show how pathways of the thermohaline circulation can open up and maintain or increase its intensity even as the basin-wide circulation spins down.

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Abstract

Analysis of surface drifter tracks in the North Atlantic Ocean from the time period 1990 to 2006 provides the first evidence that the Gulf Stream waters can have direct pathways to the Nordic Seas. Prior to 2000, the drifters entering the channels leading to the Nordic Seas originated in the western and central subpolar region. Since 2001 several paths from the western subtropics have been present in the drifter tracks leading to the Rockall Trough through which the most saline North Atlantic Waters pass to the Nordic Seas. Eddy kinetic energy from altimetry shows also the increased energy along the same paths as the drifters since 2000. These near surface changes have taken effect while the altimetry shows a continual weakening of the subpolar gyre. These findings highlight the changes in the vertical structure of the northern North Atlantic Ocean, its dynamics and exchanges with the higher latitudes. Pathways of the thermohaline circulation can open up and maintain or increase in intensity even as the basin-wide circulation spins down, and in doing so can oppose global-warming induced decline of the global oceanic overturning circulation..

Introduction

Inflows to the Nordic seas from the main North Atlantic pass through three routes: through the Rockall Trough to the Faroe-Shetland Channel, through the Iceland basin over the Iceland-Faroe Ridge and via the Irminger Current passing west of Iceland. We focus on the first two routes, which carry most of the volume flux into the Nordic Seas. There are indications that the water masses in these channels change over time, as suggested by the most recent observations from the 1990s and early 2000s *(1-2)*. During the same period other findings of major climatic fluctuations have been reported: significant decrease of deep convection in the Labrador Sea *(3-4);* the westward movement of the subarctic front in the eastern subpolar gyre *(5,* and, the weakening of the subpolar gyre associated with increased sea surface height *(6)*. Combined model results and observations *(1)* showed that the sea surface height variability is associated with a westward contraction of the subpolar gyre which allows increased salinity waters to flow northeastward towards the Nordic Seas *(1)*. This suggests that the source of the saline waters is East Atlantic Waters, which are a mix of subtropical waters and Mediterranean overflow.

Over the years there has been considerable debate over the origins of the source waters flowing to the Nordic Seas through the Faroe-Shetland Channel and between the Faroe Islands, Iceland and Greenland. Their high salinity comes from a combination of the North Atlantic Current (NAC), and Gulf Stream farther south, and the saline waters of the upper eastern Atlantic, where evaporation is intense (e.g. reviews *(7)* and *(8))*. The saline water masses in the Rockall Trough (Hatton Bank) are called Eastern North Atlantic Water (2) with origins in the eastern subtropics (where some branches of the NAC terminate). A differing view (8) is that the saline source is the NAC water masses from farther west which have gained salinity by mixing with the Mediterranean Overflow Waters before entering the Rockall Trough. Further complexity to the involvement of the NAC waters is added by the subsurface float data which show that the NAC waters below 200m in the north-east subpolar gyre circulate back to west *(9)*. Hence only the near surface NAC waters could contribute to the saline inflow to the Nordic Seas. There is also a semantic problem in that NAC waters gaining salt by mixing as they pass through the eastern Atlantic do owe their origins to the eastern subtropics as well as the Gulf Stream, and hence, in a Lagrangian sense, are a confluence of two distinct lines of circulation. The determination of the source waters is further complicated by the fact that the Rockall Trough water masses undergo significant long term changes in its temperature and salinity characteristics through both air-sea interaction in winter, and lateral mixing with prolonged recirculation *(10)*.

The surface water pathways can be followed by surface drifters, which have been deployed since the 1980s in the North Atlantic Ocean. Using the Lagrangian approach *(11)* and *(12)* show that surprisingly few subtropical surface drifters are diverted to the subpolar gyre between 1989 (the initiation of the large scale surface drifter program) and 2002. A rather different view of the surface currents is provided by the Eulerian average of surface drifter fields which shows the surface waters from the western Atlantic crossing the Mid-Atlantic Ridge (MAR) and continuing towards north to the Iceland Basin and the Rockall Trough *(13-15)*. Thus the pathways of warm and saline subtropical water reaching the Nordic Seas and feeding the overflows are not clearly known. Our objective here is to show from surface drifter movement and satellite altimetry that these pathways can change with time. Possible forcing mechanisms for the changes in pathways are also discussed.

Data sources

Our first objective is to explore current changes for which we use surface currents from NOAA/AOML Global Lagrangian Drifting Buoy Data Base. The data are available since 1989, although very sparse in the early years. The surface drifters are drogued to 15m depth below sea surface, and we will use only drogued drifters. The data base provides the drifter location and temperature every 6 hours. The lifetime of the drogues vary considerably but the average life span of the drifters (~271 days *(12))* has not changed significantly over the years. However, the number of drifters has increased significantly.

In order to support findings from surface drifters we will use altimetry data used in this study from TOPEX/Poseidon, ERS-1/2, Jason-1 and ENVISAT missions which are merged into a 1/3 degree data and are available from AVISO. Eddy kinetic energy (EKE) based on geostrophic currents is computed from altimetry data. There may be some underestimation of EKE in the subpolar gyre because of the coarse resolution compared to the baroclinic radius deformation. Despite this we expect to detect relative changes in EKE which should be an indication of the changes in the current location or enhancement of the current *(16)*.

To analyze the forcing of the surface currents we use monthly wind stress data from NCEP/NCAR Reanalysis which has been used to compute wind stress curl and its variability. We also use use QuikSCAT data for the most recent years to resolve finer resolution features in the wind stress curl.

Surface currents from drifter tracks

First we start with drifter data which shows the most apparent shift in the paths of the North Atlantic surface waters. The drifter data is divided into three periods, 1991-1995, 1996-2000, and 2001-2006. The first period represents years with high NAO index, the second period sees an intense reversal of the NAO index, and the most recent period represents years of fluctuating weak positive and negative NAO index. As in earlier work (12), we consider a limited subtropical region where the drifters are found in the given period, and their path prior and after entering this specific region. Because long-duration tracks are involved, the timing of circulation changes is slightly blurred by this technique. The drogue lifetime of the drifters can have an impact whether subtropical drifters reach the NE corner of the subpolar gyre (as noted in *(12)*). To improve the chance of subtropical drifters reaching the Rockall Trough, we chose a region in the central subtropical waters, 35N to 45N, 30W to 50W. The average salinity in this box is 35.92psu based on NOAA World Ocean Atlas 2001 data. This region is mostly west of the Mid-Atlantic Ridge, except a small area in the SE corner. The drifter tracks entering and leaving the box are shown in Fig. 1 during the three periods. (The drifter tracks before and after entering the Gulf Stream box used in ref. *(12)* for the 3 periods are shown in Fig. S1.) The drifter tracks exiting the box are colored based on their speed, below (blue) or above (red) 30cm/s. The first period is rather sparsely occupied with tracks compared to the other two, however the most apparent conclusion from the figures is the expansion of tracks northward and north-eastward with some intensification of speeds. The most recent period shows a major shift in the surface water path from the subtropics along the NAC path east and north-eastward to the Rockall Trough suggesting that salinization of the waters in the NE North Atlantic has its roots at least partially in the western subtropics. It also appears that the western Atlantic waters previously (prior to 2000) feeding the Bay of Biscay waters have turned north-east towards the Rockall Trough in the most recent years.

We can reverse-track the drifters that reached the NE corner as in *(12)*. We limit the area of interest to cover mainly the Rockall Trough by choosing area 18W to 0E, 53N to 63N. The tracks entering and leaving this box are shown in Fig. 2a-c during the three periods, where incoming drifters are again colored based on their speed (below or above 30cm/s). (Corresponding figure using the box from *(12)* is shown in Fig. S2.) Unfortunately there are too few tracks in the first period (Fig. 2a) to make any conclusions but it is shown for completeness. The middle period (Fig. 2b) shows that no drifters originated south of 45N, but it has several paths from the far western subpolar gyre. The central region between 45N and 55N is dominated by nearly zonal drifter tracks during 1996-2000: The drifters from the central Labrador Sea are imbedded in the NAC which takes them nearly zonally across the MAR at the Charlie Gibbs Fracture Zone (CGFZ) into the Rockall Trough. Another branch of tracks originates in the central subpolar gyre and moves into the Iceland Basin. Since 2001 (Fig. 2c) a different source for the path passing through CGFZ towards the Rockall Trough has developed where drifters originate from the Gulf Stream area and follow the Gulf Stream Extension into the 'Northwest Corner' at the mouth of the Labrador Sea and then zonally across to the Rockall Trough. Some subtropical drifters use more direct SW to NE route to the Rockall Trough. The arrival of the drifters in the Rockall Trough originating south of 45N is an indication of increased salt flux to the region. Besides the drifters south of 45N, there are also drifters within subpolar- and modified subpolar waters entering the NE corner as obvious from the Fig. 2c, however these drifters move predominantly into the Iceland Basin as in the earlier years. An interesting detail of the changing circulation appears at the southern coast of Iceland: Before 2000 there was a wide swath of drifter tracks moving westward out the northern box, but after 2000 across all of the western boundary of the box, drifters are moving in from the west, only a couple of drifter tracks exiting the box toward the west.

Eddy kinetic energy changes from altimetry

Surface drifters are not evenly distributed in space or time, thus conclusions of major shifts in pathways and their timing need to be supported from other sources. We invoke satellite altimetry to investigate the current fluctuations based on eddy kinetic energy (EKE). The eddy kinetic energy has been found to be an excellent way of identifying major current paths and their changes, for example clearly defining both the NAC, the Gulf Stream and intense jet-like structure of the Antarctic Circumpolar Current *(16-18)*. EKE time series can lend support in pinpointing temporal transitions in the current paths. Instead of showing EKE for the three different periods we show the linear trend in EKE from 1992 to 2006 based on 1/3 degree AVISO data set in Fig. 3. As can be anticipated EKE has increased in the eastern part of the subpolar gyre, especially east of the MAR (east of 30W). EKE has also increased in the Iceland Basin (=Maury Channel) and in the northern end of Rockall Trough. It is also interesting to note the regions where EKE has decreased: on the northern side of the Gulf Stream indicating southward shift of the stream, in the Azores Current (between 30N and 35N), and a slight weakening in the northern rim of NAC in the central subpolar gyre.

For a more detailed timing of the EKE changes we display latitude and longitude cross sections of EKE over time in Fig. 4a-b at 25W and at 52N. EKE is computed from geostrophic velocity anomalies from the whole period October 1992 to September 2006 (annual cycle is included). There are two latitude ranges of high EKE activity in the 25W section (Fig. 4a). The high EKE at 32-34N belongs to the Azores Current which is robust at this longitude (as opposed to further east longitudes). Further north, between 48N-52N, where NAC is crossing MAR in several locations (through Maxwell Fracture Zone (MFZ) at 48N and through Charlie Gibbs Fracture Zone (CGFZ) at 50N-52N), EKE increased significantly during 1999 and 2000 and has stayed elevated at least through 2005. This EKE activity has some weakening in 2006. The NAC crossing at around 40N (Kurchatov Fracture Zone; KFZ) shows elevated EKE from 2000 to 2004. The northernmost elevated EKE zone at 57N-60N in Fig. 4a lies on the central Iceland Basin and shows frequent EKE fluctuations but appears to show no trend. This trail of high EKE is likely to represent the recirculation of NAC towards the Irminger Sea. EKE at 52N section (Fig. 4b) the NAC has not split into the

Maury Channel and Rockall Trough branches. At this section NAC shows greatly increased EKE starting 2000 which continues to the end of the record. The elevated EKE appears to have eastward movement closing in to the Rockall Trough. An intense and sustained EKE directly south of Rockall Trough occurs in 2004.

These EKE changes have taken place while the altimetric sea surface height shows an increasing sea surface height in the subpolar gyre to the mid 2003 and then only a weak upturn (as of September 2006) (Fig. S3). The previous studies *((1), (6))* have shown that the increased sea surface height variability can be linked to the weakening gyre strength. Hence we have seemingly arrived at a contradiction: while the subpolar gyre weakened, the surface currents increased in the eastern basin as measured by the EKE trend. These findings can be interpreted as changes in the vertical structure of the northern North Atlantic Ocean. An example of deep structural changes is the relaxation of the Labrador Sea isopycnal dome formed by deep convection. Leveling the isopycnals allow movement of the subarctic front westward in the subpolar gyre, making the eastern part of the subpolar gyre more accessible to the southern water masses.

Forcing of surface current changes

The large EKE changes in MFZ and KFZ took place about 4 years since NAO underwent a major shift in phase (in 1996), albeit lasting only 2 winters. Since the sign change, NAO returned briefly to strongly positive values in winter 2000, but NAO behavior since 1996 shows merely fluctuations of decreasing amplitude (Fig. S4) and giving an appearance of overall decline of the amplitude. The EKE intensity shift in 2000 is possibly a delayed response to NAO change, and/or reflects the reorganization of the currents as a response to wide spread changes in the stratification. To explain the behavior of these surface drifters, we expect them to reflect both surface forcing changes, the Ekman drift and wind-stress curl changes, and the baroclinic effects driven locally or remotely. To address the wind--stress curl changes, we focus on the location of its zero-line which separates the subpolar and subtropical waters at least in the near surface. As a hypothesis we suggest that reorientation of the zero wind-stress curl allows the excursion of the subtropical drifters deep into the subpolar gyre. We display the zero wind stress curl lines from individual years during the three periods in Fig. 5a-c. During the strongly positive NAO years (Fig. 5a) the zero-curl lines were rather tightly clustered and terminated at the British Isles. The second period (Fig. 5b) shows more spread in the central subpolar gyre, but zero--curl lines still terminate at the British Isles in a tight cluster. During the third period (2001-2005) (Fig. 5c) the zero wind-stress curl lines show highly fluctuating positions from one year to another, some with strongly meridionally tilted inclination. Some years (2001, 2004 and 2005) the zero curl line approaches Iceland in the central subpolar region, or curves north of the British Isles (2001, 2003 and 2004). Increasing meridional tilt of the curl allows for the upper layer of the subtropical gyre to spread northeastward while layers below it, will shrink their north-south extent *(19)*. If the zero-curl line lies fully north and south, an anticyclonic subtropical gyre expands to fill the whole North Atlantic Basin *(19)*. Naturally the wind driven expansion of the subtropical gyre forces the subpolar gyre to shrink.

The distinguishable behavior of the wind-stress curl during the 3 periods is particularly prominent if data from the winter months (January-March) are used. The average winter wind stress curl from NCEP/NCAR Reanalysis is displayed in Fig. 6 for the 3 periods. It is apparent that the most recent years have had at the average a positive curl extending from Cape Hatteras to the Rockall Trough, guiding surface waters towards NE. This feature is distinctly different from the two earlier periods where the zero-curl line crosses nearly zonally from Labrador to British Isles, allowing the negative wind-stress curl to isolate the small area of positive curl off the eastern seaboard. In effect the increased meridonal tilt of the wind stress curl zero-line allows formation of a positive wind curl region connecting the Gulf Stream area and the Nordic Sill region. Higher resolution (1/2 degree) QuikSCAT winds are available since 1999 which support the existence of the pattern (Fig. 6c) with continuous positive-curl region extending from Cape Hatteras to north of the British Isles (Fig. S5).

The strength of the subtropical easterlies and subpolar westerlies is another important aspect of the variability and changes in their strength can force spin-up or spin down the corresponding gyres. Along with the NAO index, westerly winds have weakened since 2001 (Fig. S6), at the time when the EKE and drifter speeds increased east of the MAR. This suggests that the direct influence of the wind stress on the gyres cannot be responsible for the increased EKE or newly opened drifter paths from the subtropics to Rockall Trough. The seemingly opposite behavior of the gyre strength as measured by sea surface height and of EKE or drifter paths suggests importance of baroclinic changes in the northern North Atlantic involving the surface ocean down to the thermocline and deeper.

Conclusions

The surface currents in the northern North Atlantic have undergone major changes by opening 'new' pathways for high salinity waters from the western subtropics to the subpolar gyre and further to the Nordic Seas. This finding is important because the increased salinity of the waters flowing to the Nordic Seas helps eventually to strengthen the meridional overturning, and possibly to work against the widely predicted slowing of the global overturning induced by global warming. Decreasing deep convection follows warming and freshening of the high-latitude surface waters in the majority of the IPCC climate-model simulations *(20)*.

The pathways reported here have likely been opened and closed before but with the surface drifter observations since the late 1980s we have been able to observe these surface current changes. Opening of this pathway explains why the waters entering the Nordic Seas have become much more saline since the mid 1990s *(1)*, and particularly after 2000. The earlier saline periods in the Rockall Trough occurred during the late 1950s lasting to the arrival of the Great Salinity Anomaly in the early 1970s and in the early 1980s *(21)*. A longer time series exists from the Faroe-Shetland Channel which shows that even higher salinities were encountered in the 1930s until about 1940 (before a 5 year gap), when a strong warming occurred in the Atlantic subpolar zone *(21)*. All of these epochs were characterized by a negative NAO index during or prior to the event. Considering this past history, the newly opened pathways from the western subtropics to the Nordic Sills are not stable, and there is no guarantee that they will remain open in the future years.

Our investigation focused on the early 1990s with strong positive NAO years (1991-1995), transitioning to highly fluctuating NAO years with weak amplitude, divided into periods for 1996-2000 and 2001 -2006. To explain the surface current changes, the role of the wind-stress curl is invoked, and especially its zero-line which divides the subpolar and subtropical gyres when the zero-curl line is oriented zonally. Theoretical studies of wind driven circulation show that an increasingly meridional tilt of the wind stress curl zero-line allows the northeastward expansion of the subtropical gyre *(19)*. We find that diverse locations of the zero wind--stress curl with equally variable tilt after 1995, however, differences between the three periods emerge when forming multi-year averages of the winter wind stress curl. The last period, 2001-2006, has a positive curl extending from Cape Hatteras to Nordic Sills forming a continuous, tilted zero-curl line, unlike the two other periods when the zero-curl line crosses nearly zonally from Labrador to British Isles leaving a small isolated patch of positive curl off Cape Hatteras. The apparent NAO connection arises because a negative NAO phase is usually associated with a southward shift of the storm track allowing a positive wind stress curl region to extend continuously from the subpolar gyre to Cape Hatteras. The longer record of curl variability at the western side of Atlantic (Fig. S7) indicates that the previous epoch of positive curl stretching from Cape Hatteras to British Isles (and the tilted zero--curl line) occurred in the late 1950s and during 1960s. These are also periods of negative NAO phase and high salinity waters in the Faroe-Shetland Channel.

Altimetry can verify the drifter path changes from EKE fields which follow closely the locations of major currents such as the branches of NAC. From EKE we can determine the exact timing of the changes in any given location such as the steep increase in NAC EKE east of the Mid-Atlantic Ridge during year 2000. NAC EKE stayed elevated at least until 2005, consistent with the shift in the drifter tracks from eastward to northeastward. On the other hand, the sea surface height from altimetry indicates that as a whole, the upper subpolar gyre of the North Atlantic continues to weaken through 2005 which is opposite to the surface current/EKE behavior. In our view these two phenomena are not in disagreement, but instead point to changes in the vertical structure of the North Atlantic Ocean. The gyre effect seen by altimetry can be interpreted as shrinking of the subpolar gyre associated with the westward movement of the subarctic front. Meanwhile the information from the surface drifters shows that the most saline surface waters at the entrance to the Nordic Seas came from the western and central North Atlantic dominated by the Gulf Stream waters in the recent years and not from the eastern basin.

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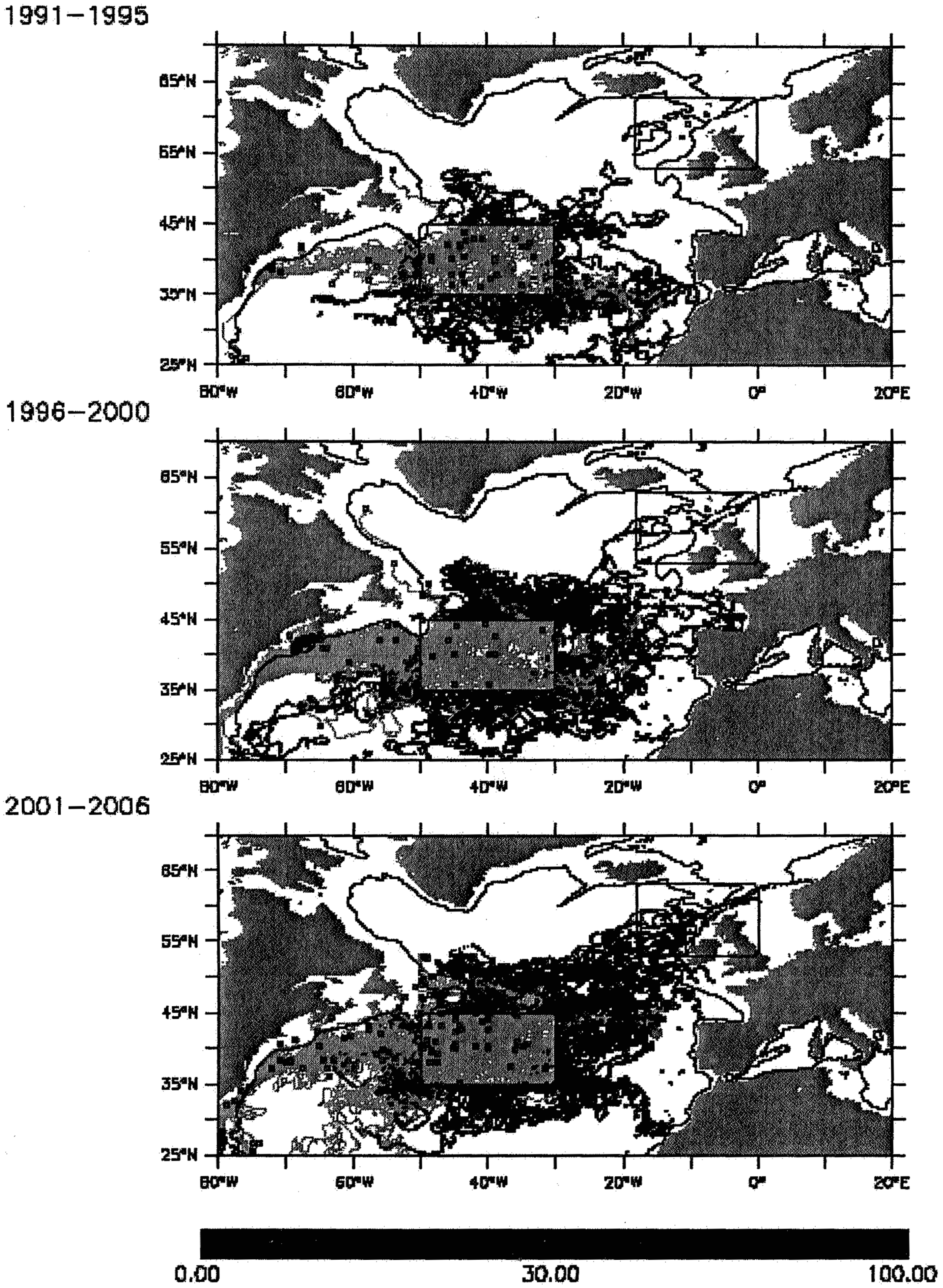


Fig. 1 Drifter tracks entering (cyan) and leaving (blue and red) the subtropical box (30W-50W, 35N-45N). Red drifter tracks have drifter velocity greater than 30cm/s.

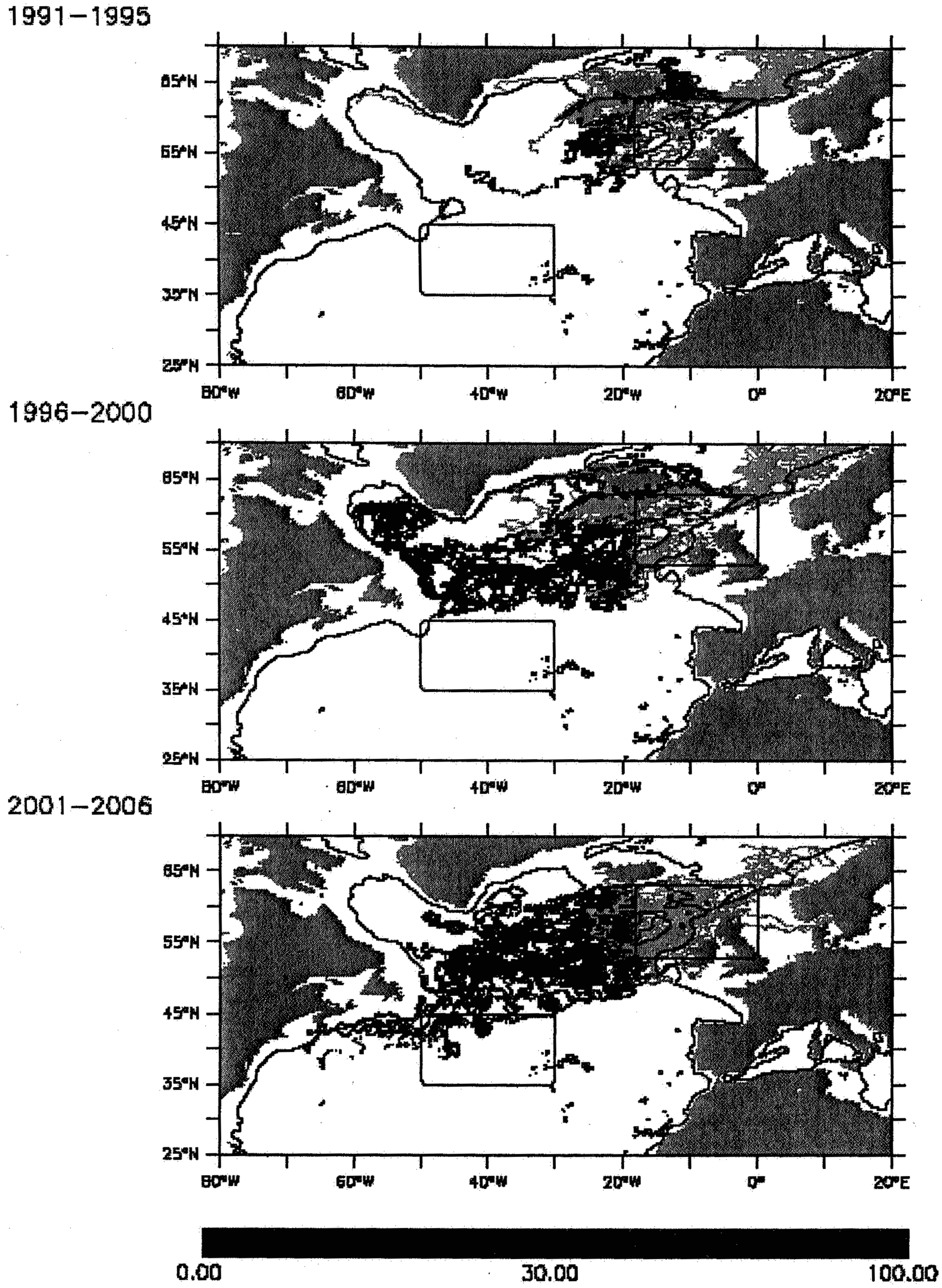


Fig. 2. Fig. 1 Drifter tracks leaving (cyan) and entering (blue and red) the subpolar box (0-18W, 53-63N). Red drifter tracks have drifter velocity greater than 30cm/s.

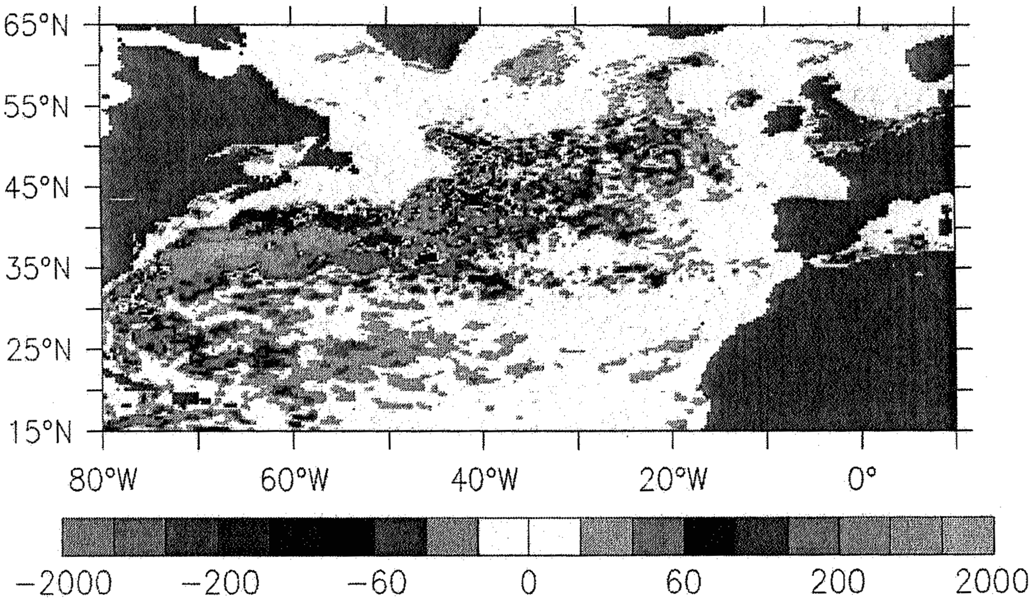
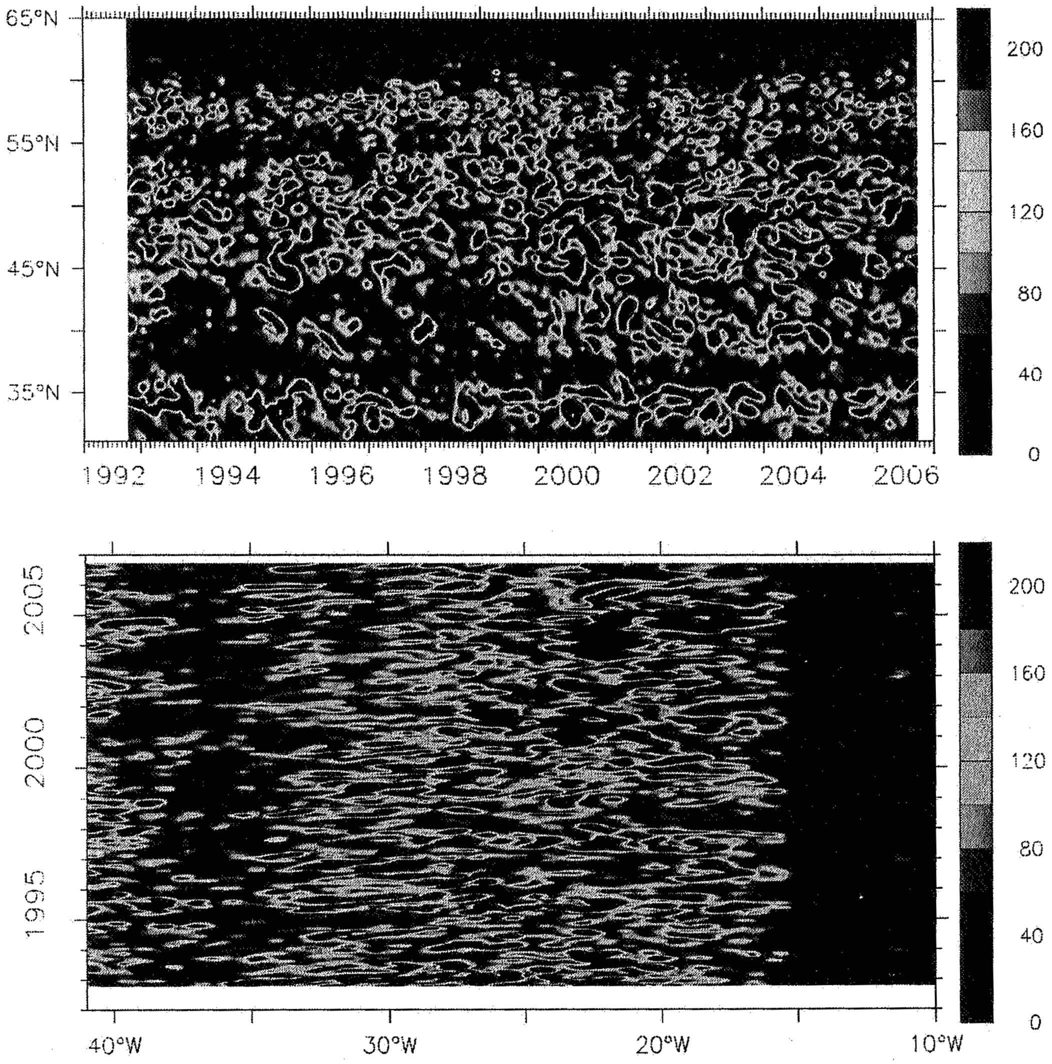


Fig. 3. Trend in EKE from 1/3 degree AVISO altimeter data (October 1992 to September 2006). Units are cm2/s2 per 10 years.



25W

At 52N

Fig. 4 EKE from AVISO altimeter data at sections 25W (upper panel) and 52N (lower) panel). Units are cm2/s2.

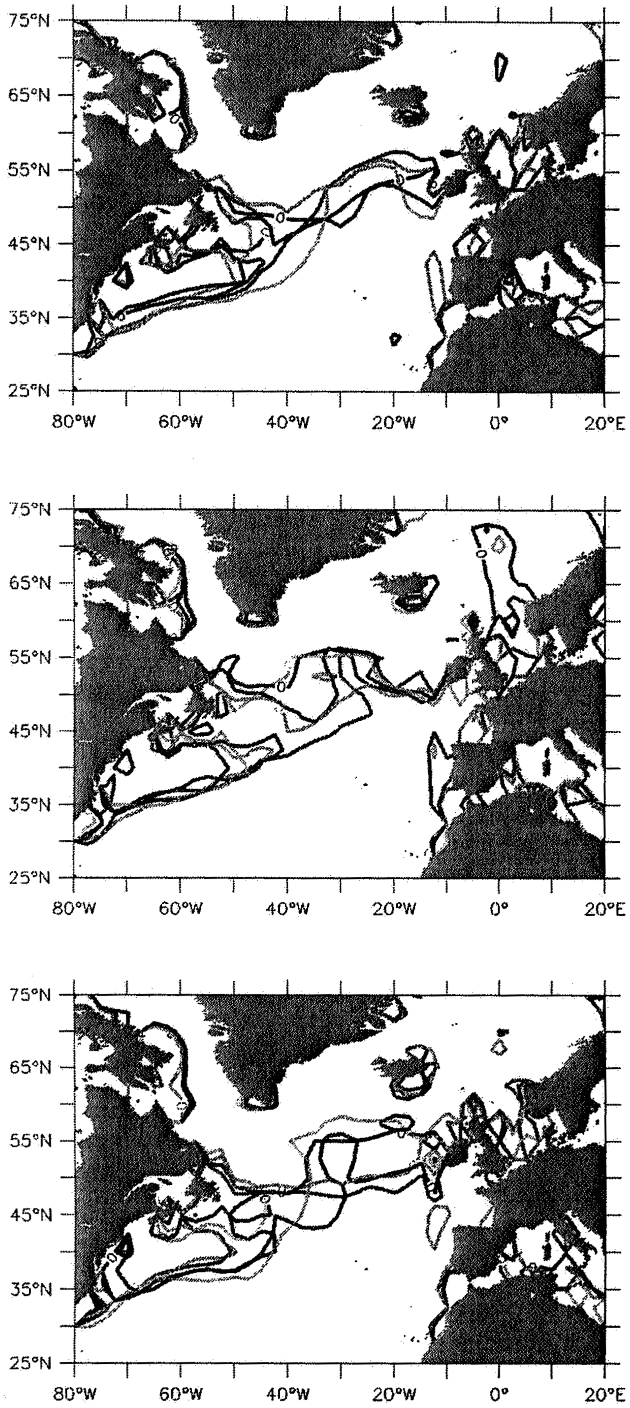


Fig. 5. The locations of the zero-line for the annual average wind stress curl from NCEP/NCAR Reanalysis for 5 year periods of 1991-1995 (top panel), 1996-2000 (middle panel), and 2001-2005 (bottom panel). The colors in each period denote: 1. year= black, 2. year= read, 3. year=green, 4.year = blue, and 5. year=cyan.

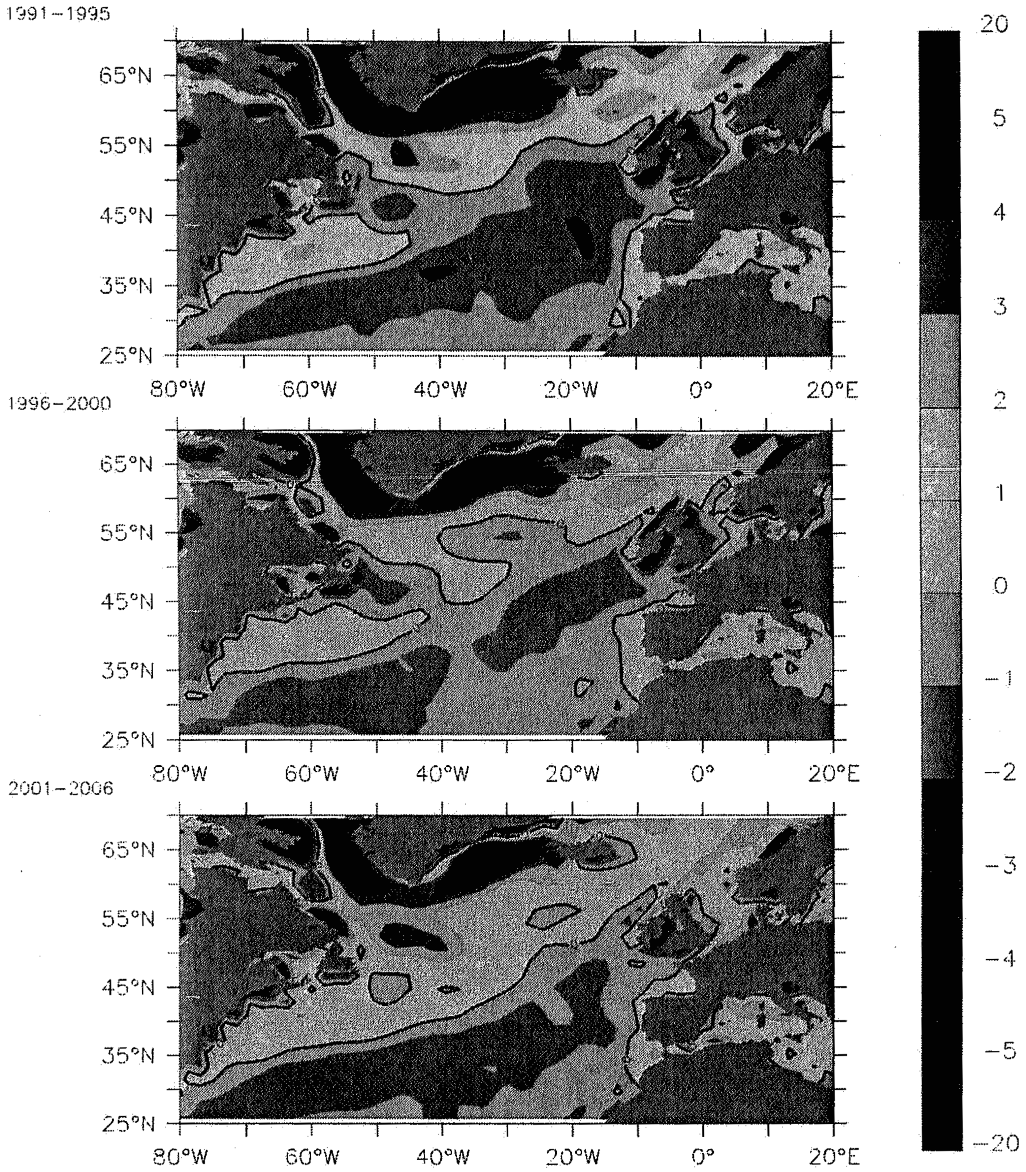


Fig. 6. Wind stress curl from January-March from periods 1991-1995 (top), 1996-2000 (middle) and 2001-2006 (bottom) computed from NCEP/NCAR Reanalysis. Units are 1.E-7 N/m3. The black line denotes zero curl isoline.

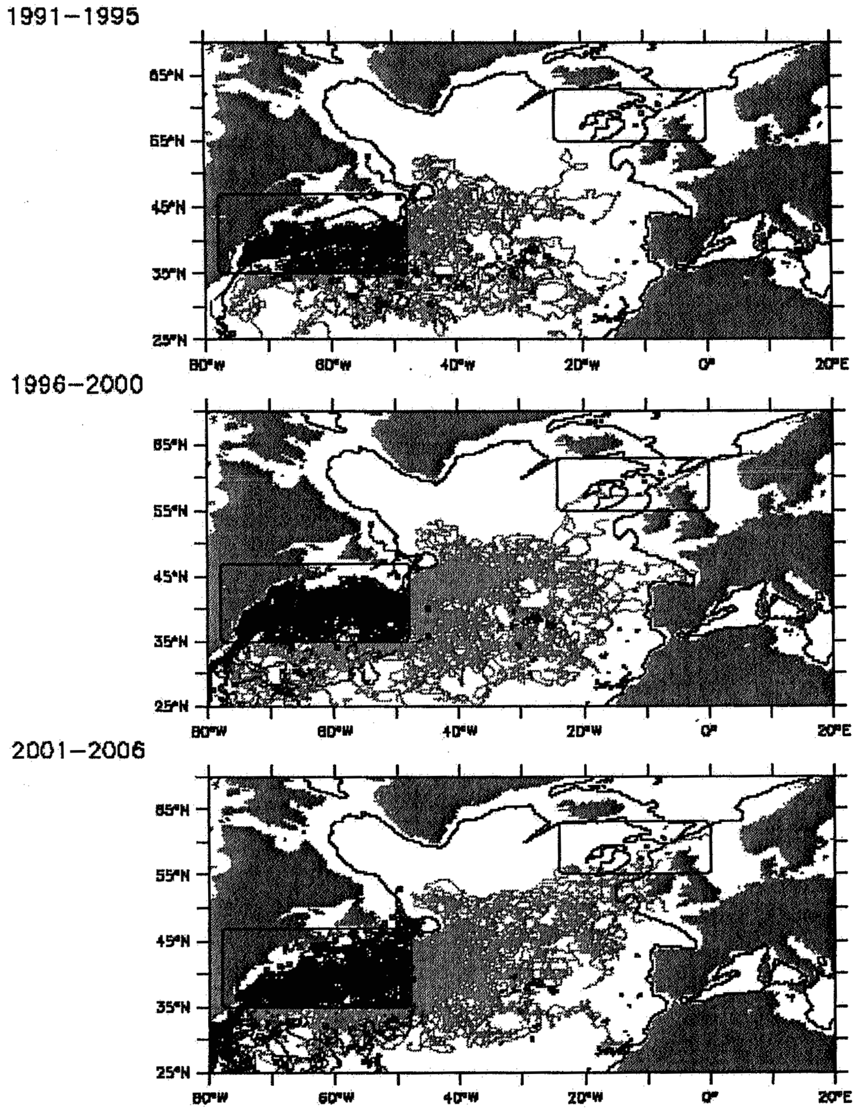


Fig. S1. Drifter tracks entering (purple) and leaving (cyan) the subtropical box (48W-78W, 35N-47N) used in Brambilla and Talley (1996) for the 3 periods shown.

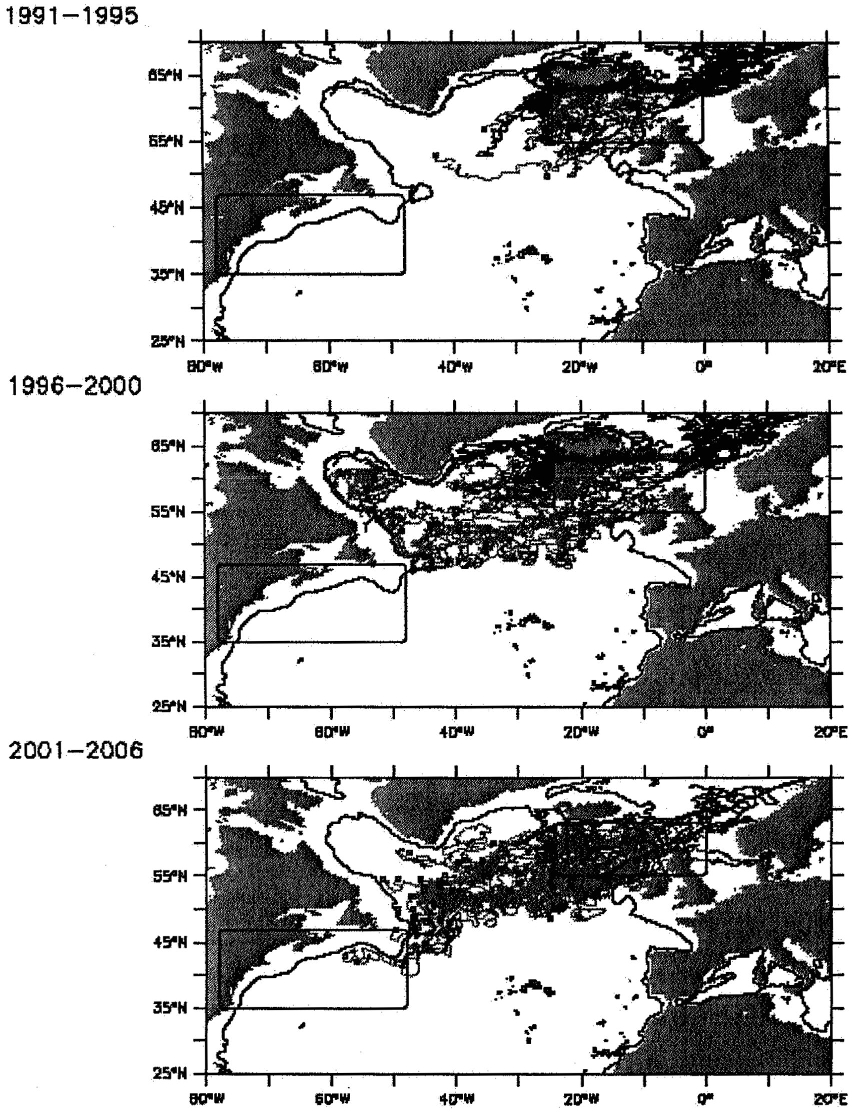


Fig. S2 Drifter tracks entering (green) and leaving (blue) the subpolar box (0W-25W, 55N-63N) used in Brambilla and Talley (1996) for the 3 periods shown.

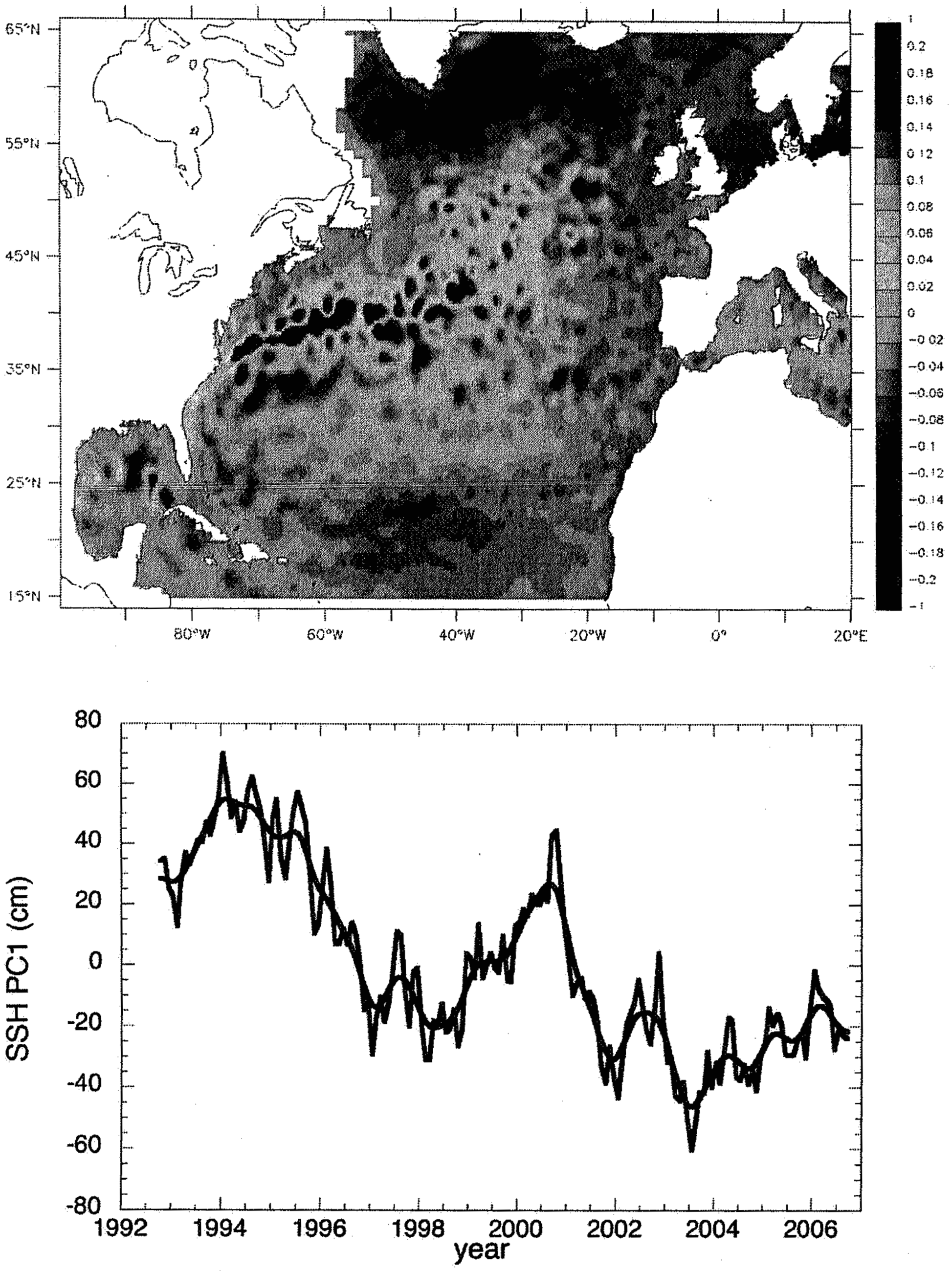


Fig. S3. The spatial pattern of the first empirical orthogonal function (top) and associated time series (bottom) for the sea surface height from AVISO altimeter data. The spatial pattern is dimensionless, the time series have units of cm.

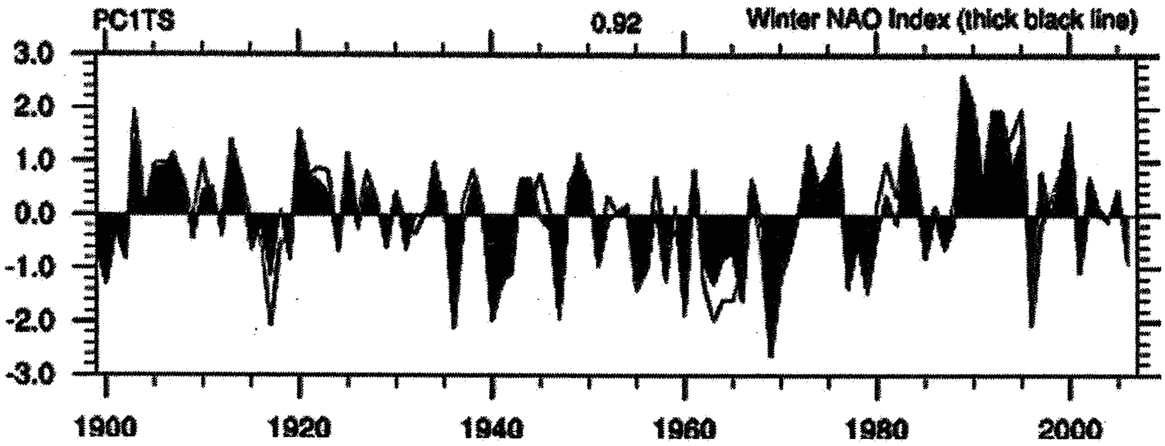


Fig. S4. Winter (DJFM) NAO index from http://www.cgd.ucar.edu/cas/jhurrell/indices.html.

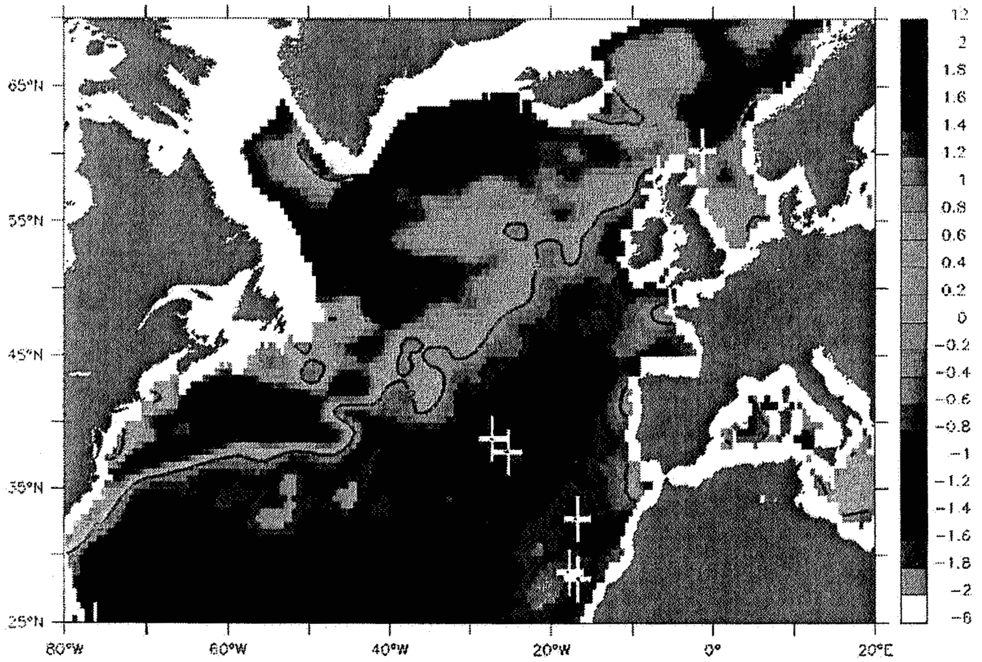


Fig. S5. Wind stress curl from January-March from 2001-2006 computed from QuikSCAT 1/2 degree data. Units are 1.E-7 N/m3.

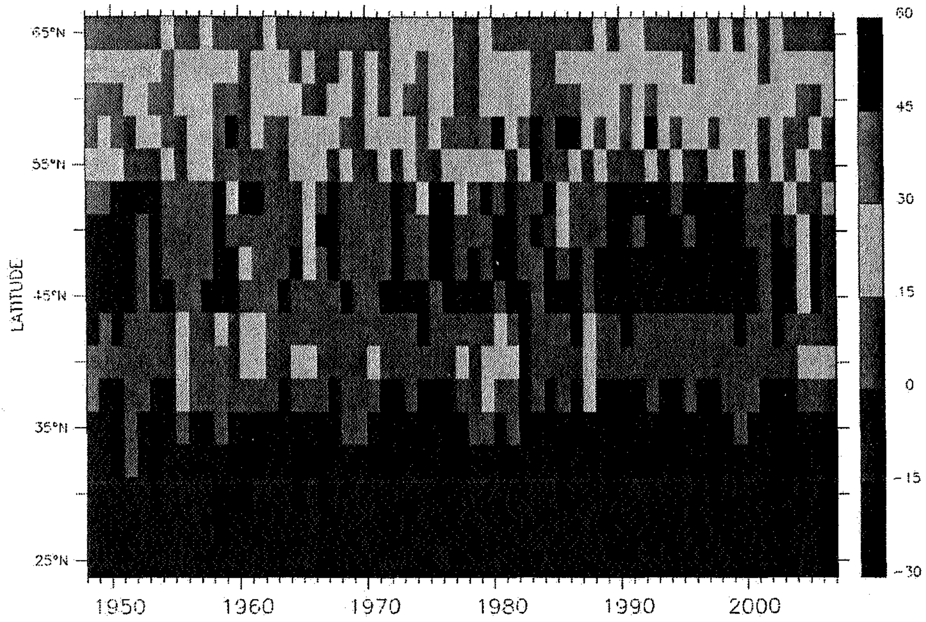


Fig. S6. Winter (January-March) wind stress curl averaged from 47.5W to 57.5W for 1948-2006. Units are 1.E-8 N/m3. Note the frequent occurrence of years with positive curl values connecting 40N and 50N (indicative of a continuous positive curl from Cape Hatteras to the subpolar gyre) from the mid 1950s to the early 1970s and lack of such years from the mid 1980s to 2001.

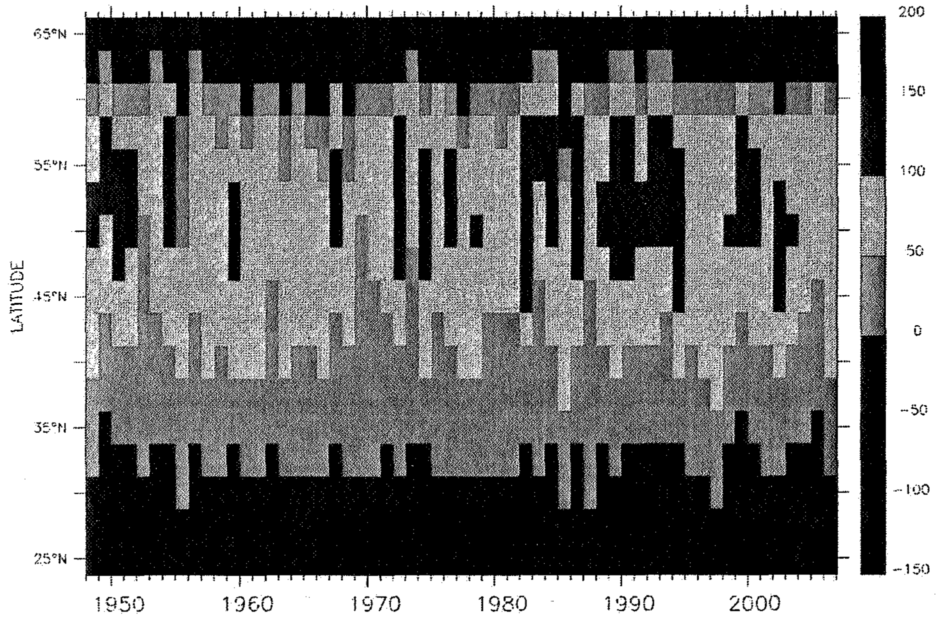


Fig. S7. Annual wind stress averaged from 50W to 10W for 1948-2006. Units are 1.E-3 N/m2.