Spin-down of the North Atlantic Subpolar Circulation

S. Häkkinen[1] and P.B. Rhines[2]

[1] NASA Goddard Space Flight Center, Code 971, Greenbelt, MD 20771
[2] Univ. of Washington, Box 357940, Seattle, WA 98195
Corresponding author e-mail: sirpa.hakkinen@nasa.gov

Abstract

Dramatic changes have occurred in the mid-to-high-latitude North Atlantic Ocean as evidenced by TOPEX/Poseidon observations of sea surface height (SSH) in the subpolar gyre and the Gulf Stream. Analysis of altimeter data shows that subpolar SSH has increased during the 1990s and the geostrophic velocity derived from altimeter data shows a decline in the gyre circulation. Direct current-meter observations in the boundary current of the Labrador Sea support the trend in the 1990s, and, together with hydrographic data show that in the mid-late 1990s the trend extends deep in the water column. We find that buoyancy forcing over the northern North Atlantic has a dynamic effect consistent with the altimeter data and hydrographic observations: a weak thermohaline forcing and the subsequent decay of the domed structure of the subpolar isopycnals would give rise to the observed anticyclonic circulation trend.

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Popular Summary

The manuscript has new information about the behavior of the North Atlantic circulation on decadal time scale as seen by satellite altimeter missions. First of all, it shows that the circulation changes during the 1990s at the high latitudes are statistically significant, while at the mid latitudes the signal is poor. Secondly it combines the 1990s altimeter data with data from earlier satellite missions to show that indeed the 1990s have been a roller coaster of changes in the subpolar gyre. And presently, as of Spring 2002, the subpoalr gyre was the weakest as measured by altimetric geostrophic velocity. Also we include hydrographic data and direct current meter measurements that support the findings from the altimetric data.

Because we lack SSH data prior to 1978, we cannot determine whether the 1990s decrease is a return to 'normal' from the extremely cold early 1990s, or the beginning of a longer term trend. Since Labrador Sea processes are intimately linked to the meridional overturning circulation (MOC), these observations of rapid climatic changes over one decade may merit some concern for the future state of the MOC. Continuation of the altimeter missions will allow us to follow the evolution of this subpolar signal and its influence on the North Atlantic. ASOF-Program observations of the subsurface oceanic circulation, hydrography and ice cover will be of great importance in establishing the origin of these climate shifts.

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Dramatic changes have occurred in the mid-to-high-latitude North Atlantic Ocean as evidenced by TOPEX/Poseidon observations of sea surface height (SSH) in the subpolar gyre and the Gulf Stream. Analysis of altimeter data shows that subpolar SSH has increased during the 1990s and the geostrophic velocity derived from altimeter data shows a decline in the gyre circulation. Direct current-meter observations in the boundary current of the Labrador Sea support the trend in the 1990s, and, together with hydrographic data show that in the mid-late 1990s the trend extends deep in the water column. We find that buoyancy forcing over the northern North Atlantic has a dynamic effect consistent with the altimeter data and hydrographic observations: a weak thermohaline forcing and the subsequent decay of the domed structure of the subpolar isopycnals would give rise to the observed anticyclonic circulation trend.

Introduction

The high northern latitudes of the Earth are experiencing rapid climate change, and there is preliminary evidence that greenhouse warming is a contributing cause *(1)*. High-latitude changes are communicated to the rest of the world through coupled circulations of atmosphere and ocean. Recent work has affirmed the essential contribution of oceanic advection of heat and fresh-water to climate variability at many time-scales *(2-4)*. One of the primary predictions of climate models, the slowing of the ocean circulation over current and future decades, is the subject of this paper.

The subpolar gyre of the North Atlantic circulates cyclonically between 50N and 65N, imbedding strong boundary currents. It is a buffer between the warm subtropics and the Arctic and sub-Arctic Seas where the horizontal gyre circulation and the up-down/north-south circulation of the global ocean circulation overlap. It is also a region of intense interaction between ocean and atmosphere: Wintertime cold winds remove heat at rates of several hundred watts m^{-2}. Deep convection, reaching as much as 2500m below the surface, mixes downward the low-salinity surface waters. The decreased dynamic height of the water column, together with barotropic effects and laterally driven circulation, controls subpolar gyre circulation. Arteries of denser water pass through the subpolar gyre from the northern overflows between Greenland and Scotland. These combine with subpolar waters to provide the origins of North Atlantic Deep Water (NADW), after modification by both mixing and air-sea interaction during their passage through the subpolar gyre. Climate models represent these processes, yet the balance between the several different production sites for NADW is very subtle and must be calibrated with observations *(5-10)*. This question of balance applies also to climatic changes in the properties and transports now being observed.

The subpolar North Atlantic undergoes a prominent decadal-to-century variability in its hydrographic properties *(11-18)*. During the 1990s, in situ data from the Labrador Sea show decreased deep convection since 1996, and much fresher surface conditions over the same area. Global climate models almost universally predict that the global MOC will decrease strongly as the result of this surface freshening and warming *(1)*. The 1990s period of strong hydrographic change overlaps with the TOPEX/Poseidon mission, which provides an opportunity to derive large-scale variability in the subpolar North Atlantic. Recent studies using TOPEX/Poseidon data have given evidence of large changes between the early and latter 1990s *(19-20)*. These changes have been interpreted as being driven by a North Atlantic Oscillation (NAO) shift that took place in winter of 1995/1996, for example, *(20)*, a wind-driven shift in location of the subpolar frontal system. In addition, the northern overflow arteries are changing: long-term hydrographic measurements carried out in the eastern subpolar gyre, Nordic and Barents Seas, all show trends implying 1990s variation in the warm, saline northward flowing Atlantic waters *(21, 30, 31)*, and in some cases changes extending back several decades.

Our objective is to build understanding of the subpolar North Atlantic circulation changes during the 1990s by using altimetry and *in situ* measurements. Satellite observations of SSH variations are usually interpreted in terms of heat storage which at temperate latitudes and tropics is mainly determined by (adiabatic) vertical movement of isopycnals due to local and/or remotely forced dynamics. Toward high latitudes this relationship is modified to some extent from the increasing salinity contribution to sea-water density and thus to SSH. Also, in the weakly stratified polar-subpolar oceans, the wind-driven barotropic ocean response contributes to SSH. From the perspective of our study, a more pressing issue is the relative contribution of dynamics and local heat flux to heat storage in the subpolar gyre where strong surface cooling can modify the stratification down to the deepest water masses. The dynamic impact of changes in ocean heat storage depends on their depth penetration, with deeper thermal anomalies bearing more potential energy and more baroclinic transport. For this reason, *in situ* current and hydrographic observations are important in validating inferences from altimetry data.

Altimetry data analysis

We use the archived one-degree resolution TOPEX/Poseidon data, which has been combined with ERS-1/2 data into the NASA Pathfinder data set. The Pathfinder data set also includes the Seasat and Geosat data which are referenced to TOPEX. The height fields are validated against the WOCE global tide gauge network and the inverse barometric effect has been removed as well as various atmospheric corrections have been applied. The accuracy of the TOPEX/Poseidon altimeter is about 4cm, while the Seasat and Geosat accuracies are of the order of 10cm or more.

Climatological sea surface height in the North Atlantic is low in the cyclonic subpolar gyre and high in the anticyclonic subtropical gyre. This surface topography reflects the thermocline structure and the sense of rotation of the gyres. We will investigate the monthly anomalies superimposed on this climatological state by using Empirical Orthogonal Function (EOF) analysis. The leading EOF mode of the SSH (explaining 11.1% of the variance) has a spatial pattern of opposing sign SSH anomalies located over the Gulf Stream and over the western and northern side of the subpolar gyre (Fig. 1). The time series of this pattern displays a decade-long trend with increasing SSH over the subpolar gyre but decreasing SSH over the Gulf Stream. The trend in the subpolar gyre ranges from 4-9 cm/decade with the largest trend in the Irminger Sea just south of the Denmark Strait. This could suggest changes in the convective processes driven by orographic winds/cooling in the wake of Greenland, as has been stressed recently *(22)*. The trend itself can be a part of a low frequency cycle *(14)*, or it could represent a secular trend due to climatic change. We know that the subpolar gyre deep waters have freshened for the last 30 years *(11, 13, 23)*. This freshening has affected also the Greenland-Norwegian Sea, and may have multiple origins in both Arctic and subpolar regions. At the surface, salinity has undergone several freshening periods with the latest in the early to mid 1990s *(15, 16)*.

Altimetric SSH anomalies, whatever their origin, balance geostrophic surface-velocity anomalies, in part corresponding to changes in gyre circulation. The geostrophic velocities are computed from SSH smoothed by one Laplacing filter. Since SSH variability is dominated by a trend, a trend in the geostrophic velocity field is recovered from the TOPEX/Poseidon-ERS-1-2 data, May 1992 to April 2002 (Fig. 2). Trend vectors trace the outline of the subpolar gyre and track the Atlantic flow northward, generally suggesting a weakening gyre circulation. Off the Labrador Coast the trend is 1-1.5 cm/s per decade which, with approximate width of 500km and depth of 1500m, would correspond to about 7-10 Sv (Sv=10^6 m^3/s). Observational estimates have roughly 40 Sv total transport in the Labrador Sea boundary current, *(24)*, thus the trend is a significant fraction of the mean flow.

The trend vectors (Fig. 2) correspond well with the shape of the western subpolar gyre; the mean circulation involves boundary currents along the Iceland-Scotland Ridge and around the Labrador Sea. The northward flow of the total circulation has components in mid-basin, along the Reykjanes Ridge toward Iceland, and also in the eastern basin, feeding the northward flow of warm Atlantic Water to the Nordic and Barents Seas and Arctic. Observations using drifting buoys and deep RAFOS floats all support the multiple (and time-variable) pathways of northward circulation in this region, with strong gyres of recirculation. In particular, isopycnal RAFOS floats show circulation at about 600m depth resembling our surface trend map, Fig.2, with much of the Gulf Stream water recirculating within the western subpolar gyre rather than extending far to the east *(25-29)*. The important question of a possible trend in the northward flow of the warm Atlantic Water into the Norwegian Sea is left unresolved in our study, yet there are indications that this is indeed happening *(30)*.

The t-test for the significance of the trend (displayed also in Fig. 2) is computed for both vector components separately, and the larger one is retained to indicate the significance of the trend vector. The resulting distribution shows the trend to be much more significant in the subpolar gyre than in the subtropics. This suggests that the subpolar ocean is particularly suitable for detecting decadal climate signals on basin scales. The same signal is likely to exist elsewhere in the North Atlantic, but the signal to noise ratio is poor.

Altimeter data is available also for the two months in 1978 (Seasat) and for nearly 4 years during the 1980s (Geosat). In an EOF analysis we can combine all of these satellite measurements to infer the strength of the gyres (assuming that the EOF is stable) at these separate time intervals. The first EOF of the geostrophic velocity field contains 9.4% of the total variance when the velocity components are normalized by the standard deviation of the current speed anomalies and then smoothed in time by 4 binomial filters. (The variance of the first mode increases to 16% for the TOPEX period with nearly identical spatial pattern of vectors.) The EOF1 in Fig. 3 displays nearly the same pattern as Fig. 2 but with opposite sign (the direction of the circulation is chosen to align with the climatological circulation). The corresponding time series (principal component; PC; also in Fig. 3) shows that the Seasat and Geosat periods appear to be about the same strength, but the 1990s data has a large amplitude change with maximum in the beginning of the 1990s during high NAO index and the lowest strength in the end of the 1990s during negative or moderate NAO index values. We caution that Seasat and Geosat have considerably larger errors than TOPEX/Poseidon. However, differencing the 44 months of the Geosat data and the first 44 months of the Pathfinder ERS-TOPEX data (not shown) contains the same large-scale pattern as in the EOF analysis. The coherence over the large basin scales supports the significance of the differences in the gyre strength indicated by the EOF analysis.

Current meter observations.

Uncertainty about altimetric data accuracy in boundary currents can be alleviated where direct current measurements are available. In October 1996 a subsurface mooring, M1244, was deployed for 19 months, by Rhines and J.R.N. Lazier of Bedford Institute of Oceanography at the 2800m isobath (55.49^{0}N, 53.655^{0}W) on the Labrador continental slope. This location is the core of the boundary current carrying Denmark Strait Overflow Water in the lower 500m, and it also captured much of the structure in the Northeast Atlantic Deep Water, Labrador Sea Water, and Irminger Sea Water above; the principal water masses of the region and dense overflows from the Nordic Seas all pass through this region. The vertical structure of the boundary current is remarkably barotropic, considering its baroclinic origins. The time-series, Fig. 4, show, first, that the upper level circulation (here observed at 200m depth) decreases by roughly 25% over the length of the record, approximately in parallel with the decrease in the PC1 time series. Taken alone, this record would not establish a longer trend, yet it supports the altimetric picture of a gyre spin-down in the mid-1990s. The vertical structure is of great importance. The expanded inset in Fig. 4 shows that the general down-trend occurs over the full water column, between 200m and 2750m. This suggests that the trend in the altimeter observations may penetrate vertically, through all the major water masses of the subpolar gyre. A contribution to the trend in the deepest water masses may also come from farther north: the Faeroe-Shetland Channel contribution to the NADW overflow has experienced a down-trend since 1996 based on direct ADCP current measurements and inferred from hydrography to have continued 50 years into the past *(31)*.

In addition to our current record above, a much longer record, 1979-present (M3, Fig. 4) from the 1000m isobath upslope of the 1244 mooring (maintained by Bedford Inst. of Oceanography, Canada), suggests that the mid-1990s were unusually energetic, relative to the 1980s and late 1990s. The time-series of the along-isobath current and temperature, *(not included)*, show the decadal variation of Labrador Sea Water temperature, and also a mid-1990s maximum in current. The deceleration from mid-1996 to 2000 resembles the PC1 altimetric record. The currents before the long data gap in 1993-96 show little annual or interannual variability. This would be consistent with the the unusually strong circulation in the early-mid 1990s.

Possible causes for the spin-down

The 1990s climate in the North Atlantic is dominated by a large shift in NAO intensity; from an extreme high index phase to a low index one, which influences both the buoyancy and wind stress curl over the subpolar ocean. The trend can originate from several sources: the effects of wind-stress, local air-sea buoyancy forcing, and distant air-sea interaction propagated into the region by the circulation itself, as well as the interplay between fast, barotropic response to wind-stress *(32-33)* and barotropic gyre response to the baroclinic overflows entering the region *(34)*. There are indications of enhancement of both cyclonic circulation and the MOC following cold, windy winters seen in distant boundary currents *(35-36)*, consistent with our results. Despite the complexity of the problem, the buoyancy and wind stress forcing can be analyzed to determine their variability and to infer their dynamic influence on the subpolar gyre. First we establish the depth of penetration of the baroclinic signal. The potential density field (Fig. 5) and heat-storage, integrated over the water column, both exhibit the expected trend following the cold, dense extreme reached in 1993. Both properties extend deeper than 2000m and contribute much of the altimeter signal, while the column-integrated salinity change shows no such trend. Dynamic height increases about 10 cm during 1993-2002 which is comparable with the altimeter trend.

To explore causes further, we utilize EOF analysis applied to the wind stress curl and net heat flux (NCEP/NCAR Reanalysis) for 1978-2002. The spatial pattern of the leading EOF mode for the wind stress curl (19.2% of variance) and net heat flux (19.4% of variance) are shown in Fig. 6a-b, where the sign convention is such that a positive curl corresponds to cyclonic circulation and a positive heat flux is upward.

The time series associated with the spatial patterns in Fig. 6a-b of the wind stress curl and net heat flux are plotted against the altimetric velocity field in Fig 6c along the wintertime (Nov-April) NAO index. There are several features to observe:

(1), As noted earlier, the NAO has fluctuated wildly, but has returned to positive range by the end of the 1990s. However the air-sea heat-flux pattern normally associated with the NAO has not developed, as the Atlantic storm track has migrated east since 1995 *(37)*.

(2), Wind stress curl and heat flux PC1 both contain a downward trend since 1994, but the wind stress curl has large fluctuations similar to the NAO index for the obvious reason that it reflects the NAO variability;

(3) Only the net heat flux and geostrophic velocity PC1 follow the overall downward trend of the 1990s, with only modest fluctuations about the trend;

(4) The relationship between NAO and the wind driven curl is such that positive NAO, (corresponding with positive windstress curl north of roughly 60^0N and negative curl to the south) corresponds to an anticyclonic circulation anomaly in the subpolar gyre *(32-33)*. The form of the fast response to the observed wind-stress curl PC1 is simply not that of the SSH PC1, which resembles the mean subtropical and subpolar gyres. It is a result of theory and models, in which wind-driven currents are set up by propagation of topographic Rossby waves along f/h (Coriolis frequency/total depth) contours, eventually approximating a topographic-Sverdrup balance. This produces over a matter of a few weeks a single anticyclonic gyre, or 'inter-gyre', centered at 50^0N latitude, at the boundary between subpolar- and subtropical gyres. The Mid-Atlantic Ridge dominates this f/h waveguide *(38-39)*.

Property (4) implies that the *barotropic* response to the wind stress curl anomaly in the 1990s gives an increasingly cyclonic spin to the subpolar gyre. However, the altimeter and current meter results suggest the opposite, a decay of the cyclonic gyre (i.e. anticyclonic anomaly). On the other hand, model studies suggest that the *baroclinic* response to the wind stress curl is a delayed process and would retard the existing cyclonic circulation. We would expect this influence to manifest itself with large reversals in PC1 of the geostrophic velocity like the variations in the curl PC1 or NAO with a 3-5 year delay. Figure 6c shows that there are peaks in geostrophic velocity PC1 with such a delay but they are small compared to the overwhelming background trend.

Moreover, the NAO has returned to more moderate high-index values, but the associated strong heat loss in the subpolar ocean has not returned. On the contrary Figs 5, 6c shows nearly continous weakening of the subpolar air-sea heat loss. From observations we know that deep convective conditions in the Labrador Sea have been absent since the early 1990s. The altimetric results suggest that deep convection is important for the strength of the cyclonic subpolar gyre by maintaining a cold core around which the lighter water masses circulate. Once deep convection ceases, the gyre starts to decay. Based on this reasoning, the 1990s heat flux trend can result in a dynamical impact that can act parallel to the observed trend in the gyre strength: The weak wintertime heat loss fails to support a strong convection and upwardly tilting isopycnals in the Labrador Sea. This decrease in the cold core of the Labrador Gyre is observable in hydrographic data (Fig. 5d). The heat-storage time-series for the Labrador Sea shows a cold extreme was reached in 1994, followed by warming through the rest of the 1990s. A massive inflow of column-average freshwater occurred in the 1960s-70s, but does not continue in the 1990s because weakened circulation and warmer conditions make the deep water more saline while the surface waters become fresher.

The involvement of the greater climate system in the strong circulation of the early 1990s and downward trend since must be acknowledged as a possibility. NAO air/sea heat flux, precipitation and windstress affect the Arctic and subtropics as well as the subpolar zone.

Conclusions

Altimetric geostrophic circulation observations and supporting deep-sea current meter observations suggest significant changes over the last decade, with increasing sea surface height and weakening subpolar gyre circulation. By comparing the dynamic consequences of three mechanisms, barotropic and baroclinic response to wind stress curl and buoyancy forcing, we conclude that it is unlikely that the gyre weakening in the 1990s was caused by wind stress changes associated with NAO. A more likely cause of the trend is the local buoyancy forcing which has mimicked low NAO heat fluxes even though the index itself has reversed itself twice during the 1990s. The weakening-gyre-scenario of the 1990s parallels the warming in the central subpolar gyre which is the well-observed relaxation (increase in buoyancy) of the water column following the intense winter convection period of 1989-1994. The decrease of the NADW overflow in the Iceland-Scotland section *(31)* can also enhance the decay.

Because we lack SSH data prior to 1978, we cannot determine whether the 1990s decrease is a return to 'normal' from the extremely cold early 1990s, or the beginning of a longer term trend. Since Labrador Sea processes are intimately linked to the meridional overturning circulation, these observations of rapid climatic changes over one decade may merit some concern for the future state of the MOC. Continuation of the altimeter missions will allow us to follow the evolution of this subpolar signal and its influence on the North Atlantic. Field observations of the subsurface oceanic circulation, hydrography and ice cover *(40)* will be of great importance in establishing the origin of these climate shifts.

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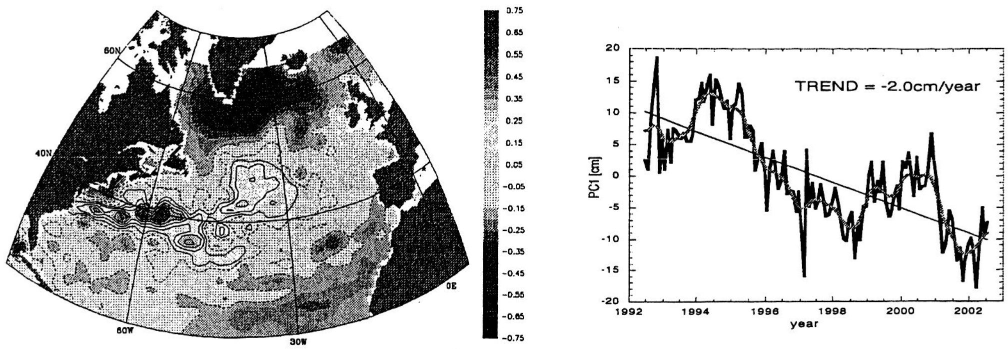


(a) (b)

FIG. 1. (a) EOF1 of altimeter SSH and its PC1 [cm] with 11.1% of the variance. EOF1 is non-dimensional with contour interval of 0.05 for negative values and 0.1 for positive values. (b) The trend in PC1 is significantly different from zero at 95% level. The blue curve is the binomially smoothed PC1.

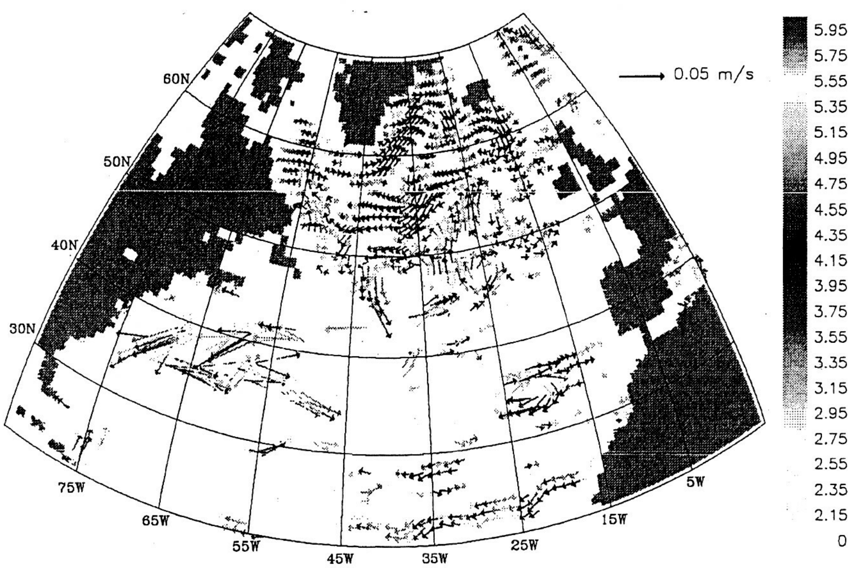
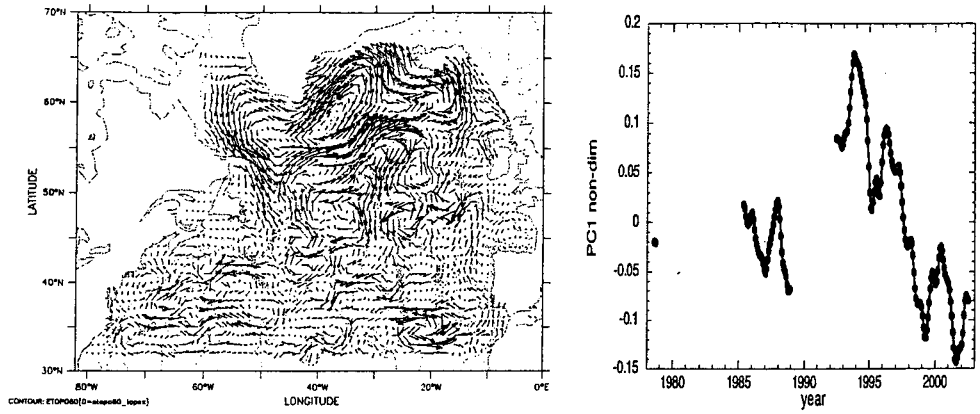
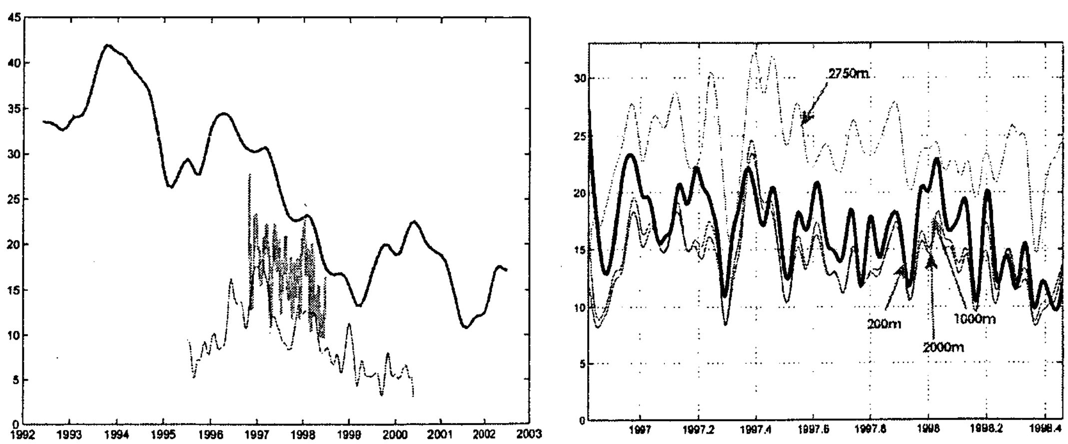


Figure 2. The trend of the of the geostrophic velocities (cm/s per decade) derived from altimeter data for the period 1992 May to 2002 June. Colors represent the t-test value. Values above 2.0 are significant at 95% level, only vectors above this significance level are shown. Velocities above 5cm/s per decade are truncated.



(a) (b)

FIG 3. (a) EOF1 of the geostrophic velocity field derived from the altimeter data with 9.4% of the variance. The vectors are non-dimensional due to normalization of each velocity component by the standard deviation of the current speed anomaly. Dashed red lines are topographic contours with 2000 meter interval starting from 1000m. (b) PC1 of the geostophic velocity field in non-dimensional units.



(a) (b)

Fig. 4. (a) Current meter records from the subpolar Atlantic, with the time-series of the first principal component of the TOPEX altimetry (blue curve) . The 200m level along-isobath velocity at the 2850m isobath in the Labrador Sea boundary current shows a downtrend over 19 months (green curve; due to differing units the *slopes* of velocity and PC1 curves cannot be compared). The along-isobath velocity at 990m depth (purple curve) on the 1000m isobath, 45 km southwest, has a similar, more marked downtrend after 1996.

(b) The vertical structure at the 2800m isobath shows similar downtrend in deep circulation and water masses from the Denmark Strait Overflow and Iceland-Scotland Overflow.

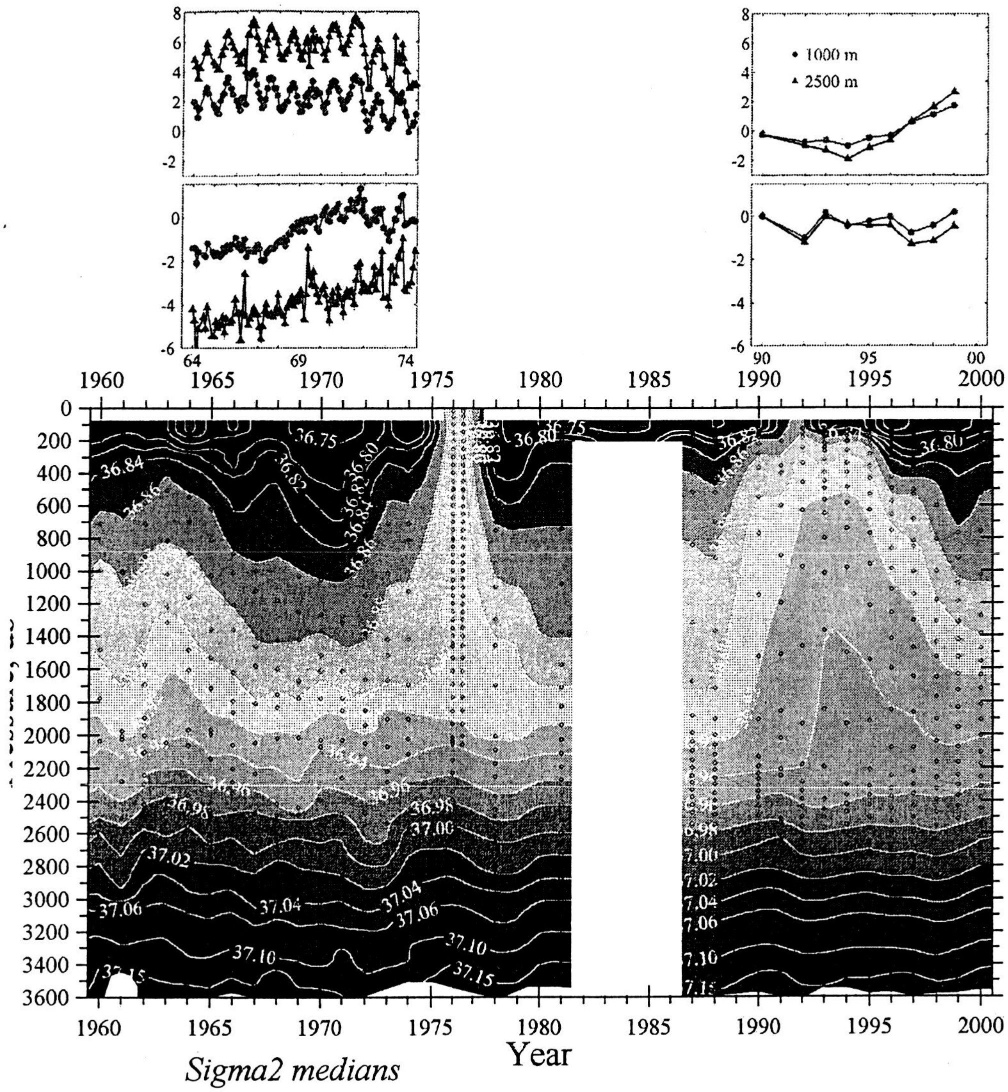
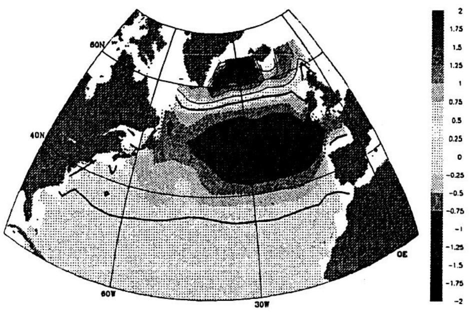
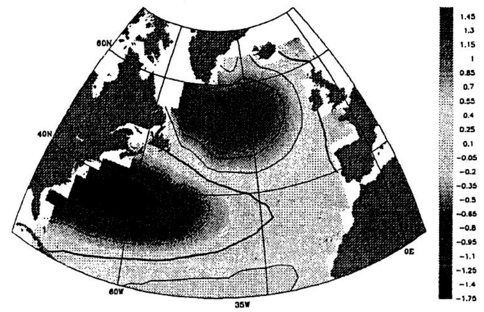


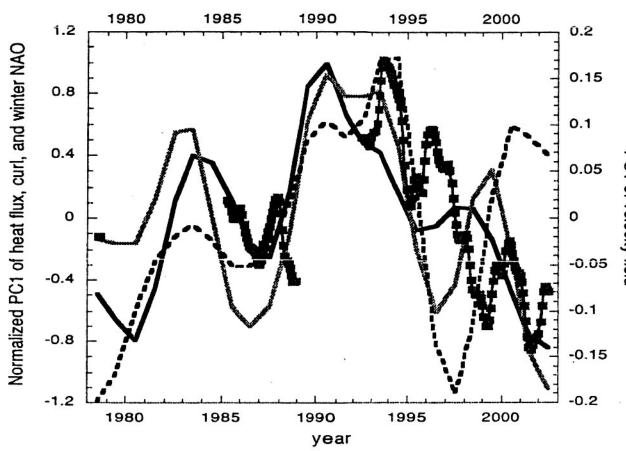
Fig. 5. Time-series of potential density showing the deep penetration of density change in the central Labrador Sea (lower panel, figure by Dr. I. Yashayaev). The extraordinarily cold winters of the early 1990s increased this density in the top 2500m of the Sea, and its warming and decrease in density after 1993 is evident. The upper curves show integrated heat content (10^9 J m^{-2}) to 1000m (blue) and 2500m (green) including the seasonal cycle (left) and for the 1990s, just the early summer data. The middle curves show the corresponding column integrated fresh-water change (in m). The altimetric trend corresponds to the period after 1992, of increased total heat content, decreasing density and nearly constant average salinity. *Major change occurs both over 40 years (1960-2000) and during the decade of the 1990s*



(a)



(b)



(c)

Figure 6. Wind stress curl (a) and net heat flux (b) EOF1 explaining 19.2% and 19.4% of the variance respectively. Positive values mean cyclonic curl and mean upward flux (heat loss from the ocean) respectively. (c) The geostrophic velocity PC1 (red squares) plotted against winter NAO (dashed black) and normalized PC1 of wind stress curl (blue) and heat flux (black solid).