

Low Frequency Change of Sea Level in the North Atlantic Ocean as Observed with Satellite Altimetry

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Abstract. The TOPEX/POSEIDON and ERS-1/2 satellite altimetry missions have revealed significant low-frequency changes of sea level in the North Atlantic Ocean. This work describes the changes that occurred from 1993 to 2001. Decomposition of total variance in three main modes of variability - annual, inter-annual and high frequency (basically eddies) - has been performed. As the analysis has shown, the annual and inter-annual signals are responsible for a greatest portion of variability in the northern North Atlantic outside the North Atlantic Current and its branches. In the areas where the inter-annual change is found to be significant, the sea level change followed the North Atlantic Oscillation index when it changed from its positive phase to negative in winter of 1995 – 1996 and 2000 – 2001.

Keywords. Sea level, satellite altimetry, North Atlantic Ocean

1 Introduction

We studied a 5°W – 65°W, 30°N – 65°N sector of the North Atlantic Ocean (fig. 1). The surface circulation is governed by the Gulf Stream extension in the west, the North Atlantic Current (NAC) separating anticyclonic subtropical and cyclonic subpolar ocean-scale gyres, the Azores Current flowing to the east along the subtropical front at about 33°N and a system of weaker currents within the subpolar gyre. The most recent view on the circulation features in this region may be obtained from Reverdin et al. (2003), Fratantoni (2001), Käse and Krauss (1996), Krauss (1995), Krauss (1986), Krauss and Käse (1984), Otto and van Aken (1996), van Aken and Becker (1996) and Valdimarsson and Malmberg (1999).

Sea level changes occur mainly due to the variations of heat and mass fluxes within the system ocean – atmosphere, the variations of heat and salt budget due to advection, direct influence of atmospheric pressure (inverse barometer effect),

baroclinic instability (eddies), storm surges occurrences etc. Thus, sea level is a good indicator of changes occurring in the upper ocean water properties (expansion and contraction of the water column due to changes in temperature and salinity) as well as in the oceanic circulation (shifts in position of currents and fronts). In this work we distinguish three general modes of the sea level variability present in the ocean:

(1) inter-annual change - the change, which may have an irregular oscillating nature as well as a linear trend;

(2) annual signal, which is a result of ocean-atmosphere interactions at annual frequencies in terms of solar radiation changes, heat fluxes, wind forcing etc.;

(3) high-frequency changes (periods less than 1 year) induced by direct wind forcing and current meandering resulting in eddies generation (periods 10 to 100 days). Another type of oscillation at periods longer than 100 days is propagation of Rossby waves across the ocean basins.

The annual signal of sea level change in the North Atlantic has recently been studied by Ferry et al. (2000). Using both numerical simulation and in situ data, they concluded that in large parts of the North Atlantic the annual cycle is mainly caused by the steric changes induced by heating. However, near the western boundary current and in areas that are the pathways of the NAC, like the Iceland Basin for example, the contribution of advection to the annual signal may also be important (Ferry et al., 2000, Volkov and van Aken, in press).

The inter-annual variations of sea level mainly occur due to changes in heat content of water column induced by alternation of heat and mass exchange between ocean and atmosphere and advection. The latter becomes particularly important on the inter-annual time scales (Reverdin et al., 1999) and varies due to changes in wind stress curl (White and Heywood, 1995), which effects surface oceanic circulation and, hence, the redistribution of water masses with different heat content. The atmospheric circulation pattern with

its wind stress curl has an oscillating pattern in the Northern Atlantic and is usually described by the North Atlantic Oscillation (NAO) index (Hurrell, 1995). The sea level variability in the North Atlantic Ocean has a basin-wide coherent dipole structure between the subtropical and subpolar gyres and changed its sign between 1995 and 1996, coinciding with a change of sign of the NAO (Esselborn and Eden, 2001).

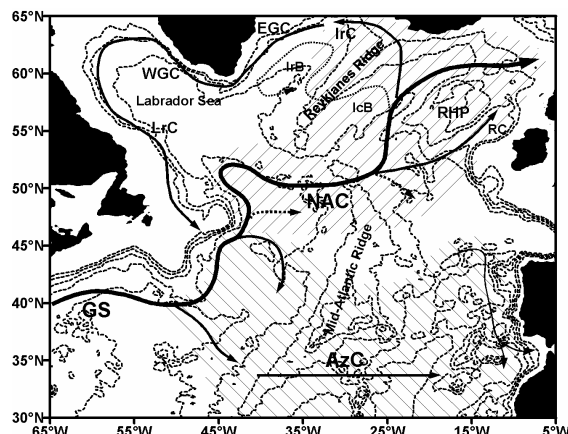


Fig. 1 Map of the study region with bathymetry every 1000 m and surface circulation. The right tilted shading indicates the region where the warm waters of the Subpolar Front are spread. The left tilted shading represents a part of the subtropical gyre (adapted from Krauss, 1986). Abbreviations used: GS – Gulf Stream extension, NAC – North Atlantic Current, AzC – Azores Current, IrC – Irminger Current, EGC and WGC – East and West Greenland Current, LrC – Labrador Current, RC – Rockall Channel, RHP – Rockall-Hatton Plateau, IcB – Iceland Basin, IrB – Irminger Basin.

In this study we emphasize on two first modes of sea level variability and leave the third, although very interesting, out of consideration. Our prime goal is to assess the portion of variance the low frequency change (annual and inter-annual) is responsible for. Another goal is to understand physical mechanism driving the change at inter-annual frequencies, in particular, the influence of changes in atmospheric circulation pattern.

2 Data Used

In this study we used combined TOPEX/POSEIDON (T/P)+ERS-1/2 and T/P alone SLA data from October 14, 1992 to February 13, 2002, produced by the CLS Space Oceanography Division as part of the Environment and Climate EU ENACT project (EVK2-CT2001-00117) with support from CNES (Centre National d'Études Spatiales) and distributed by AVISO (Archiving,

Validation, and Interpretation of Satellite Oceanography Data) operations center (Le Traon et al., 1995 and 1998, Le Traon and Ogor, 1998).

The combined T/P + ERS-1/2 data provide more homogeneous and reduced mapping errors than either individual data set (Ducet and Le Traon, 2000). However this data have a gap of more than one year from January 1994 to March 1995 during ERS-1 ice monitoring and geodetic missions. To fill this gap, the T/P data alone were used for this period. Although there is a little discrepancy between both data sets due to a different accuracy between the T/P tracks imposed by the mapping error (Ducet and Le Traon, 2000), we believe that it does not introduce a spurious variability on the investigated temporal and spatial scales. Moreover the discrepancy becomes even smaller after a spatial smoothing of the data.

The SLA data are mapped on a $1/3^\circ$ Mercator projection grid. There is one map every 7 days. All data have been corrected for instrumental errors, environmental perturbations (wet tropospheric, dry tropospheric and ionospheric effects), ocean wave influence (sea state bias), tide influence (GOT99 tidal correction) and inverse barometer effect corrected with a variable mean pressure (Dorandeu and Le Traon, 1999).

To couple the sea level variations with variations in atmospheric forcing the seasonal North Atlantic Oscillation (NAO) indices, based on the differences of normalized sea level pressure between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland were examined (from J. Hurrell, 2003, <http://www.cgd.ucar.edu/~jhurrell/nao.html>). The sea level pressure anomalies at each station were normalized by division of each seasonal mean pressure by the long-term standard deviation. Since the NAO is most pronounced in winter when it accounts for more than one-third of the total variance in sea-level air pressure (Cayan, 1992), we considered only the winter (December through February - DJF) indices.

3 Sea Level Anomaly Variance Decomposition

As has been mentioned above, we consider the SLA time series $\zeta(x,y,t)$ as a composition of inter-annual, annual and high frequency (mainly eddies) signals $\zeta(x,y,t)=i(x,y,t)+a(x,y,t)+e(x,y,t)$.

The high resolution gridded data set used in this work is very sensitive to sea level variations caused by eddies in high variability regions such as the Gulf Stream and NAC. These variations may bias

the inter-annual signal if there are somewhat larger eddies in one year compared to another or the ratio

of anticyclonic and cyclonic eddies is different.

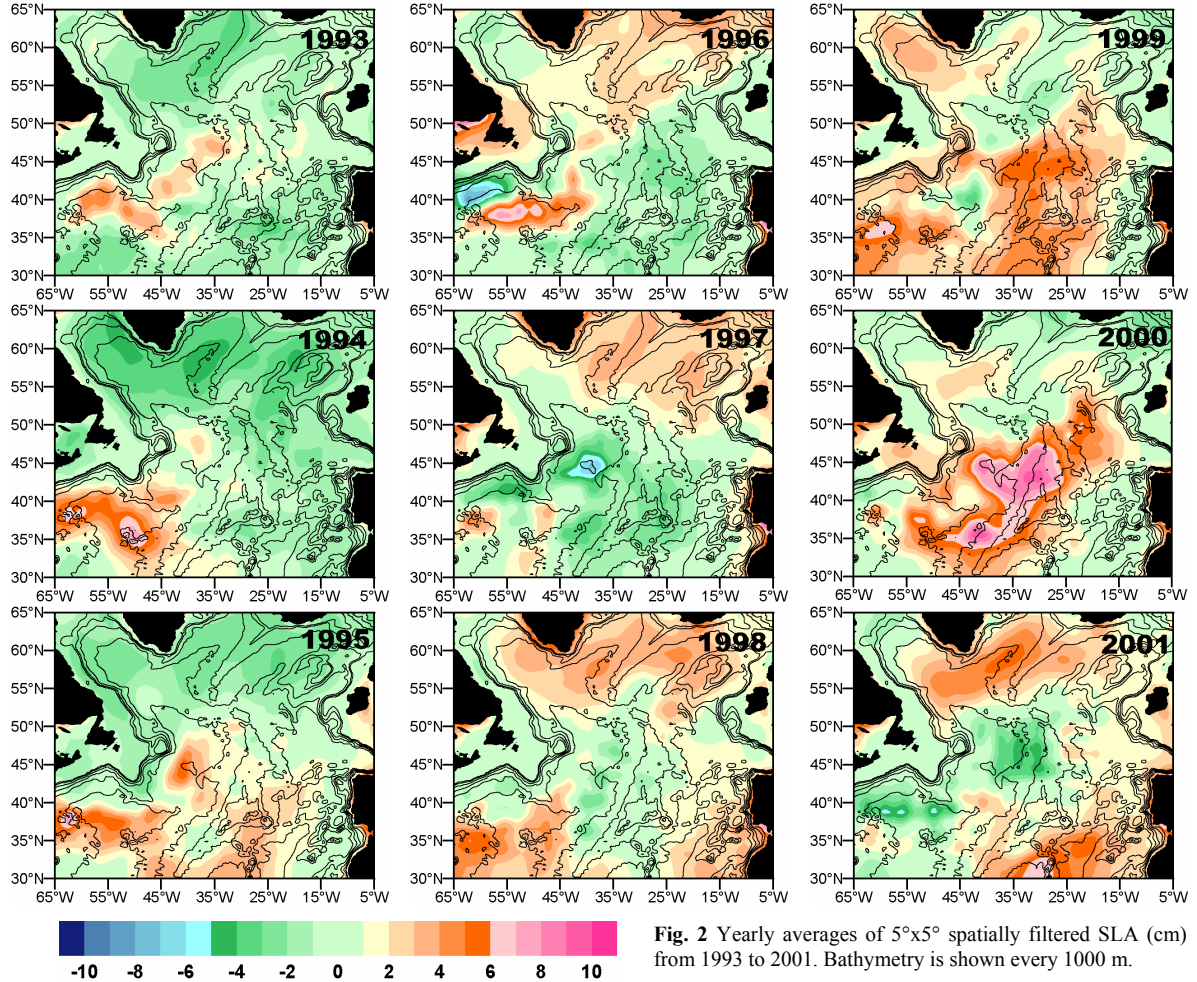


Fig. 2 Yearly averages of 5°x5° spatially filtered SLA (cm) from 1993 to 2001. Bathymetry is shown every 1000 m.

To reduce the error, a spatial median filtering of the SLA data over 5° by 5° squares has been applied. Then yearly averages have been estimated to visualize the inter-annual change of SLA from 1993 to 2001 (fig. 2). One can see that this procedure has eliminated most of eddy-like and left only large-scale features in the yearly SLA maps.

In fig. 2 it is possible to distinguish the difference between the SLA change in the subpolar and subtropical gyres. Lowest sea level in the subpolar gyre was observed in 1994. Then the sea level started to rise until it reached its maximum in 1997–1998 in the Iceland and Irminger Basins and in 1999 in the Labrador Sea. The decrease of the sea unfiltered SLA data. To test whether the aliasing of the inter-annual signal by eddies is important, we have compared a yearly running mean of an SLA

level within the subpolar gyre in 1999 and 2000 was followed by another rise in 2001. The subtropical gyre manifested minimum SLA in 1996 – 1997 and maximum in 1999 – 2000. Hence, fig. 2 confirms the existence of a dipole-like variability pattern (Esselborn and Eden, 2001). The first Empirical Orthogonal Function (EOF) of the yearly averaged and spatially filtered SLA data, which explains 48% of variance, also reveals this basin-scale dipole (not shown). When the sea level is high in the subpolar gyre, it is low in the subtropical gyre and vice versa.

However, to achieve our main goal, i.e. to estimate contribution of the annual and inter-annual signals to the total variance, we need to deal with time series at one grid point in the NAC area (~42°W, 42°N) with a yearly running mean of the same time series but edited by removing several

spikes of extreme SLA values associated with eddies. There was no significant difference between the running means. Therefore, we believe that it is acceptable to estimate the inter-annual signal by applying a running mean with a window equal to 1 year. After, it was subtracted from the initial SLA data to allow approximation of the annual cycle. It is important to extract the inter-annual change prior to estimation of the annual cycle in order to avoid an inevitable underestimation of the latter.

The annual cycle has a determined harmonic shape with a frequency ω of 1 cycle/year given by physical nature of the process. Lowest values of SLA are observed in spring whereas highest SLA values are typical for autumn. These variations are out of step with the atmospheric seasons because of the thermal inertia of the sea. The annual cycle was approximated by a sine function $a(x,y,t)=A(x,y)\cdot\sin[2\cdot\pi\cdot\omega\cdot t+\phi(x,y)]$. The parameters of the function (amplitude A and phase ϕ) were evaluated using a least squares method minimizing the variance of the residual high frequency signals.

After we have separated all the investigated modes of variability, we may fulfill one of our objectives - to compare the variance of total V and estimated annual/inter-annual/residual V' SLA time series, thus showing percentage of variance, explained by each of them (the determination coefficient - $D=100\cdot V'/V$ %). The determination coefficients were calculated separately for the annual $a(x,y,t)$ and inter-annual $i(x,y,t)$ signals (fig. 3 A, B) to estimate the contribution of each in total variance and for the residual high frequency elements $e(x,y,t)$ (fig. 3 C).

The variance explained by the annual signal (fig. 3A) constitutes over 1/3 of total variance outside dynamically active areas of the Gulf Stream, NAC, Azores Current and West Greenland Current. Along the subpolar front in the Iceland Basin the determination coefficient of the annual signal exceeds 50%, which is possibly an indication of local influence of seasonal displacements of the front on the annual cycle of sea level height. The annual signal is dominant in the eastern areas over and next to the continental shelves and slopes of Europe and Africa (determination coefficient > 50%), where the inter-annual and high frequency eddy signals are small.

Largest contribution of the inter-annual change is observed in the northern areas of the study region above 55°N, in particular in the Irminger Basin and Labrador Sea, and in the areas over the Mid-Atlantic Ridge (MAR), where the inter-annual signal explains 20-40% (fig. 3B). The proportion of the inter-annual variability in the western

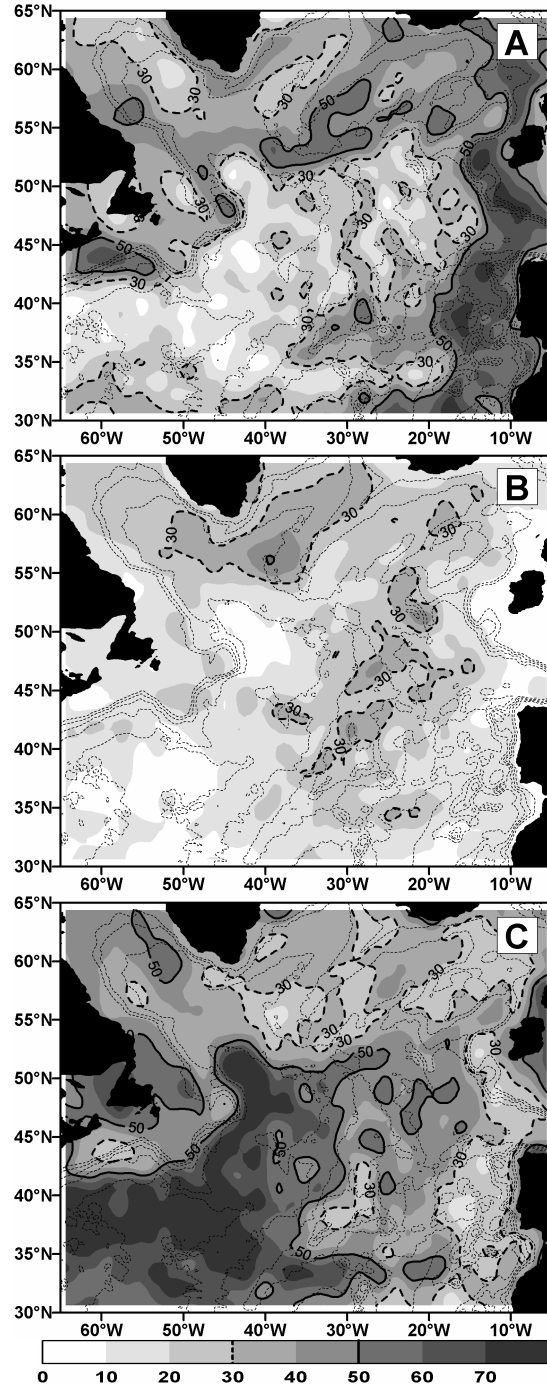


Fig. 3 The determination coefficient (%) of the annual (A), inter-annual (B) and residual high frequency (C) SLA signals. Bold continuous line = 50%, bold dashed line = 30%. Bathymetry (dotted lines) is shown every 1000 m.

boundary current is small, often less than 10% of total variance. There are two visible maxima of the inter-annual signal determination coefficient: one in the Irminger Basin and Labrador Sea, which represents the subpolar cyclonic gyre, and another

elongated along the MAR within the subtropical anticyclonic gyre (fig. 3B). However, if a large contribution of the inter-annual sea level change in the former is primarily a result of heat advection (Esselborn and Eden, 2001, Volkov and van Aken, in press), the latter may be biased by presence of large long-living eddies, which is probably the case near the southwestern margin of the Rockall-Hatton Plateau – an obstacle on the pathway of the NAC.

The determination coefficient shows that over the northern North Atlantic north of the NAC and largest part of the eastern North Atlantic east of the MAR, the SLA variability is mostly governed by the annual and inter-annual change. The total determination coefficient of annual and inter-annual signals in most of these areas exceeds 60%. In southern parts of the Irminger and Iceland Basins, over the Rockall-Hatton Plateau and in the east of the study region, the variance explained by these modes of variability even exceeds 70% (fig. 3). Along the areas greatly influenced by the Gulf Stream, NAC and the Azores Current the annual and inter-annual variability is overpowered by high frequency change (mainly eddies) (fig. 3C).

Fig. 4A represents amplitudes of the inter-annual sea level variations, computed as half the range $A=0.5 \cdot [\max\{i(x,y,t)\} - \min\{i(x,y,t)\}]$ of the inter-annual SLA time series obtained by filtering the initial data with a 1 year running mean. The largest amplitudes are observed along the major currents, especially along the Gulf Stream and in the NAC at about 43°W, 43°N, where they exceed 15 – 20 cm. Along the Azores Current and the NAC northeastern drift, the amplitudes range from 5 to 10 cm. In the northern part of the study region (55°N – 65°N) the amplitudes are mainly equal to 4 cm with three maxima (amplitudes > 5 cm) in the Labrador Sea, Irminger Basin and along the NAC branch flowing across the Iceland Basin. The relatively high amplitudes of the inter-annual signal in the Irminger Basin are probably a consequence of strong dependence of the sea level change here upon temporal restructuring of the NAC branches leading to a possible increase/decrease of advection of warm and saline water into this area (Bersch, 1999). The inter-annual change of sea level in the Labrador Sea seems to be coherent with the change in the Irminger Basin and follows the latter with some delay (fig. 2).

Amplitudes $A(x,y)$ of the annual signal are presented in fig. 4B. The maximum amplitudes exceeding 10 cm are observed along the Gulf Stream. The NAC and southern part of the study region including the Azores Current have amplitudes of 5-10 cm. Other regions have

amplitudes of order 3 - 5 cm. These values resemble those, estimated by Ferry et al (2000). A local maximum of the annual SLA amplitudes (over 5 cm) in the Iceland Basin is possibly associated with seasonal displacements of the subpolar front (Volkov and van Aken, in press).

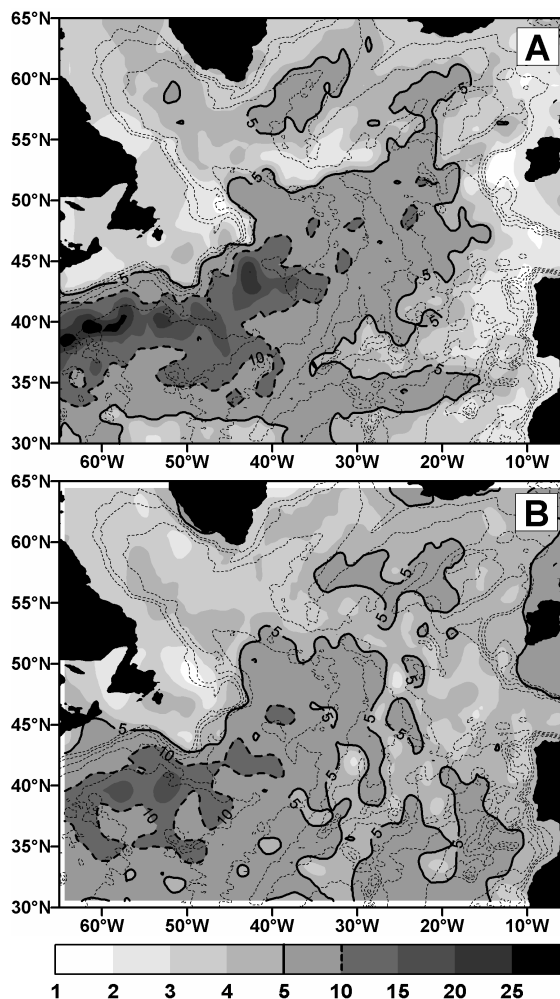


Fig. 4 Amplitudes (half the range) of the inter-annual (A) and annual (B) signals (cm). Bold continuous line = 5 cm, bold dashed line = 10 cm. Bathymetry is shown every 1000 m.

The phase $\phi(x,y)$ of the annual cycle, which we represent as a day number of the annual maximum, shows that in the Labrador Sea, Irminger and Iceland Basins maximum takes place in the end of October – beginning of November, which is about one month later than in shelf areas, especially in the east (beginning of October) (fig. 5). The thermal inertia of the sea, advection and precipitation may be the factors responsible for the shift of the annual sea level maximum and minimum relatively to the annual peaks of heat influx. Hence, it is reasonable

to suggest that in these areas advection may play an important role. The phase of the annual signal in the areas of the Gulf Stream, NAC and the Azores Current is confused by eddies.

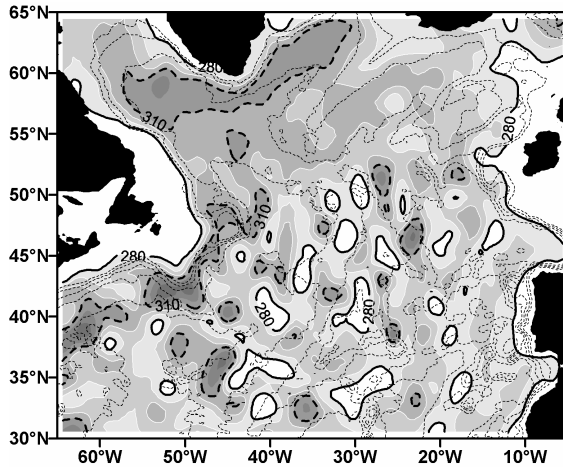


Fig. 5 Phase (day number of annual maximum) of the annual signal; bold continuous line = 280, bold dashed line = 310. Bathymetry is shown every 1000 m.

4 North Atlantic Oscillation (NAO)

As has already been mentioned, the inter-annual changes in atmospheric circulation, and therefore atmospheric forcing of the ocean, may be expressed by the North Atlantic Oscillation (NAO) index. The NAO, being a large-scale alternation of the atmospheric pressure difference between the Icelandic Low and Azores High centers, is a dominant mode of the atmospheric processes over the North Atlantic. From time to time the NAO turns from its positive phase to negative and vice versa, defined by the change of the NAO index (Hurrell, 1995). The positive phase represents low pressure over Greenland, adjoining a region of high pressure to the south, thus causing strong mid-latitude westerly winds. The negative phase is characterized by reduced pressure gradient with weak westerlies (Hurrell, 1995). The NAO is particularly important during the winter period when it accounts for more than one-third of the total variance in sea-level pressure (Cayan, 1992). The winter season has the strongest inter-decadal variability, when the pressure pattern over the North Atlantic has a strong influence on the weather conditions over the vast areas of the Northern Hemisphere.

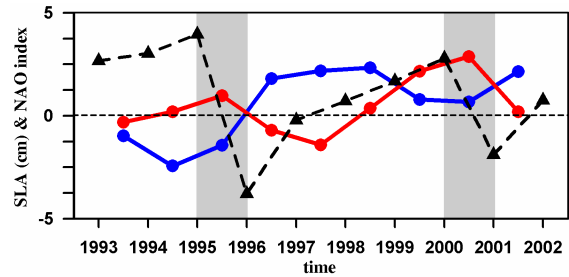


Fig. 6 The time series of the $5^\circ \times 5^\circ$ spatially filtered yearly SLA (cm) averaged over the northern $50^\circ\text{N} - 65^\circ\text{N}$ (blue dotted line) and southern $30^\circ\text{N} - 50^\circ\text{N}$ (red dotted line) parts of the study region and winter (DJF) NAO indices (dashed black line with triangles). Periods when the NAO index changed from positive to negative are shaded in grey.

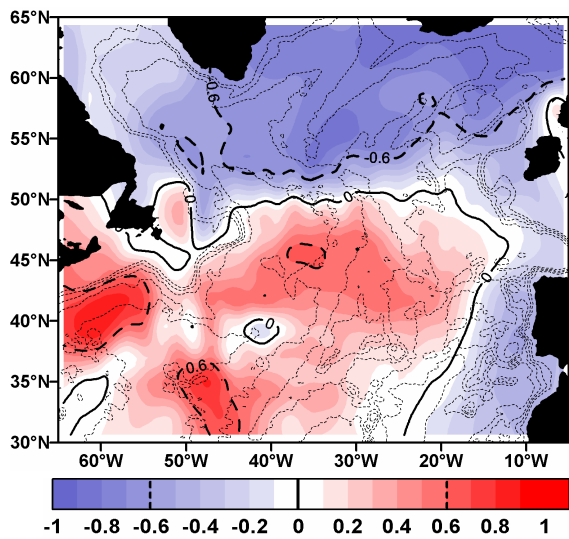


Fig. 7 The correlation coefficient between the winter (DJF) NAO indices and $5^\circ \times 5^\circ$ spatially filtered yearly SLA values. Significance level is ± 0.6 (dashed lines). Bathymetry is shown every 1000 m.

The time series of the $5^\circ \times 5^\circ$ spatially filtered yearly SLA averaged over northern $50^\circ\text{N} - 65^\circ\text{N}$ and southern $30^\circ\text{N} - 50^\circ\text{N}$ parts of the study region and winter (DJF) NAO indices are shown in fig. 6. One can see that the inter-annual variations of sea level in the northern and southern parts, representing the subpolar and subtropical gyres correspondingly, are in antiphase. The change of sea level in both areas appears to be influenced by the NAO. When the NAO index changed from positive to negative values in 1995 – 1996 and in 2000 – 2001 the sea level started to increase in the subpolar gyre and to decrease in the subtropical gyre.

To define a connection between the NAO and the sea level in the Northern Atlantic on the inter-annual time scales, we estimated the correlation coefficients for each grid point of the yearly SLA

data and NAO winter (DJF) indices. More frequent SLA time series contain the annual and higher frequency (e.g. eddies) signals, which are not driven by inter-annual changes of atmospheric forcing, but mainly by seasonal ocean – atmosphere heat flux variations and, in the case of eddies, by baroclinic instability. The result is presented in fig. 7. The 95% significance level for 9 years of data is ± 0.6 (Dixon and Massey, 1969). The correlation coefficient distribution reveals the same dipole structure as the first EOF of the yearly SLA. In spite of short data length, we obtained significant negative correlation over largest part of the northern North Atlantic ($>50^\circ\text{N}$). There is no significant correlation in the Labrador Sea because the sea level response to the atmospheric forcing occurs here with some delay compared to the neighboring Irminger Sea (fig. 2). In the south, below 50°N , the correlation is positive and in most areas closed to significant values.

Thus, it seems possible that changes in the atmospheric forcing over the North Atlantic related to the NAO, indeed, effect the SLA on inter-annual time scale. It appears that the North Atlantic responds as a dipole system: during strong westerlies (positive NAO) with a sea level increase in the subtropical gyre and a decrease in the subpolar gyre and another way round during weak westerly winds (low or negative NAO). When the NAO turned from its positive to negative phase in 1995/1996 and 2000/2001, the ocean responded with a sea level rise over the northern areas of the North Atlantic in the subpolar gyre and a decrease in the subtropical gyre.

5 Summary

In this paper we decomposed total variance of the SLA in the North Atlantic Ocean ($5^\circ\text{W} - 65^\circ\text{W}$, $30^\circ\text{N} - 65^\circ\text{N}$) in three basic modes: annual, inter-annual and high frequency (period less than 1 year) change. We considered two first modes and showed that in the northern areas within the subpolar gyre and in the east most of variance ($>60\%$) is determined by the annual and inter-annual components. In the subtropical gyre in the dynamically active areas west of the MAR more than 50% of total variance is explained by the high frequency signals. The contribution of the inter-annual component is considerable in the areas elongated along the MAR (20-30%). The annual signal is responsible for 30-40% of variance in the

subpolar gyre regions and over 50% in the eastern near-shelf areas.

A comparison of the inter-annual SLA time series and winter (DJF) NAO indices indicated on a direct dependence of sea level on the atmospheric circulation pattern expressed by the NAO index in the subtropical gyre and an inverse dependence in the subpolar gyre.

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