Sea surface height anomalies in the Norwegian Sea

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Abstract

Five years with altimeter data, from end of 1995 to the beginning of 2000, are analyzed for studying sea surface height variability in the Norwegian Sea. A complex empirical orthogonal functions analysis of the data shows that the annual cycle explains 64% of the total variability. Largest amplitudes are seen in the Lofoten and Norwegian Basins. The first mode has a southward phase shift, starting north in the Lofoten Basin in December-January when the ocean-atmosphere heat loss is largest. From 1996 to 2000, a trend with increasing amplitude of the seasonal signal is seen. This trend can not be related to changes in the winter ocean-atmosphere heat loss through steric height. Instead, it may be connected to an atmospheric forcing change through an increased divergence of the surface layer in the Norwegian Sea.

1. Introduction

Gill and Niller's (1973) analysis of seasonal variability in the ocean identified the local heat flux as the prime agent of the seasonal oceanic heat content change, excluding the equatorial regions and regions near the boundaries. The results are basically in accordance with Ferry et al. (2000) who combined altimeter sea surface height (ssh) data and model results to investigate the seasonal cycle in the North Atlantic. Ferry et al. (2000) found the largest deviation in the eastern North Atlantic. To investigate to what extent the variability within the Nordic Seas follows that of the North Atlantic is essential for their exchanges of fluxes.

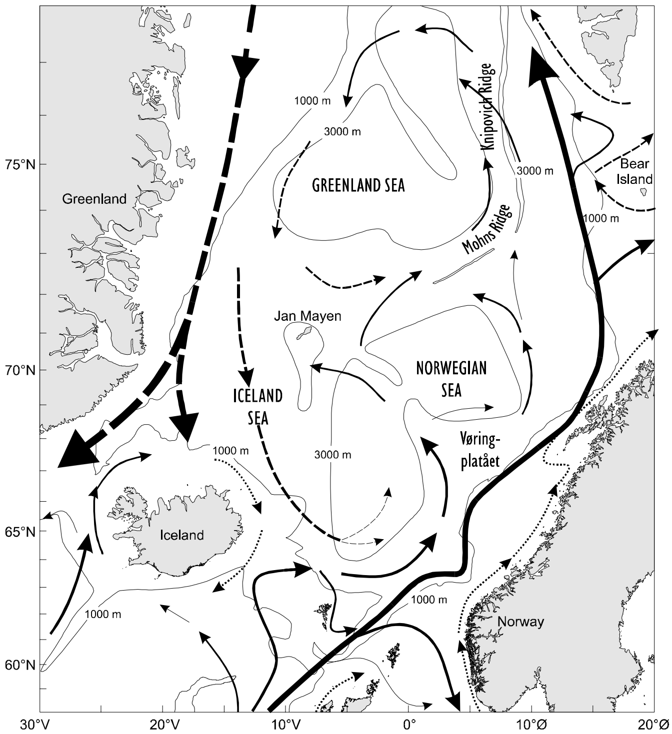


Figure 1 Overview of the study area with main currents. Solid line: flow with Atlantic water, dashed line: flow with Arctic water and dotted line: flow with coastal water.

Skagseth (2002) found that there is a positive correlation between the sea surface slope from the North Atlantic to the Nordic Seas (Iceland, Norwegian and Greenland Seas), with strong seasonality, and that this variability is positively correlated with the strength of the Norwegian Atlantic Current (NAC). Harmonic analysis of the

SSH data show that the amplitudes are larger in the Nordic Seas as compared to the northern North Atlantic (Ferry et al.,2000; Skagseth, 2002).

Not only is the North-South difference in SSH important for the NAC but also the East-West gradient is important through geostrophy. Both Pistek and Johnson (1992) and Samuel et al. (1994) have monitored the inflow of Atlantic water to the Nordic Seas. Variation in the SSH may also reflect changes in density. For instance, convection in the winter due to large heat loss from the ocean to the atmosphere will result in a depression of the water column.

The focus of this work is to investigate the variability of the SSH in the Nordic Seas by considering complementary data that resolve various forcing terms affecting the SSH. In section 2 terms that influence the sea level are proved. The spatial distribution of SSH variability in the Nordic Seas is shown in section 3 while the data and method of analysis are described in Section 4. In Section 5 results from the analysis are described including a discussion.

2. The hydrostatic relation and sea level variation

In order to establish the framework for a discussion on the sea-level variation, a careful consideration of the hydrostatic relation is required. Following the notation of Gill and Niller (1973) the equation is:

$$p_z = -\rho g \,, \qquad (1)$$

where p is the hydrodynamic pressure, z is the distance measured upwards, g is the gravity, and ρ is the in-situ density of the water. At the free surface of the ocean

$$z = \eta(\lambda, \phi) \qquad (2)$$

where λ and ϕ are the longitude and latitude, the pressure is equal to

$$p(\lambda, \phi, z = \eta) = p_a(\lambda, \phi) \qquad (3)$$

The integration of (1) from z to η give the pressure at level z by

$$p = p_a + g \int_z^\eta \rho \, dz \,. \qquad (4)$$

In particular the pressure at the bottom z=-H(λ,ϕ) is given by:

$$p_b = p_a + g \int_{-H}^\eta \rho \, dz \,. \qquad (5)$$

Equation 5 states that the pressure at the bottom is the sum of the atmospheric pressure at the surface and the weight per unit are of the water column. Equation (5) can be approximated by:

$$p_b = p_a + g \int_{-H}^0 \rho \, dz + g\rho_0 \eta \,, \qquad (6)$$

where ρ_0 represents the constant density. Since the density varies little (within 1% of the mean value) the Boussinesq approximation is reasonably accurate. Now the purpose is study variation from the mean state. Representing variables

$p = p + p'$, $\rho = \rho + \rho'$, $\eta = \eta + \eta'$. (7)

where overbar represents mean values and prime represents deviation. Taking the difference between (6) and its time average:

$$p'_b = p'_a + g\int_{-H}^{0} \rho' dz + g\rho_0\eta' . \qquad (8)$$

The steric level deviation is defined as:

$$\eta'_s = -\frac{1}{\rho_0}\int_{-H}^{0} \rho' dz . \qquad (9)$$

Changes in the steric level are caused by changes ion the density of the column implying expansion or contraction. The barometric correction to sea level is:

$$\eta'_a = -\frac{p_a}{g\rho_0} . \qquad (10)$$

An increase in p_a of 1 mbar corresponds to a sea level depression of approximately 1 cm. Using (9) and (10) equation (8) can be written as:

$$\eta' = \eta_a' + \eta_s' + p_b'/g\rho_o \qquad (11)$$

The barometrically corrected sea level is thus

$$\eta' - \eta_a' = \eta_s' + p_b'/g\rho_o \qquad (11).$$

Contributions to sea level change

For the North Atlantic, the contributions to sea level change are (Gill and Niller's, 1973):

- the response to changes in the atmospheric pressure is important (of the order several centimeters at high latitude), but dynamically uninteresting since temperature and currents are hardly changed.
- *barotropic* response to change in the wind stress. This cause small variation in the sea level and corresponding change in the bottom pressure p_b .
- steric change in sea level due to expansion/contraction of the water column above the seasonal thermocline.
- less important changes connected to changes in the wind stress a) changed in the mixed layer due to convergence of heat and salt, and b) Ekman pumping which act to displace the main seasonal termocline (*barocline* response).

In the Nordic Seas it is likely that some of mentioned contributions will have another role due to, for instance, its coastal boundaries, Arctic climate in north and its wind systems.

3. SSH variabiliy in the Nordic Seas

The standard deviation of the SSH derived from the altimeter data is shown in Fig.2. Largest variability is seen in the Norwegian and Lofoten Basins while lowest variability is southwest of the Faros.

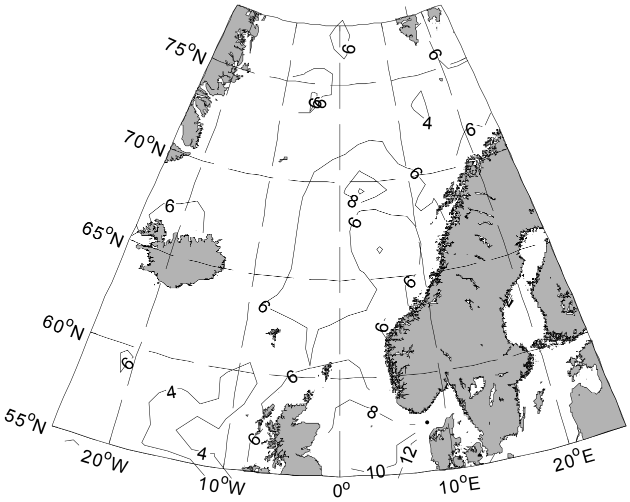


Figure 2. Standard deviation of SSH (cm) from altimeter data (1995-2000).

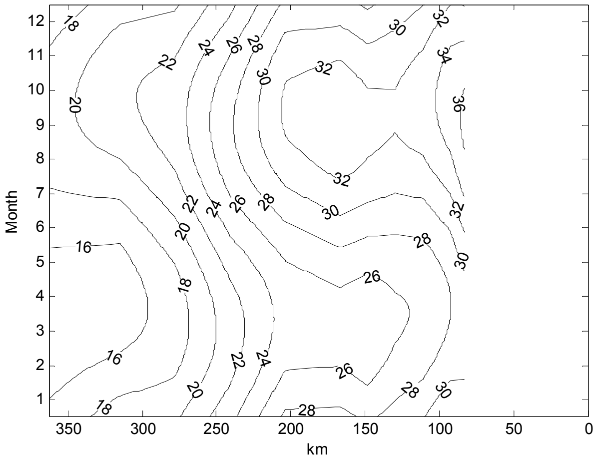


Figure 3. The annual harmonic mode of the steric height (cm) in the Svinøy section. Right side is at the Norwegian coast and the kilometres in the x-axis indicate distance from the coast.

The steric height in the Svinøy section during the year is shown in Fig. 2. The section runs NW from about 62^{o}N on the Norwegian coast to 64^{o}40'N on the zero meridian. The section is strategically placed as it covers both the Atlantic inflow to the Norwegian Sea and influence of Arctic water in the west.

An annual harmonic mode is adjusted to the calculated steric height for all stations in the section that at least reach down to 700 m depth which is used as the reference depth. The 700 m limit is well below the maximum depth of Atlantic water that typically reaches down to about 500 m depth at the slope. Largest seasonal change is found in the region with the inflow of Atlantic water with annual amplitude of about 4 cm. Offshore the amplitude is about 3 cm.

4. Data and methods

The altimeter data used in this study are the CLS gridded data set based on the merged TOPEX/POSEIDON and ERS data sets. The data set is also corrected for the inverted barometer effect. The time range is from 1995 to 2000 with an interval of 10 days. The data were averaged in space from the originally grid, 0.5^{o}x0.5^{o}, to the 2^{o}x1^{o} grid in longitude and latitude, respectively. Only data in location where the bottom depths are larger than 300 m are used to avoid variability on the shelf. Also, the data have been weighted by the square root of cosine of latitude such that equal areas have equal weights.

The principal component (PC), also called empirical orthogonal function (EOF) analysis is a powerful statistical method to explore spatial and temporal variability of geophysical data by reducing large data sets to few dominant modes. While conventional PC analysis can only detect standing waves, the complex principal component (CPC) analysis has the advantage to also detect propagating waves. An introduction of the CPC analysis with examples can be found in Horel, 1994.

To perform CPC analysis on the altimeter data complex data series are first derived from the original data series. The real part is the original data and the imaginary part is the Hilbert transform where each component phase, from the original data, is rotated 90^o at every frequency. The new complex data set (F) can then be represented as a sum of contributions from N principal components:

$$F_j(t) = \sum_{n=1}^{N} e_{jn}^* \, P_n(t) , \qquad (12)$$

where j denotes the spatial position and t is the time. The e_{jn} are the complex eigenvectors or the complex empirical orthogonal functions (CEOFs) while the $P_n(t)$ are the CPCs. The asterisk (*) denotes complex conjugation. The CEOFs are orthogonal $\left\langle e_{jn}^* e_{jm} \right\rangle_j = \lambda_n \delta_{nm}$ and the CPCs are orthonormal $\left\langle P_n^*(t) P_m(t) \right\rangle_t = \delta_{nm}$, where λ_n are the real eigenvalues and δ_{nm}= 1 for n=m and δ_{nm}= 0 for n≠m. The total variance of the data equals the sum of variance in eigenvalues. Reconstruction of a fraction of each complex time series that is explained by the *n*th component yields:

$$F_j^{'}(t) = e_{jn}^* \, P_n(t) . \qquad (13)$$

Since both the CEOFs and the CPCs are complex they have both an amplitude and a phase component.

5. Results and discussion

The first mode of the SSH variability from the CPC analysis which is shown in Fig.4. explains 64% of the total variability. This variability is mostly annual (see for instance the CPC phase). Largest amplitude of the variability (CEOF amplitude) is in the Norwegian and Lofoten Basins. The influence of this mode is less in the vicinity of the slope current of the NAC, i.e. near the Norwegian shelf edge and south of the Spitsbergen. Also, the topographic effect of the Vøring Plateau can be seen in the CEOF amplitude. The CEOF phase indicates a phase shift, starting in December/January northeast in the Lofoten Basin. The phase of the interior of the Nordic Seas leads that of the eastern slope region of the order one month. The increasing PC amplitudes from the yrs 1995-96 to the subsequent yrs 1997-99 (Fig. 4., CPC amplitude) indicate that the amplitude of the seasonal cycle in SSH increases.

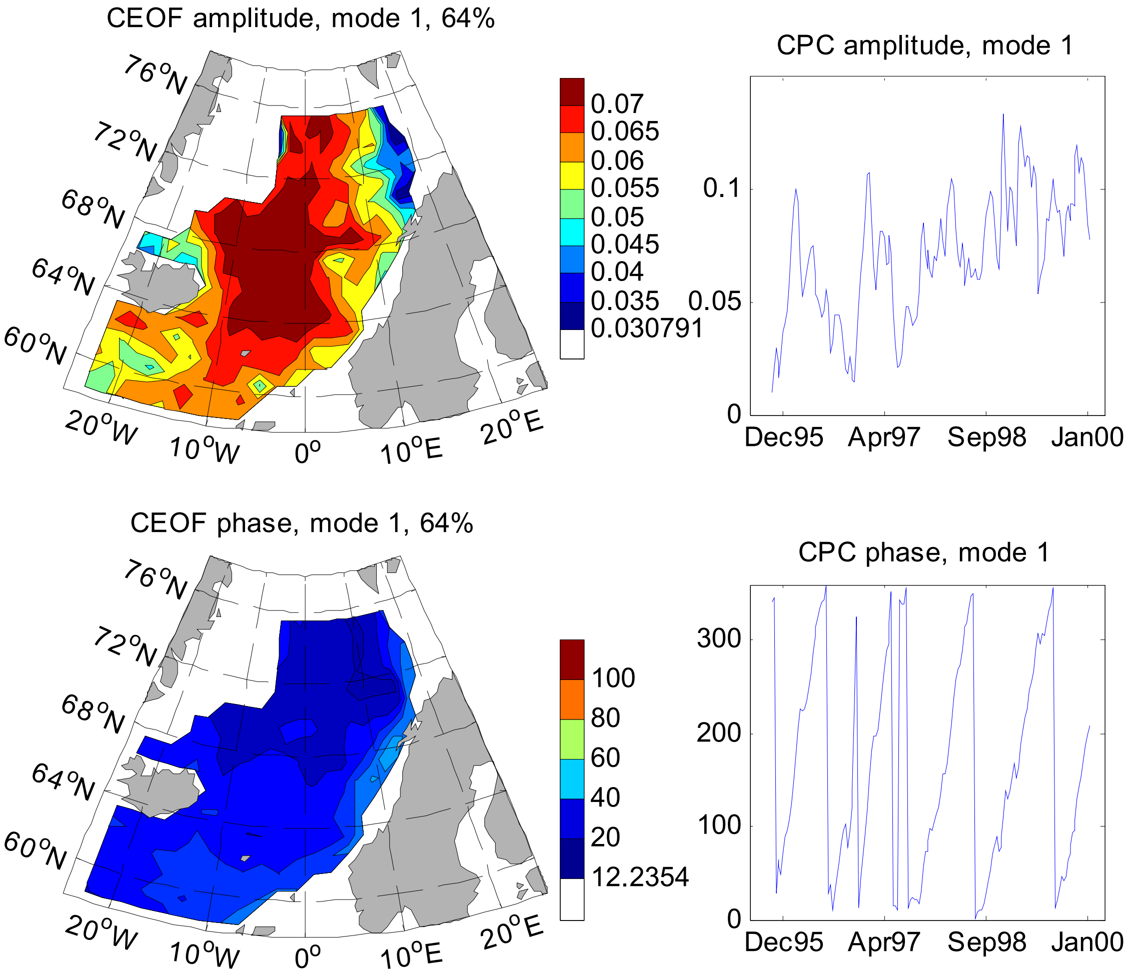


Figure 4. The first mode of the SSH from the altimeter data which accounts for 64% of the total variability.

Why is the amplitude larger in the interior basin?

In the absent of strong current the water masses in the interior basins can be longer exposed by the ocean-atmosphere heat flux. A cooling of the upper layer results in a depression of water column. The seasonal SSH variations can at least partly be explained by the seasonal change in the steric height. Typical value of the winter ocean-atmosphere heat loss is about 250 W/ m^2 from December to February (see Fig. 5.). A heat loss of 250 W/m^2 over three months (December-February) cools an upper layer of 100 m depth with 4.6°C resulting in a 4-5 cm depression of the water column.

What is the cause of increasing amplitudes in the PC from 1995-96 to 1998-99 (see CPC, amplitude)?

Is there a change in the ocean-atmosphere heat flux from 1995-96 to 1998-99 that can explain this trend through steric height? A comparison between the ocean-atmosphere heat flux winters (Dec-Feb) 1995/1996 and 1998/1999 show only small differences in the Norwegian Sea (Fig. 5.). The difference between the two years is mainly less than 20 W/m^2, which is too small to explain the SSH difference for the two periods.

Another possibility is changes in the wind forcing from 1995-96 to 1998-99. The increased seasonality in the SSH for the years 1995-96 relative to the years 1998-99 coincide with changes in the atmospheric forcing. Three month averages (Dec. – Feb.) of mean sea level pressure (mslp) show substantial changes for the winters of 1996 and 1999 (Fig. 6.). These years are associated with low (1996) and high (1999) winter values of the North Atlantic Oscillation (NAO) revailing the strength of the westerlies on the eastern part of the basin, and northeasterly wind in the western part of the Nordic Seas. These changes in the windstress across the Nordic Seas affects the SSH by divergence/convergence in the surface Ekman transports. An investigation of the wind-stress curl over the period from 1955 to the late 1980ies show marked seasonal and inter-annual variability in the wind-stress curl over the Nordic Seas (Jonsson, 1991).

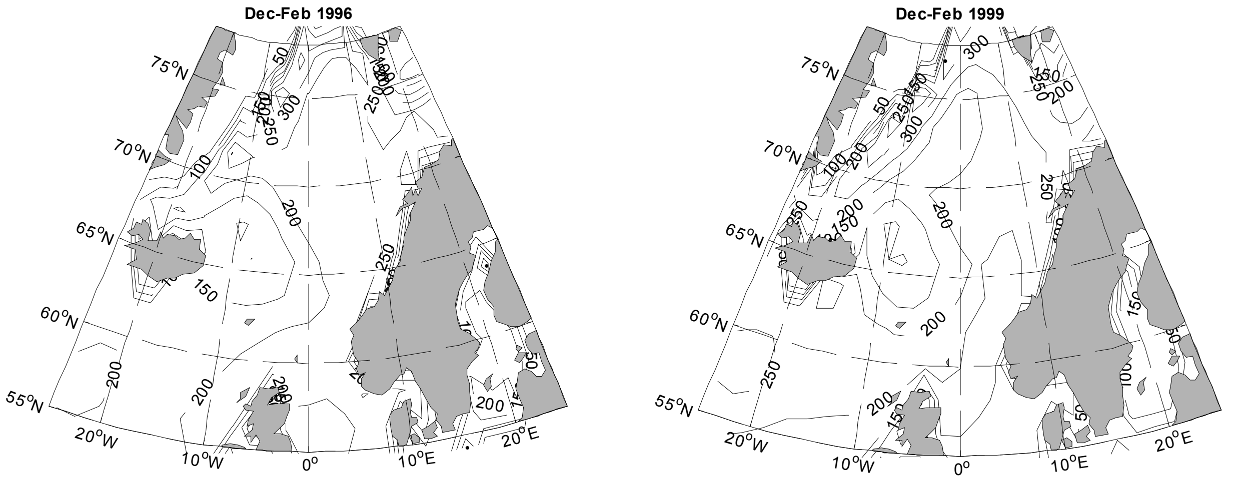
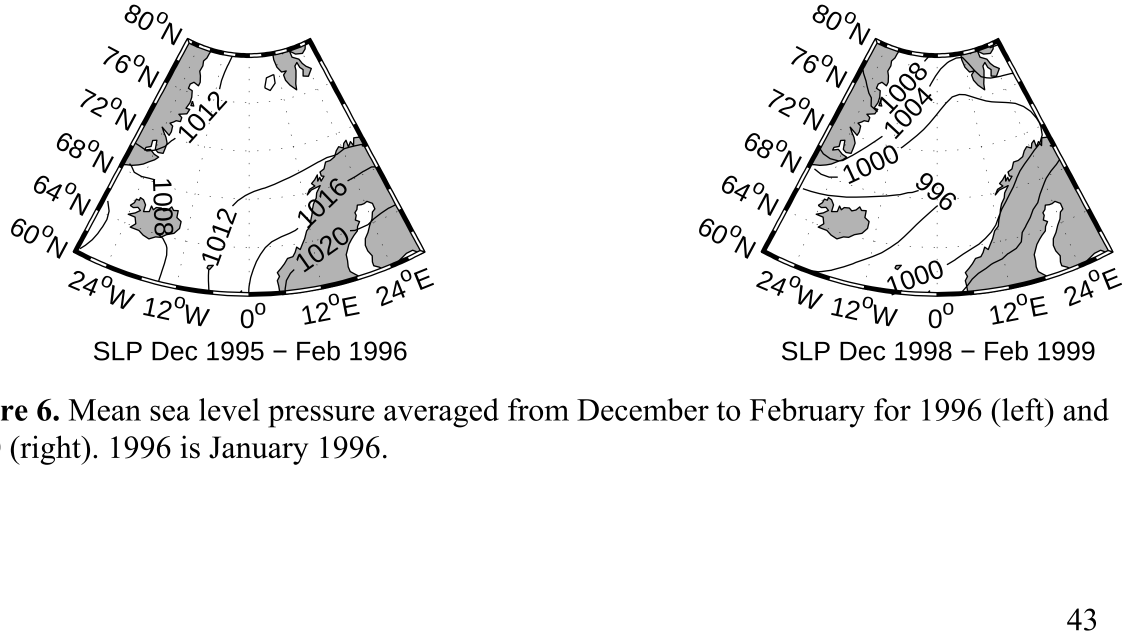


Figure 5. Net ocean-atmosphere heat loss (W/m^2) for December-February. Left figure: 1996, right figure:1999



SLP Dec 1995 − Feb 1996

SLP Dec 1998 − Feb 1999

Figure 6. Mean sea level pressure averaged from December to February for 1996 (left) and 2000 (right). 1996 is January 1996.

This study reveals only the first mode of the CEOF analysis but it can be mentioned that the second mode, accounting for 8% of the total variability, shows a northward phase shift with slow temporal change in phase. The third mode, which explains 5% of the total variability, is more related to the fast slope current with large temporal variability.

Conclusion

A complex empirical orthogonal functions analysis of the data shows that the annual cycle explains 64% of the total variability. Largest amplitudes are seen in the Lofoten and Norwegian Basins. The first mode has a southward phase shift, starting north in the Lofoten Basin in December-January when the ocean-atmosphere heat loss is largest. The trend with increasing amplitude of the seasonal signal from 1996 to 1999 cannot be related to changes in the ocean-atmosphere heat flux through steric height. It may rather be connected with changes in the wind forcing through an increased divergence of the surface layer in the Norwegian Sea.

Acknowledgements

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