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Comparing the steric height in the Nordic Seas with satellite altimeter sea surface height

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Abstract

In this study the steric height anomaly which is calculated from the hydrological data (EN3) is compared with the sea level anomaly derived from satellite altimetry in the Nordic Seas. The overall pattern of steric height is that it is higher in the margin area and lower in the middle area. The extreme values of steric height linear change from 1993 to 2010 occur in the Lofoten Basin and off the Norwegian coast, respectively. Such a distribution may be partly attributed to the freshening trend of the Nordic Seas. The correlation between SLA (sea level anomaly) and SHA (steric height anomaly) is not uniform over the Nordic Seas. The time series of SLA and SHA agree well in the Lofoten Basin and northern Norwegian Basin, and worse in the northern Norwegian Sea, implying that the baroclinic effect plays a dominant role in most areas in the Norwegian Sea and the barotropic effect plays a dominant role in the northern Norwegian Sea. The weaker correlations between SLA and SHA in the Greenland and Iceland Seas lead a conclusion that the barotropic contribution is significant in these areas. The area-mean SHA over the entire Nordic Seas has similar amplitudes compared with the SLA during 1996–2002, but SHA has become lower than SLA, being less than half of SLA since 2006.

Key words: steric height, EN3 hydrological dataset, altimetric sea level anomaly, Nordic Seas

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1 Introduction

In the context of significant climate change, the Nordic Seas is a crucial region for both responding to the climate change and affecting it through influencing the Atlantic Meridional Overturning Circulation (AMOC) (Zhao et al., 2006). Sea level change is an important component of climate change. It can be affected through two ways: the water mass change in a given location and the density variation in the constant mass (Gilson et al., 1998), or the barotropic effect associating with bottom pressure (Willis et al., 2003) and the baroclinic effect related to density change, which is the so-called steric height. Since baroclinic current can be derived from steric height, it's usually known as dynamic height in some research. For clarification, we use the name steric height in this paper.

The changes of temperature and salinity in the ocean can give rise to density variation, which will affect the height of water column through hydrology relationship. Steric height has a thermosteric component and a halosteric component. Generally, steric height in the global ocean is dominated by the thermosteric effect, e.g., Willis et al. (2003) suggested that change in the sea level is caused by changes in temperature of the upper few hundred meters. In the Nordic Seas, the spatial temperature variations determine the pattern of the mean steric height field while salinity contribution plays a secondary role and is only crucial in the fresher regions such as coasts (Mork and Skagseth, 2005). But some researchers have the opposite opinions. Antonov et al. (2002) found that the halosteric anomaly can compensate the thermosteric anomaly in some areas such as the sub-polar North Atlantic at least in their study period, but their study area is limited to the south of 65°N. Similarly, Ivchenko et al. (2007) found the sea level anomaly (SLA) and steric height anomaly (SHA) showed an improved agreement when considering the halosteric effect.

Some previous studies compared the steric height anomaly derived from hydrographic data such as Argo (Array for Real-time Geostrophic Oceanography) profiles and sea level anomaly from satellite altimetry, and found that the two fields agreed well in the Indian Ocean (George et al., 2011) and the Pacific Ocean (Guinehut et al., 2006). Gilson et al. (1998) compared the sea level anomaly of altimetry and steric height anomaly from the hydrographic data during cruises (in the Pacific Ocean, between 10–38°N), and found the root mean square difference (RMSD) between the two is 5.2 centimeters. Mork and Skagseth (2005) combined the altimeter, wind, and hydrographic data to study the annual variability in the Nordic Seas, and evaluated the main contributions to the SSH (sea surface height) with error estimates. They found that the amplitude of the annual variation of SSH is 4–8 cm, while the largest value is in the deeper basins and off the coast of Norway. Siegismund et al. (2007) used an extensive dataset to examine steric height variability on multiple time scales. They argued that annual variability is only a minor part of the monthly variability in most areas of the Nordic Seas, and the thermosteric component has a north-south dipole pattern, which affects the steric height variability in the eastern region.

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2 Data and methods

The EN3 hydrological dataset (Ingleby and Huddleston, 2007) originates from the Met office of the UK's national weather service. This dataset is composed of multiple observation data, such as WOD05 (World Ocean Database 2005), GTSPP (Global Temperature and Salinity Profile Project), and ARGO (which has been operational since 1999). As for the Arctic Ocean, the EN3 dataset includes the ASBO (Arctic Synoptic Basin-wide Oceanography), which comprises a number of observation projects and datasets, such as Hydrobase, NPEO (North Pole Environmental Observatory), etc. Horizontal resolution of EN3 monthly data is 1°×1°, the data coverage is 0°–360°, 83°S–89°N. There are 42 layers in the vertical with different thicknesses ranging from 10 m in the upper layer to 300 m in the deep ocean.

The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from CNES (http://www.aviso.oceanobs.com/duacs/). The monthly sea level anomaly data we used are created from daily Sea Level Anomaly (SLA) maps in Mercator projection and with horizontal resolution (1/3)°×(1/3)°. This dataset has been corrected with considering the atmospheric pressure, tides and dry tropospheric effects. The validations of satellite data in the Nordic seas is also provided by Volkov and Pujol (2012).

The satellite data are for the same period as the hydrological data, both from January 1993 to December 2010. For comparison, the satellite data are interpolated into 1°×1° grid of EN3 dataset.

In order to calculate the steric height, the density is calculated using GSW tool box. The steric height is calculated through the following equation from Gill (1982):

$$h_{\text{steric}}(x,y,t) = \int_0^D \frac{\rho_0(x,y,z) - \rho(x,y,z,t)}{\rho_0(x,y,z)} \mathrm{d}z,$$

here D is the reference water depth, $\rho_0(x,y,z)$ is the standard seawater density, which is the function of reference temperature (T_0=0), salinity (S_0=35) and depth. According to the the above equation on the steric height, the low density (high temperature and low salinity) will give rise to the high steric height, and vice versa.

3 Results

3.1 *Sensitivity to the reference depth*

Ideally, the steric height should be accumulated from sea surface to the horizontally homogeneous layer. Guinehut et al. (2006) compared altimetry data and steric height in the global ocean. They found that the root mean square difference (RMSD) decreased from 7.79 cm with reference depth 700 m to 7.03 cm with 1 500 m. However, in some deep basins of the Nordic Seas, e.g. the Lofoten Basin, the density gradient under 1 500 m is still significant (Orvik, 2004; Shao and Zhao, 2014). In order to clarify the influence of different reference depths, we calculate the steric height with different reference depths, i.e., every 200 m from 400 m to 2 000 m, and the results show that the steric height increases with deeper reference water depth within 1 000 m, while stays almost constant when the reference depths exceed 1 000 m, except for the Lofoten Basin. The steric height in this basin increases about 2 cm when the reference depth changes from 1 000 m to 2 000 m.

We choose an area in EN3 dataset with largest density of data, and calculate the correlation and RMSD between the sea level anomaly (SLA) observed by altimeter and steric height anomaly (SHA) obtained with different reference depth. The results (Fig. 1) show that the correlation and RMSD change little, when the SHA data are obtained with different reference depth of 800 m, 1 000 m and 1 200 m. Siegismund et al. (2007) showed that the variation of hydrological data mostly occurred in the water shallower than 1 000 m for the most areas in the Nordic Seas. Hence, we choose 1 000 m as the reference depth.

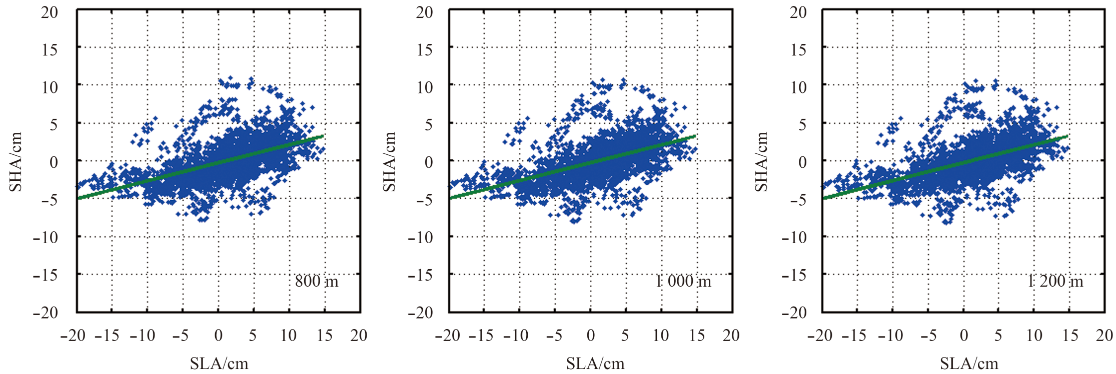

Fig. 1. Clusters of SLA (cm) and SHA (cm) obtained with different reference depths: a. 800 m, y=0.238 5x–0.256 3, R=0.53, $RMSD$ =2.34 cm; b. 1 000 m, y=0.236 2x–0.253 8, R=0.52, $RMSD$=2.36 cm; and c. 1 200 m, y=0.236 9x–0.254 6, R=0.52, $RMSD$=2.36 cm.

3.2 *Steric height*

3.2.1 *Mean steric height*

Our result shows that, basically, steric height is higher in the surrounding area and lower in the middle in the Nordic Seas (Fig. 2). As described above, the steric height is closely related to the seawater density field with an inverse relationship. High steric height is located off the Norwegian coast and in the Lofoten Basin, which should be attributed to the influence of the North Atlantic water (Orvik, 2004). The slight high steric height off the Greenland coast may be caused by the seasonally melted sea ice and runoff. The lowest steric height occurs in the Greenland Sea, and the secondary one in the Iceland Sea. The difference between the extreme values can reach about 42 cm. This steric height pattern favors a basin-scale cyclonic circulation in the Nordic Seas, and may suggest the sub-basin scale enclosed gyre circulation (Siegismund et al., 2007). Unfortunately, we fail to get another minimum in the Iceland Sea as indicated by Siegismund et al. (2007), which may be caused by missing the fine structure of seawater density due to the coarse grid of EN3 dataset. The pattern of steric height in Nordic Seas is maintained basically by the cyclonic wind which benefits the lower steric height in the central area and the higher steric height in the margin area.

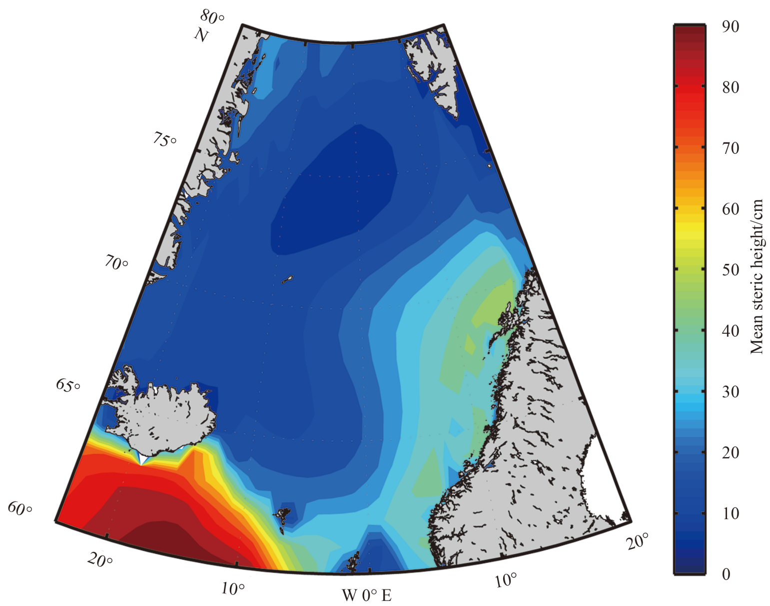

Fig. 2. Mean steric height in the period 1993–2010.

The steric height in the Nordic Seas is far smaller than that in the North Atlantic Ocean, with the difference reaching up to 50 cm. Thus the mean seawater density above the depth of 1 000 m in the Nordic Seas is much higher than that in the North Atlantic Ocean. However, due to the barrier and dynamic effects of Greenland-Scotland Ridge (GSR), the steric height difference between the Nordic Seas and the North Atlantic Ocean cannot effectively induce corresponding baroclinic flows.

3.2.2 *The linear trend of the steric height*

The linear trend of steric height (SH) time series in the Nordic Seas during the period 1993–2010 is shown in Fig. 3. The extreme values of linear change from 1993 to 2010 occur in the Lofoten Basin and off the Norwegian coast, 0.54 and –0.72 cm/a, respectively. The trend is trivial for most areas in the Nordic Seas. Recently, there has been a freshening trend in the Nordic Seas (Siegismund et al., 2007), which has significant impact on the eastern Nordic Seas dominated by the warm and salty North Atlantic water.

3.3 *Altimetry derived SLA vs. SHA*

3.3.1 *The linear trend of the steric height*

The correlation between SLA and SHA is not uniformly distributed over the Nordic Seas (Fig. 4). Since the East Greenland Shelf is ice-covered, no available satellite data can be obtained. Therefore, we don't compare the altimetry derived sea level and steric height there.

The fact that SLA and SHA do not agree well with each other can be attributed to strong barotropic contribution or great density variability below the reference depth in this region. The former refers to bottom pressure associated with the entire water column (non-steric), while the latter is steric effect with depth below the reference depth. In Section 3.1, we compare three cases obtained with different reference depths and find that the change of steric height calculated with reference depth below 1 000 m is negligible compared with those obtained above 1 000 m.

The SHA represents a pure steric effect (George et al., 2011) related with baroclinic contribution. Altimetry derived SLA includes both barotropic and baroclinic contributions. One can expect high correlation between SLA and SHA in the regions with strong baroclinic effect. As shown in Fig. 4, the high correlations between SHA and SLA with its value larger than 0.70 appear in the Lofoten Basin and northern Norwegian Basin (Region 1 in Fig. 4), implying that this area is dominated by strong baroclinic effect. A weakest correlation between SHA and SLA with a minimum of 0.15 is found in the northern Norwegian Sea (Region 2 in Fig. 4), implying that the barotropic effect is dominant there. In addition, weaker correlations between SHA and SLA with a range of 0.35–0.50 are found in the Greenland and Iceland Seas, implying that the barotropic effect is significant there.

The stronger the barotropic effect is, the weaker the correlation between SLA and SHA will be. The Greenland and Iceland Seas have week stratification due to deep convection, as well as high Coriolis parameter, so they are dominated by barotropic flows (Guinehut et al., 2006). Gilson et al. (1998) calculated that the RMSD between SLA and SHA is 5.2 cm in the Pacific Ocean, while the RMSD associated with bottom pressure in the basin-wide spatial mean is 2.4 cm. Mork and Skagseth (2005) found that the annual variation in the bottom pressure is largest in the Greenland Basin and off the Norwegian coast, which can reach 3–5 cm. However, they suggested that the bottom pressure effect is significant in Lofoten Basin, too, which is contrary to our result that Lofoten Basin is strongly baroclinic. The difference between the two results may be related to the wind.

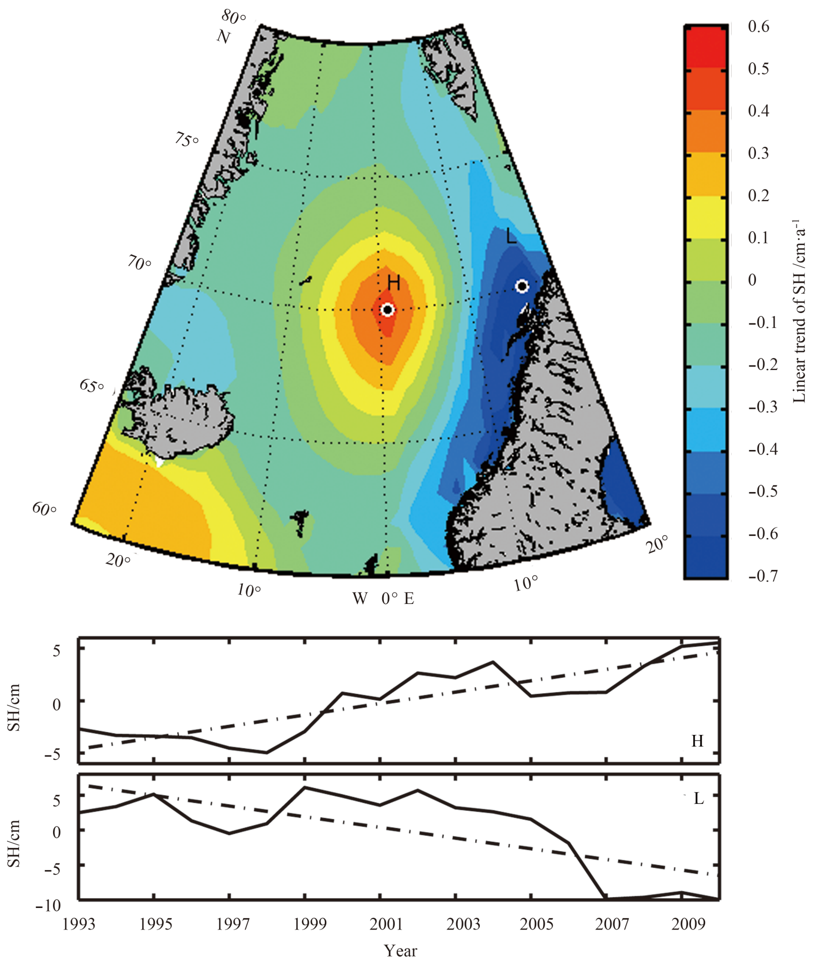

Fig. 3. Linear trend of steric height time series in the Nordic Seas during 1993–2010 (cm/a): the maximum value of linear trend, 0.54, occurs at the locations with "H" in the Lofoten Basin; the minimum value, –0.72, occurs at the location with "L" off the Norwegian coast (upper panel). The solid lines represent steric height time series, and dashes lines show the linear trends (lower panel) at the two locations, respectively.

3.3.2 *Time series of SLA and SHA*

Time series of SLA and SHA averaged over the entire Nordic Seas match each other very well in phase (see the upper panel in Fig. 5). The amplitudes of SHA are basically identical to those of SLA during 1996–2002. Besides, the amplitudes of SLA are all larger than those of SHA. Especially after 2006, the change of SHA can only explain 49.1% of SLA. The linear trends show that steric height anomaly stays nearly constant while the sea level anomaly appears to be on the rise (see the red dashed line and red solid line in the upper panel in Fig. 5, respectively). The difference between the two can be attributed to the thermohaline expansion in the deep ocean and changes in total water mass in the Nordic Seas, which may be caused by exchanges with adjacent seas or ice melting. A warming trend has been detected in the deep Nordic Seas (Østerhus and Gammelsrød, 1999), which gives a directly positive contribution to the sea level rise (Richter et al., 2012). On the other hand, Cazenave and Llovel (2010) quantified the processes causing the sea level change, and suggested that ice sheets melting gave a contribution of 40% during the period 2003–2007.

The seasonal cycle is significant in the Nordic Seas, with minimum and maximum values in spring and autumn, respectively (see the lower panel in Fig. 5). The largest differences between SHA and SLA occur in April and October, which are 2.54 cm and –2.30 cm, respectively. The seasonal variation of sea level is caused by steric effect, i.e., the density changes above the reference layer, which is similar to the situation in the Atlantic Ocean (Volkov and Van Aken, 2003). Details of seasonal variability of steric height in the Nordic Seas and its contributions are presented by Mork and Skagseth (2005). They pointed out that the main contribution is the seasonal ocean-air heat flux variation, which can explain 40% of the sea level variation. On the other hand, Siegismund et al. (2007) suggested local meridional wind stress could give rise to inter-annual variation of steric height through redistributing the Arctic water and the Atlantic water.

4 Summary and conclusions

In this study, we use the EN3 dataset to obtain steric height, which is further compared with altimetry-derived sea level anomaly. Mean steric height is dominated by the density variation above the reference depth (1 000 m), while density variation below this depth is insignificant. This conclusion is consistent with previous study.

The spatial pattern of the mean steric height of Nordic Seas

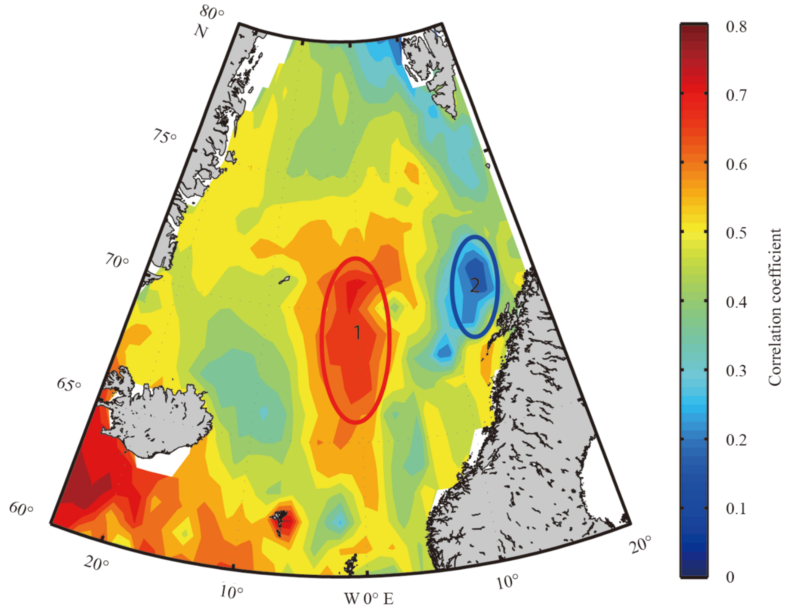

Fig. 4. Correlation between SLA and SHA. Two regions mentioned in the text: 1. Lofoten Basin and northern Norwegian Basin, and 2. northern Norwegian Sea.

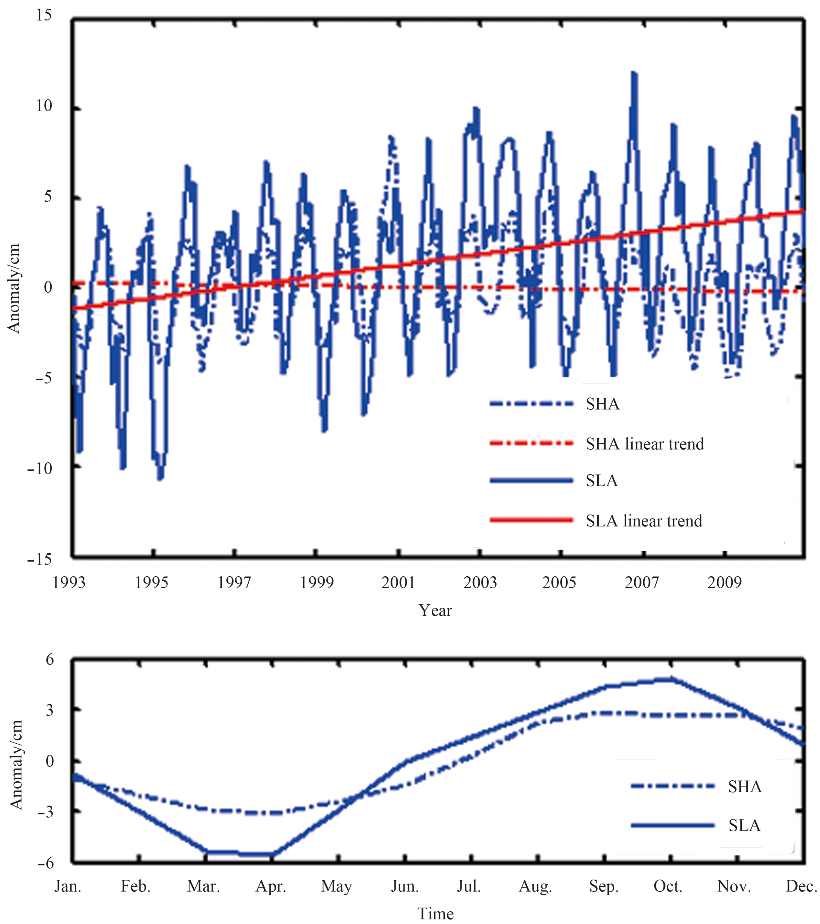

Fig. 5. Comparison of SLA and SHA averaged over the Nordic Seas.

during the period 1993–2010 shows high in the margin and low in the middle. The minimum and maximum values are in the Greenland Sea and off the Norwegian coast, respectively, which is closely related to the current in the Nordic Seas. In the period analyzed, the extreme values of steric height linear change occur in the Lofoten Basin and off the Norwegian coast, respectively.

This distribution can be partly attributed to the freshening trend of the Nordic Seas, which has significant impact on the eastern Nordic Seas dominated by the warm and salty North Atlantic water.

The correlation between SLA and SHA is not uniform over the Nordic Seas. The two series agree well in the Lofoten Basin and northern Norwegian Basin and worse in the northern Norwegian Sea, implying the baroclinic effect plays a dominant role in the Lofoten Basin and northern Norwegian Basin while the barotropic effect plays a dominant role in the northern Norwegian Sea. The weaker correlations between SLA and SHA in the Greenland and Iceland Seas lead a conclusion that the barotropic effect is significant in these areas, which is distinguished from the previous studies.

The amplitude of SHA over the entire Nordic Seas is similar during the period 1996–2002, but overall lower than that of SLA, being only less than half of that of SLA since 2006. The minimum and maximum occurs in spring and autumn, respectively. The SHA contributes a great part to SLA in overall. This difference may be due to the changes of seawater property in deep ocean and total water mass, which should be investigated in the future work.

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