STERIC SEA LEVEL CHANGES FROM ENVISAT AND GRACE IN THE NORDIC SEAS

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Abstract:

Steric sea level changes are estimated over the Nordic Seas using ENVISAT (Environmental Satellite) altimetry and GRACE (Gravity Recovery and Climate Experiment) gravity data. We have used altimetry data from the ENVISAT during October 2002 to October 2010, cycles 10 to 93, and the GRACE level 2 RL04 data released by GFZ (German Research Center for Geosciences) processing center during October 2002 to October 2010. It should be noted that some months are missing for the GRACE data set. Correction terms are applied to properly combine the altimetry and GRACE data, including the inverted barometer term, dynamic ocean and atmospheric terms and GRACE coefficients with degrees 0, 1, and 2 (with order 0). Finally, the steric sea level changes are derived over the Nordic Seas for October 2002 to October 2010.

Keywords: ENVISAT altimetry data; GRACE gravity data; steric sea level; Nordic Seas.

1. Introduction:

Steric sea level and water mass change are two major components of sea level variability. The steric sea level is due to variations in the sea water temperature and salinity at all depths and the other component, water mass change, is due to the ocean mass redistribution or water mass flux. Because of variations in density, the sea water temperature and salinity variations cause the dilatation/ contraction in the ocean column which has been observed as basin-wide fluctuations in sea level as large as ±10 cm in some areas of the world.

Using oceanic in situ temperature and salinity data, the steric sea level variation can be estimated alone (see for example [1], [2], [3], [4]), but generally, there is no sufficient spatial and temporal coverage for the in situ data archives which have been provided in high levels of smoothing, and they cannot adequately resolve eddies, frontal regions and boundary currents (e.g. [5], [6]). In addition, most of the existing data archives have been provided by averaging data from several periods meanwhile they represent the oceanic condition within a set period ([5], [7], [8]). Due to such procedures, there might be an unrealistic representation of boundary currents and other small scale features in the in situ data archives. [9]

Satellite altimetry measures the combined effect of the steric and mass variations precisely. Although the altimeters have the high accuracy, they cannot distinguish between steric and non-steric effects. Therefore the steric height estimation is downgraded in accuracy by the non-steric effects. Satellite gravity observations, on the other hand, can be used to estimate the non-steric effects. The water mass variations cause the temporal variations of the gravity field [10]. In the ocean, sea level variations and ocean density changes cause the local water mass changes ([11], [12]). The steric component of the sea level variation is just due to the dilatation/contraction in the sea water, i.e. no change in the density, a fact that we will use in this study for the separation of the steric component from the mass change and the other phenomena such as Rossby waves, Kelvin wave and gravity waves.

The twin satellites of the GRACE were launched in March 2002 as a joint partnership between the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR) [13]. GRACE measures Earth gravity changes in high level of accuracy by high-precision tracking of the satellites and changing distance between them which is being combined with the data of the on-board accelerometers and the Global Positioning System (GPS) receivers. Several research groups have used satellite altimetry and GRACE data to estimate the steric sea level change. Chambers used actual observations from Jason-1 and Release-02 GRACE data to determine monthly steric sea level variations [14]. It was found that using GRACE improves the ability to recover the dominant mode of steric sea level variability over using altimetry data alone (ibid.). Lombard et al. estimated the mean steric sea level variations over the $60°S - 60°N$ oceanic domain during August 2002 to April 2006, by combining sea level data from Jason-1 altimetry with two different sets of GRACE geoid solutions (GRGS-EIGEN-GL04 and GFZ EIGEN-GRACE04S). They found satisfactory agreement between their estimate of the annual steric sea level and one deduced from in situ ocean temperature data [15]. Kuo et al. conducted a comparison of the GRACE observations of global and Southern Ocean mass variations during April/May 2002 to June 2006 with the steric-corrected JASON-1 and ENVISAT altimetry, using the steric sea levels from WOA01 climatology and Ishii06 models [4], and with the ocean bottom pressure estimates of the ECCO ocean data assimilation model. Their study indicated that GRACE and ENVISAT observations are viable to supply an improved constraint of oceanic mass variations in the Southern Ocean [16].

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In this study, we investigate the steric height variability over Nordic Seas based on ENVISAT altimetry and monthly GRACE solution during October 2002 to October 2010. The Nordic Seas is the common name for the Greenland, Iceland and Norwegian Seas ([17], [18], [19]). The region is bounded by the Arctic Ocean to the north, the deep North Atlantic Ocean to the south, and the shallow North Sea to the southeast (Figure 1). The ocean mass changes, the sea level anomaly changes and the variability of steric sea level anomaly over the Nordic Seas during October 2002 to October 2010 are derived. To the best our knowledge this is the first analysis of this kind for the Nordic Seas, using ENVISAT and GRACE satellite data.

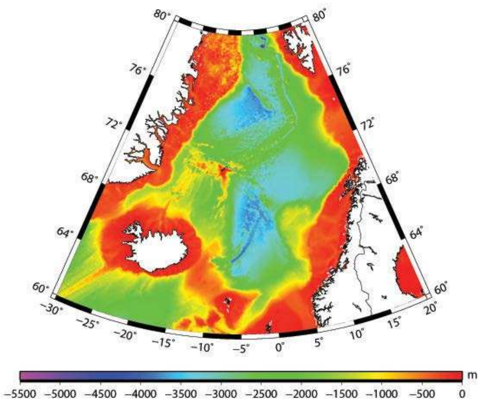

Figure 1. Bottom topography for the Nordic Seas

2. Steric sea level change from satellite altimetry and GRACE

Chambers demonstrated a method for calculating the ocean's steric height change from combination of satellite altimetry and GRACE data [14]. It included two steps: i) ocean mass variations computed from GRACE gravity coefficients and ii) sea level anomaly estimation from satellite altimetry data. In this way, the altimeter variations have to be smoothed to be comparable to the GRACE maps. In addition, several important corrections must be made in order to reconcile the GRACE data with the altimetry measurements.

2.1. Ocean mass variations from GRACE

The mass redistribution in an area causes the density distribution and the geoid to change. It mainly concentrates in the thin layer of thickness of the order 10 ~ 15 km at the Earth's surface in annual cycle, which indicates the total variations including the atmosphere, oceans, ice caps and ground water storage [10]. Assuming the thickness of the layer is thin enough, according to the relationship between the changes in spherical harmonic geoid coefficients and the density redistribution [10], and taking into account the anelastic deformation of the solid Earth, the density change of ocean in terms of change of spherical harmonic coefficients can be determined by [10]:

$$\Delta\sigma(\varphi,\lambda) = \frac{a\rho_{\mathrm{ave}}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\overline{P}_{lm}(\sin\varphi)[\Delta C_{lm}\cos m\lambda + \Delta S_{lm}\sin m\lambda] \qquad (1)$$

where a is the mean Earth's radius, ρ_{ave} is the mean Earth's density (=5517kg/m^3), φ and λ are the latitude and longitude of the point of interest and (l, m) are the degree and order of the spherical harmonic coefficients. $\overline{P}_{lm}$ is the normalized associated Legendre function of the first kind. ΔC_{lm} and ΔS_{lm} are time variations of the GRACE observed Stokes coefficients which are computed as changes relative to the mean of the monthly solutions. The load Love number coefficients k_l are also given in [10]. Because of the nature of the measurement technique in GRACE and mission geometry, the GRACE observed Stokes coefficients are polluted with short-wavelength noises [20]. The non-white correlated and resolution dependent noise in the coefficients is manifested as unrealistic North-South striping. Based on the Tikhonov-type regularization, Kusche devised a non-isotropic filter algorithm which reduces the impact of the noise at increasing degree [21]. Kusche et al. have analyzed GRACE RL04 monthly gravity solutions in the three non-isotropic filters corresponds to Gaussian filter lengths of 240, 340 and 530 km [20]. In this study, the corresponding Gaussian filter length has been inferred based on comparing the 'isotropic part' of the non-isotropic decorrelation filter with the Gaussian filter in terms of matching the particular spectral degree where the filter weight drops to 0.5 (see also [22]).

Due to the smoothing on global spherical harmonics, the average over the ocean within the smoothing radius will be affected by any large change over land. To mitigate this problem, all the grids on land will be masked and their effects are not included in the computations on the Nordic seas (see [22]). The ocean mass change derived from GRACE data reflects the sum of all geophysical process associated with mass transport in the study area, including postglacial rebound signal. The model of Paulson et al. is used to correct the obtained estimates for the postglacial rebound signal [23]. Further description of the mass change estimation using GRACE gravity models can be found in [22].

2.2. Sea level anomaly from satellite altimetry

A Sea Level Anomaly (SLA) is a Sea Surface Height (SSH) minus a Mean Sea Surface Height (MSSH) along the ground track of the satellite. Having the height of the satellite above some reference ellipsoid, the SSH can be calculated by subtracting the instantaneous range measured by the altimeter from the satellite orbit height. There are separations about 1 or 2 km for the ground tracks of altimetric satellites with repeated orbit missions. The unexpected temporal variations of SSH, caused by some significant oceanographic phenomena during particular seasons or years, will be reduced by the time-averaged altimetric SSH data with repeated orbits for all available cycles. The selected reference tracks and the related collinear tracks are used to derive the mean track (see e.g. [24]). After determining the reference tracks, two methods are used to compute the SSH of each point of the collinear tracks, which corresponds to the point of the reference. One method is collinear analyses, and the other is to make geoid gradients corrections. In this study, the time-averaging of SSH is computed by the collinear analysis. In this method, along track SSH profiles are averaged to a regular grid (the cell size (called 'bin') is approximately 6×2 km) and the mean tracks or geoid is subtracted from each individual SSH. Further description of the SLA estimation using satellite altimetry data can be found in [24].

2.3. Reconciling GRACE and altimetry data

The GRACE and satellite altimetry data processing techniques are different and non-consistent. The important issues that affect consistency of the GRACE and satellite altimetry data are discussed below.

2.3.1. GRACE coefficients with degrees 0 and 1

GRACE data do not include degrees 0 and 1 spherical harmonic coefficients. The degree 0 coefficient represents the total mass of the Earth, and the position of the Earth's center of mass in a terrestrial reference frame is represented by the degree 1 terms. Regarding the degree 0 and 1 terms, the data reconciliation is important in the combination of satellite altimetry with the GRACE data. Because of the degree 0 coefficient (C_{00}) represents the total mass of the Earth, ΔC_{00} from GRACE can be assumed to be zero at all times [10], and the degree 1 coefficients are estimated from the variations of the Earth's center of mass proposed by [25]. Following Equation (2) below, we can convert geocenter variations $(\Delta x(t), \Delta y(t), \Delta z(t))$ to degree 1 gravity coefficient anomalies.

$$\Delta C_{10}(t) = \frac{\Delta z(t)}{a\sqrt{3}} \\ \Delta C_{11}(t) = \frac{\Delta x(t)}{a\sqrt{3}} \\ \Delta S_{11}(t) = \frac{\Delta y(t)}{a\sqrt{3}} \qquad (2)$$

where a is the mean Earth's radius.

2.3.2. GRACE coefficient with degree 2 and order 0

The Earth's oblateness which is represented by the degree 2 and order 0 coefficient (C_{20}) [26], has not been well observed by GRACE [13]. Because of Satellite Laser Ranging (SLR) time series are less noisy than the GRACE time series, Chen et al. have shown that the estimation of mass variations from GRACE is improved by using C_{20} coefficient estimation from the monthly SLR time series [27]. In this study, the monthly SLR estimates are used to replace the estimates from GRACE. The SLR time series for C_{20} coefficient are taken from J. Ries (personal communication, 2010).

2.3.3. Background barotropic model and ocean and atmospheric mass terms

The atmospheric mass and ocean barotropic variations are processed as departures from the GRACE time-variable gravity models. For oceanographic analysis, it is necessary to add back the modeled ocean and atmospheric mass variations to the GRACE data, which is also necessary for comparison with the altimetery data. This is done using models which are available in the GFZ processing center data set (see Section 3.1). Meanwhile, an inverted barometer correction (IB) is applied to altimeter data (e.g. [28]). The IB can be easily computed from the following formula:

$$IB = -9.948\ (P_0 - P_{ref}) \qquad (3)$$

where, IB is in mm and P_0 is the sea level pressure in mb. In this study, IB model is presented in which mean pressure (P_{ref}) is calculated using the local mean sea level pressure, which is adjusted for temporal variations in the global mean pressure of European Centre for Medium-Range Weather Forecasts (ECMWF), as the spatial average of the surface pressure over the global ocean [29]. To reconcile GRACE with altimetry, the IB correction is subtracted from the altimetery data.

3. Numerical Investigations

3.1. Ocean mass variation from GRACE

We estimate the ocean mass variation in the Nordic Seas using more than 8 years of GRACE level 2 RL04 data set released by GFZ processing center during the period October 2002 to October 2010, missing out the data for December 2002 and January 2003 and 2004 due to missing accelerometer data. RL04 coefficients are distributed on the level-2 data archives as GAC, GAD and GSM files (GAC, GAD and GSM are file extensions). The GSM files contain spherical harmonic coefficients representing the gravity field of the Earth.

The atmospheric and oceanic mass signals effects have been removed from these coefficients. The GAC and GAD files include the modeled atmospheric and oceanic contributions to the GSM coefficients. The GAC files include the global atmospheric and oceanic effects and the GAD files represent ocean bottom pressure variations. For comparison with the altimetry data, the modeled ocean and atmospheric mass variations should be added back to the GRACE data. Before computing the ocean mass variation, the modeled atmospheric and oceanic contributions could be restored to the GSM coefficients by adding the GAD and GAC coefficients.

Equation (1) which is used to compute the ocean mass variation is formulated to use gravity coefficients down to degree 0. As mentioned in Section 2.3.1, ΔC_{00} from GRACE can be assumed to be zero at all times and the degree 1 coefficients are estimated from the variations of the Earth's center of mass proposed by [25]. The monthly SLR estimates for C_{20} coefficient are used to replace the estimates from GRACE to complete the data reconciling step.

The monthly solutions of the GRACE when computing ocean mass variations include an unphysical striping error pattern which can be considered as noise and must be decorrelated/filtered. They have been filtered using Kusche et al. method by the corresponding Gaussian radius of 530 km [20].

Using Equation (1) and after the data reconciling, we estimate ocean mass variations in the Nordic Seas on a $0.5^{\circ} \times 0.5^{\circ}$ grid during the period October 2002 to October 2010. Next step is to form an approximate estimate of total mass change for each month, by summing over grid elements with cosine latitude weighting. Figure 2 shows the estimated ocean mass variations over the Nordic Seas using GRACE data. As mentioned above, the reconciled data have been decorrelated in the corresponding radius of 530 km. GRACE data reflects the postglacial rebound signal associated with mass transport in the study area. Using Paulson et al. model [23], the obtained estimates have also been corrected for the postglacial rebound signal.

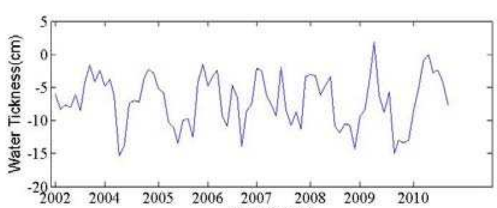

Fig 2. Ocean mass changes over the Nordic Seas during the period October 2002 to October 2010.

3.2. ENVISAT altimetry data

Using sea surface height data from the ENVISAT altimeter during October 2002 to October 2010, cycles 10 to 93, we estimate sea level anomaly over the Nordic Seas. In this study, sea surface height data retrieval and reduction are carried out using the Stackfiles database [30]. The sea surface height data in the Stackfiles database have been corrected for orbital altitude, instrument bias, sea state bias, ionospheric delay, dry and wet tropospheric corrections, solid Earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias and inverse barometer correction. The corrections were done by applying specific models for each satellite altimetry missions in the Stackfiles database [30].

As mentioned in Section 2.2, we compute the mean tracks of ENVISAT altimeter, cycles 10 to 93, as shown in Figure 3. It should be noted that the presence of sea ice (such as in the East-Greenland Current, the Greenland Sea and in the Fram Strait) requires estimation of freeboard height in order to allow the mean sea surface to be determined from altimetry. The mean tracks of altimetry data in the sea ice areas have large standard deviations. In our study, we used the mean tracks with the standard deviation less than 50 cm in the sea ice area and therefore the masked areas in Figure 3 is resulted. Inverse barometer correction is subtracted from the altimetry-based sea surface height data, to be consistent with GRACE data that observe the real water mass signal. Glacial Isostatic Adjustment (GIA) causes a secular increase in the volume of the ocean basins, which reduces global mean sea level by approximately -0.3 mm/year [31]. Thus, in order to account for GIA, a linear -0.3 mm/year correction is subtracted from the mean tracks.

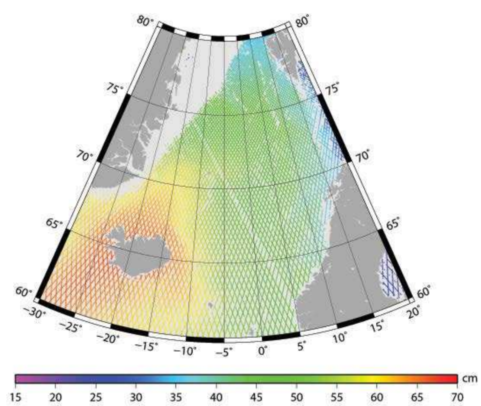

Fig 3. Mean tracks of ENVISAT altimeter over the Nordic Seas during October 2002 to October 2010

Subtracting the tracks from the mean tracks, the SLA is estimated for all the ENVISAT cycles. In addition, for each cycle, the SLA is gridded on a $0.5^{\circ} \times 0.5^{\circ}$ grid using GEOGRID program [32].

Next step is to form an approximate estimate of total the SLA for each month, by summing over grid elements with cosine latitude weighting.

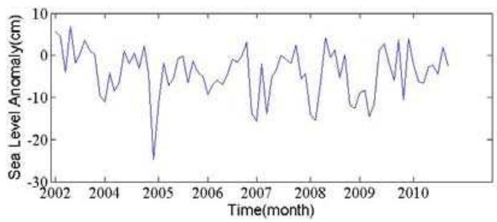

Fig 3. Sea level Anomaly changes over the Nordic Seas during October 2002 to October 2010.

3.3. Steric sea level change from ENVISAT and GRACE

Subtracting the SLA and the ocean mass variation in the Nordic Seas for each month, the Steric Sea Level Anomaly (SSLA) is estimated for each month. Figure 4 shows the variations of the SSLA over the Nordic Seas during October 2002 to October 2010.

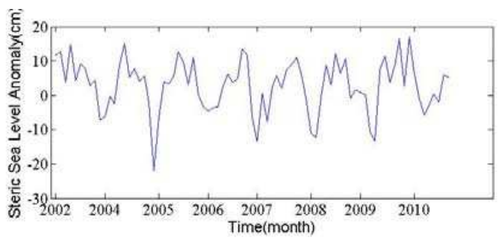

Fig 4. Steric sea level anomaly changes over the Nordic Seas during October 2002 to October 2010

4. Conclusion

Steric sea level variations over the Nordic Seas are determined from combined ENVISAT altimetry and GRACE data, at monthly interval, from October 2002 to October 2010. Note that this method provides an estimate of the total steric (thermosteric plus halosteric, for the entire water column) sea level anomaly variations. The combination of satellite altimetry with the ocean mass change observations from the GRACE mission offers a superior method for estimating the steric sea level changes over using altimetry alone, or in situ observations of temperature and salinity from the profiling floats to be used in the Argo float program. Several correction terms are applied in order to reconcile the GRACE data with ENVISAT altimetry data.

5. References

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