Journal of Geodetic Science

• 1(2) • 2011 • 181-190 DOI: 10.2478/v10156-010-0021-4 •

Mean Sea Surface and ocean circulation in North Atlantic and the Arctic Sea

Research Article

Kourosh Ghazavi*, Hossein Nahavandchi

Division of Geomatics, Norwegian University of Science and Technology (NTNU), N-7491 Trondheim, Norway

Abstract:

High resolution Mean Sea Surface (MSS) model and its error estimation over the study region (56°N<ϕ<82°N, 45°W<λ<33°E) have been determined to evaluate Mean Dynamic Topography (MDT) in the Fram Strait and adjacent seas. Multiple high-latitude observing satellite radar altimetry data were used to determine a new MSS model that, hereafter, is called NTNU MSS. Sea Surface Height (SSH) values of the NTNU MSS model vary between 15 to 70 m over the study region, and the internal consistency or the quality estimate for the model ranges from 1 to 5 cm. External comparisons have been performed to validate the NTNU model applying available MSS models such as KMS04, mean and Standard Deviations (SD) of the differences are 1.7 cm and 8.9 cm, respectively. To assess the compatibility of the NTNU MSS model, residual analysis has been carried out relative to geoid and Oceanographic MDT (OMDT) models. Utilizing OCTAS04 geoid and OCCAM MDT models, the SD and mean of the residuals are 13.1 cm and 10.1 cm, respectively. Finally, the surface geostrophic velocities have been computed and compared with the velocities extracted from the OCCAM and KMS04. Differences between the geostrophic velocities derived from the NTNU Synthetic MDT (SMDT) and the OCCAM OMDT are 4.97 and 2.94 cm/s for the mean and SD values.

Keywords:

Satellite altimetry • MSS • MDT • geoid • geostrophic velocity • residual analysis • collinear analysis • Stackfiles • Fram Strait • Arctic

© *Versita Warsaw and Springer-Verlag Berlin Heidelberg.*

Received 20 December 2010; accepted 17 March 2011

1. Introduction

Ocean transport through the Fram Strait and Gulf Stream is known to play an important role in the global circulation. However, one can only understand the importance of the high latitude Nordic Sea's circulation for the North European and polar climate by obtaining a complete picture of the North Atlantic circulations.

In the context of ocean monitoring a major task is to determine an accurate high resolution Mean Sea Surface model (as the absolute reference surface for the ocean circulation, after subtracting a geoid model) to improve the determination of the mean ocean circulation in order to understand the role of the ocean mass and heat transport in the climate change (see e.g. Solheim et al., 2007).

For more than two decades, the satellite radar altimetry surveys have provided nearly global SSH by continuous and repeated observations for studying the ocean circulation and its changes. Therefore, merging multi-satellite altimetry observations has provided several global and regional MSS models; such as OSU95 (the Ohio State University; Rapp and Yi, 1997), GSFC00.1 (NASA's Goddard Space Flight Center, USA; Wang, 2001), NCTU01 (the National Chiao Tung University, Taiwan; Hwang et al., 2002), CLS (Collecte Localisation Satellites, France) MSS models (see e.g. Hernandez et al., 2004), and KMS (Kort-og Matrikelstyrelsen, Denmark) MSS models (see e.g. Andersen et al., 2006).

The main objectives of this study were to provide an accurate high resolution Mean Sea Surface model (the NTNU MSS) and its associated quality estimation from multiple high-latitude satellite radar altimeters data for the study region (56°N< ϕ <82°N, 45°W< λ <33°E). This accurate MSS combined with geoid and

---

*E-mail: ghazavi@ntnu.no; Tel.: + 47-73594575; Fax: + 47-73597021

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

MDT models (with high accuracy) can lead to an improvement in our understanding and knowledge about the ocean circulations over the Nordic Seas. A challenging issue in the determination of the MSS model (over the high latitudes) was gaps in the altimetry data over the northwest part of the study area, which is covered by ice or sea ice. Hence, in this study attention to the enhancement of MSS quality along the Greenland coast and in the Fram Strait has been considered of great importance.

2. Methodology

The idea behind altimetry is to utilize the highly stable platform provided by a satellite as a moving reference system where vertical measurements to the ocean surface are made. If the height of the satellite above some reference ellipsoid is known then the height of the sea surface above the reference ellipsoid (SSH) can be calculated by subtracting the instantaneous range from the satellite orbit height (see e.g. Chelton et al., 2001). The SSH is related to the geoid and the Mean Dynamic Topography of the ocean as well as the time varying Dynamic ocean Topography (DT). The SSH varies significantly from one region to another, mostly caused by the geoid. Besides, even the along-track locations of the data points vary from cycle to cycle (time period) for a set of repeat tracks because the altimeter data are output by the time not by the location. Thus, a reduction of the SSH value to the nearest common point which is representative of all repeat cycles is necessary to compute a time average of the SSH values (MSSH) uncorrupted by errors due to the geoid gradients.

Altimetry data which have been used in the determination of the NTNU MSS model were extracted from the so-called 'Stackfiles' altimetry database at the Ohio State University (Yi, 2010). The altimeter Stackfiles database can be regarded as a reorganization of the altimeter measurements per geographical location. The most straightforward analysis for which the altimeter Stackfiles is designed is the 'colinear' or 'repeat track' analysis, which is the earliest method of correcting the MSSH along track gradients (Sandwell and Zhang, 1989). The advantage of utilizing the repeat track analysis is that the satellite follows the same ground track over the ocean, and successive passes can be averaged to reduce constant errors and remove outliers. In this method, along track SSH profiles were averaged to a regular grid (or 'bin', approximately 6×2 km) and a MSSH gradient from one grid to the next was computed. The second step is to constitute residual for each individual SSH, by subtracting the MSSH or geoid. MSSH and RMS (Root Mean Square, σ) about the MSSH are stored in the header of the Stackfiles record. Hence, one fundamental assumption in the MSS corrections (with a long enough sample of data in time, time series) is that the real sea level variability will average out and MSSH can be determined. Therefore, part of the analysis of the ocean altimeter Stackfiles involves with the computation of the MSSH, geoid gradients; and annual, semi-annual and secular trend signals per geographical bin (Kruizinga, 1997). The following model is used in the Stackfiles to estimate the above-mentioned parameters (see e.g. Shum and Braun, 2004):

$$SSH(\phi,\lambda,t) = N(\phi,\lambda) + T(\phi,\lambda,t) \qquad (1)$$

where, $N(\phi,\lambda)$ is geoid (stationary part of the SSH), $T(\phi,\lambda,t)$ is the time varying part of the SSH, ϕ and λ are latitude and longitude of the bin center and 't' is time of a SSH measurement. On the other hand, one can mention:

$$N \approx SSH(\Delta x,\Delta y) = a + b.\Delta x + c.\Delta y \qquad (2)$$

where, 'a' is the height of plane at the bin center (this is equivalently the bin's MSSH, after correcting for the gradients), 'b' is the along track sea surface gradient, 'c' is the cross track sea surface gradient, Δx is the along track displacement from the bin center and Δy is the cross track displacement from the bin center. The time varying part can be written as:

$$T = [B + At] + [S_1 \sin(2\pi t) + C_1 \cos(2\pi t)] + \\ [S_2 \sin(4\pi t) + C_2 \cos(4\pi t)] + e \qquad (3)$$

where, 'B' is offset (linear trend intercept, bias), 'A' is the secular rate (linear trend slope), S_1, C_1, S_2 and C_2 are amplitudes of the sine and cosine terms (harmonic constants for the annual and semi-annual signals), and 'e' is noise. In fact, the computation is done in an iterative fashion that can be described briefly as follows:

1. Estimation of the offset, secular rate, annual and semi-annual variations, Eq. (3), and then removing the secular rate, annual and semi-annual variations from the original measurements ($\mathrm{SSH}_{ori.}$):

$$SSH_1 = SSH_{ori.} - SSH_{(ann.+semi\_ann.+sec.)} \qquad (4)$$

2. Estimation of the along tack sea surface gradient (b) and the cross track sea surface gradient (c) applying the SSH_1, and then removing the sea surface gradients from the original measurements.

$$SSH_2 = SSH_{ori.} - b.\Delta x - c.\Delta y \qquad (5)$$

3. Re-estimation of the offset, secular rate, trend, annual, and semi-annual variations employing the SSH_2, and removing new estimates of the secular rate, annual and semi-annual variations from the original measurements.

$$SSH_3 = SSH_{ori.} - SSH_{(ann.+semi\_ann.+sec.)} \qquad (6)$$

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

4. Estimation of the MSSH (a), along track and cross track sea surface gradients, Eq. (2), by the SSH_3.

This iterative process is continued until the values for the geoid gradients, MSSH, annual, semi-annual and secular trend signals have converged. The iterative process was chosen for computing the along track MSSHs to determine the NTNU MSS model. The estimated parameters retained a more physical meaning when estimated separately in an iterative fashion as compared to a simultaneous solution of all parameters (Chambers et al., 1998).

It should be mentioned that besides the colinear analysis, along track and grid comparison which have been applied in this study, the crossover analysis (out of the scope of this study) can be considered as an appropriate tool to qualify altimeter data, i.e. some conclusions on quality and consistency of the collected data can be drawn by comparing measurements in the same satellite position (satellite track crossovers).

3. Data Processing and Results

The overall aim of this study was to compute an accurate MSS model (the NTNU MSS) and its quality estimation utilizing the high latitude operating satellite radar altimeters over the area of interest. Furthermore, to validate and assess the quality of the produced NTNU MSS, external comparison has been carried out against some available MSS models. Then, by applying different MSS and geoid models, Synthetic MDTs (SMDT) have been computed and were used for the residual analysis. The residual analysis was performed in order to assess the compatibility of the NTNU MSS relative to the geoid and Oceanographic MDT models. Finally, the surface geostrophic velocities have been derived from available models.

Altimetry datasets, extracted from the Stackfiles, included data from ENVISAT (ENVIronmental SATellite), ERS-1 (European Remote Sensing satellite), ERS-2, GFO (Geosat Follow On), TOPEX/Poseidon (T/P) and Jason-1 satellite altimeters. T/P and Jason-1 data cannot be used in the study region (due to the limited latitude coverage beyond 66°N). Also note that the coverage of GFO, used in this study, is only to 72°N. Therefore, only European Space Agency (ESA) satellites, i.e. ERS-1, ERS-2 and ENVISAT can provide full coverage over the area of interest (to 82°N). Among these three satellites, ENVISAT is the only one that still collecting the Altimetric data. ENVISAT (cycles 10-52, 10.2002-11.2006), ERS-2 (cycles 1-85, 05.1995-07.2003), ERS-1 ERM (phases C, 04.1992-12.1993; and G, 04.1995-06.1996) and GFO (cycles 37-168, 01.2000-03.2006) data, have been applied to determine the NTNU MSS.

3.1. Evaluation of the existing MSS, Geoid and MDT Models

MSS: The global KMS04 and regional CLS04 were evaluated. The KMS model was computed and delivered by National Survey and Cadastre (Denmark) on a $2'$ grid (about 4 km at the Equator) ocean wide, within the latitudes $\pm 82°$, and the CLS model has been determined by the CLS Space Oceanography Division (France). In the determination of these models, generally the same altimeter data have been used, but the methodology and applied corrections were slightly different (for more details; see e.g. Hernandez et al., 2004 and Andersen et al., 2006). The KMS04 and CLS04 models have good coverage over the study region, also compared with the other MSS models which were available for this study (such as KMS01, KMS03, CLS01, OSU95 and GSFC00); they have used longer time series of the altimetry data and more updated geophysical correction.

Geoid: The OCTAS project used new airborne gravity data, adjusted marine gravity data and new satellite based geopotential models to determine OCTAS04 gravimetric geoid. The OCTAS04 is calculated using the remove-restore technique and the Wong-Gore modified Stokes' function with truncation at degree 80 and long-wavelength part of it, is determined from the global geopotential model GGM01C to degree and order of 200 (Omang et al., 2006).

MDT: The Ocean Circulation and Climate Advanced Modeling (OCCAM) MDT is based on an ocean primitive model assimilating Altimetric data to provide a more realistic ocean description. Initialized from the Levitus climatology model, an 8-year spin-up has been performed on the OCCAM using the climatological monthly atmospheric forcing, also the Altimetric SSH data from T/P and ERS-1 are assimilated and referenced to a 3-year mean (1993-95). The OCCAM MDT (see e.g. Fox and Haines, 2003) offer the better view of the North Atlantic circulation over the study area, as the model exhibits the clearer circulation pattern with good coverage to 82°N, and also it has finer spatial resolution. The MDT model has been reformatted into a common grid and in order to obtain clear pattern of the currents, spatial smoothing (filtering) has been performed to remove noises.

3.2. Data analysis

The iterative process was implemented in the computation of the MSSHs at each bin (along track MSSH). The MSSH computed by the iterative process which is corrected for the geoid gradients and ocean variability signals, hereafter is called 'AMSSH' (Adjusted Mean Sea Surface Height; along the track). Applying the iterative process, a model which includes nine unknown parameters, see Eqs. (2) and (3), should be adjusted to the SSHs of each bin. Thus, it is necessary to acquire at least nine data (cycles) to perform the adjustment. Considering the fact that the study area is located at the high latitudes, there are relatively large areas covered with sea ice and therefore a lack of altimetry data. This is due to the instability of the sea level conditions during different seasons (e.g. melting of ice), which in the initial data processing leads to rejecting the data and thus yields less data over the sea ice. Consequently, the iterative process cannot be performed to calculate the AMSSH over the areas covered with the sea ice, which contain many bins with less than nine data points. Besides, if any of the annual

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

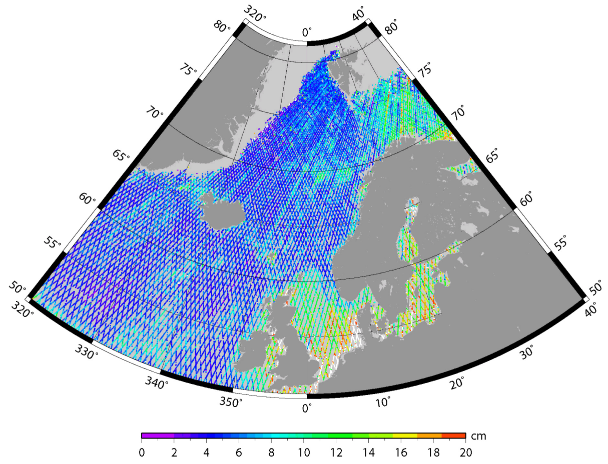

Figure 1. SD of the ENVISAT AMSSH data.

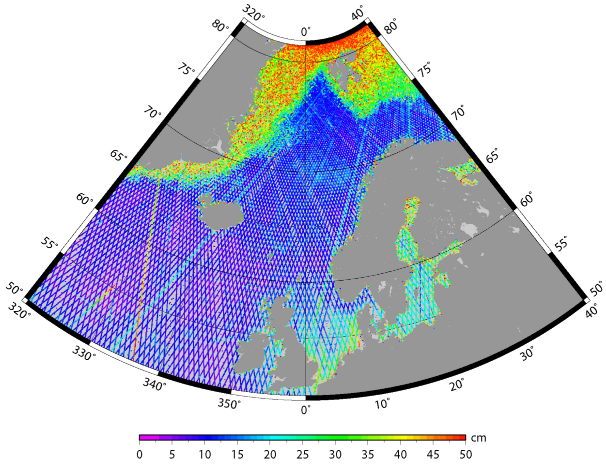

Figure 2. SD of the ENVISAT SMMSH data.

estimates are too large or the estimated gradients are more than ±320 micro-radians (mm per km), they were edited (rejected) by the programs (to compute mean tracks) in the Stackfiles (coded by D. Chambers and modified by Y. Yi).

The statistics for data quality analysis of the AMSSH over the study area showed that, at least 95% of all data have the SD less than 20 cm (except for the ERS-2 data, which are contaminated by large orbital errors). Therefore, in order to employ more accurate AMSSHs, a 20 cm SD (30 cm for ERS-2) is an appropriate value to detect and exclude outliers. As an example it can be seen in Fig. 1 that for the high latitude operating satellites, there is a large gap in data in the north and northwest part of the area, where is covered by ice or sea ice. These data gaps are mainly made by the editing criteria (data are contaminated by large error values or there are not enough data), which lead to reject computation of the AMSSH in many bins. On the other hand, the gap covers relatively large part of the study region (where the important Fram Straight cold current follows east of the Greenland coast). Existence of this large area covered with the sea ice is one of the major problems to compute MSS models and thus to derive an accurate MDT. Therefore, in order to improve the quality of the MSS and MDT models; filling this gap with as much as possible high quality data has a great importance in this project.

To overcome this problem one solution is to avoid applying the iterative process over the sea ice. Therefore, MSSHs which are corrected for the geoid gradients, Eq. (2), can be used over such areas to avoid further gaps in the data. This kind of MSSH data over each bin, hereafter, is called SMSSH (Simple Mean Sea Surface Height); which are contaminated by the ocean variability signals. In order to fill the gaps, with as much as possible data with optimal error values, a statistical analysis was performed for the SMSSH data to find suitable thresholds of the SD for each satellite dataset. Results indicated that, a 50 cm threshold value for the SD (except for ERS-2, 1 m) is almost suitable for all datasets. Moreover, Fig. 2 depicts that employing the SMSSH is useful to overcome the problem regarding the lack in data over the sea ice. Although, the ocean variability signals remain in the SMSSH, but the positive result is to retrieve the SSH data and fill the gap over the sea ice with a relatively acceptable quality. This is very important in the determination of an improved and accurate MSS model over such a high latitude region. Finally it can be stated that, referring to the previously mentioned results and also from Figs. 1 and 2, one can divide the study region into two parts; identified by relatively small error values (hereafter, 'A_main' part) and over the sea ice where the quality of data significantly decreases (hereafter, 'B_ice' part).

3.3. Determination of the NTNU MSS model

In order to determine the NTNU MSS; the AMSSH of the ENVISAT, ERS-2, ERS-1 ERM (Exact Repeat Mission), and GFO datasets were derived (using the Stackfiles database) over the study area. The editing procedures have been applied for different datasets to exclude mean tracks and SSH data which were contaminated by large error values. Mean and corresponding SD of the annual and semi-annual amplitude, linear trend slope, and linear trend intercept (bias) of the ocean variability signals (time varying part of the SSH) were computed by the iterative process, see Sec. 2, and the results are shown in Table 1. Then, an effort has been done to fill the gaps (over the B_ice part) applying the SMSSH data (corrected for the geoid gradients).

Satellite altimeters give different SSH signals, mainly due to the systematic radar instrument biases between the missions. Moreover, each satellite dataset is processed independently and corrected for orbital altitude, onboard instrumental drifts, sea state bias, atmospheric delays, tides, sea state bias and inverse barometer correction (see e.g. Chelton et al., 2001). Therefore the biases

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

Table 1. The statistics for the analysis of the ocean variability parameters.

Dataset	Annual amplitude (cm)		Semi-annual amplitude (cm)		Linear bias (cm)		Linear slope (cm/year)	
	mean	SD	mean	SD	mean	SD	mean	SD
ENVISAT	6.22	2.96	3.26	1.95	2.47	7.55	-0.92	3.27
ERS-2	6.35	2.65	2.55	1.83	0.07	2.39	-0.11	0.66
ERS-1 ERM	7.10	3.62	4.00	2.12	-2.01	4.46	3.48	6.46
GFO	4.14	1.81	1.57	0.92	-0.92	4.05	0.23	0.77

between these individual datasets should be determined and adjusted. The grid comparisons have been fulfilled to extract the biases, i.e. each dataset was gridded (grid spacing $\Delta\phi = 3'$, $\Delta\lambda = 6'$) using GEOGRID program (coded by R. Forsberg, 2003) in the GRAVSOFT software package, which applies LSC (Least Squares Collocation) to interpolate the irregularly distributed data on a regular grid. The results of the grid comparisons are given in Table 2.

Table 2. The statistics for the grid comparisons, unit: cm.

Grids	$\phi < 82°$N		$\phi < 72°$N	
	mean	SD	mean	SD
ENVISAT – ERS-1 ERM	9.1	16.9	—	—
ENVISAT – ERS-2	42.4	12.5	—	—
ERS-1 ERM – ERS-2	33.6	12.9	—	—
ENVISAT – GFO	—	—	42.6	6.5
ERS-1 ERM – GFO	—	—	38.3	8.8
ERS-2 – GFO	—	—	0.6	7.9

As can be verified from Table 2, the mean value of the differences between the ERS-2 and GFO grids is about 0.5 cm, therefore these two datasets were merged after applying the bias to the ERS-2 dataset (this combined datasets is called E2GF dataset, hereafter). In the determination of the NTNU MSS model a four-parametric transformation model (Rapp et al., 1994) has been utilized to estimate the grid biases and to fit the combined gridded dataset.

$$H = SSH - MSS = B + \Delta x \cos\phi \cos\lambda + \Delta y \cos\phi \sin\lambda + \Delta z \sin\phi \tag{7}$$

where, Δx, Δy and Δz are the origin shift parameters and 'B' is an offset parameter. After applying the adjusted transformation parameters in the model, Eq. (7), mean values of the residual biases (after fit) were removed from the datasets. The statistics for the grid biases before and after fitting are given in Table 3.

Finally by combining all data to generate a unique dataset, the merged dataset was gridded by the GEOGRID program to produce the NTNU MSS model. The NTNU MSS model represents the MSSHs over the Nordic seas (Fig. 3). The internal consistency or the quality

Table 3. The statistics for the grid biases before and after fit, unit: cm.

Data set	bias before fit		bias after fit	
	mean	SD	mean	SD
ERS-1 ERM	40.1	20.1	1.2	14.7
E2GF	1.7	19.9	0.3	15.3
ENVISAT	49.8	14.4	0.7	12.5

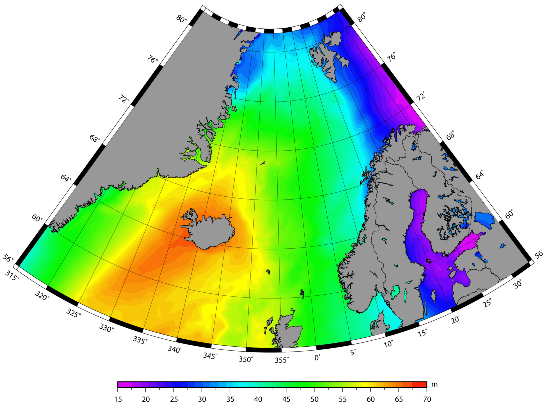

Figure 3. The NTNU MSS model.

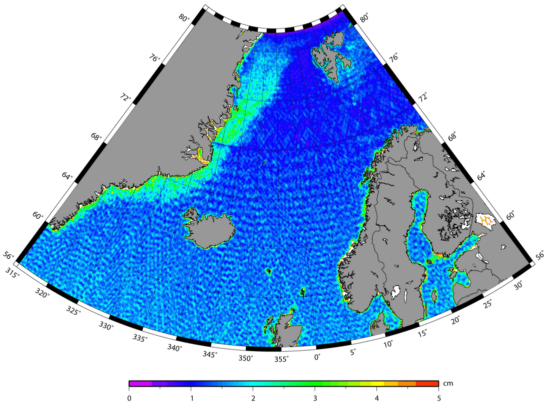

Figure 4. The associated error estimation of the NTNU MSS model.

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

estimate of the NTNU MSS ranges from 1 to 5 cm over the study region (Fig. 4). This quality estimate is based on the residuals from fitting data to the model using the LSC method. A value of 3 cm is recommended to screen the regions with relatively poor quality in the MSS, e.g. over the sea ice.

3.4. Validation of the NTNU MSS and Residual Analysis

The global KMS04 and regional CLS04 MSS models have been employed to validate the NTNU MSS model. In the determination of the KMS04, CLS04 and NTNU MSS models, slightly different methodology and altimetry datasets (referred to the different time periods), also various applied corrections have been used. The external comparison (after outlier rejection for the confidence interval of 3σ) resulted that the mean and SD of the differences between the NTNU MSS and KMS04 are 1.7 cm and 8.9 cm (Fig. 5). These values applying the CLS04 model are 0.6 and 6.6 cm, respectively.

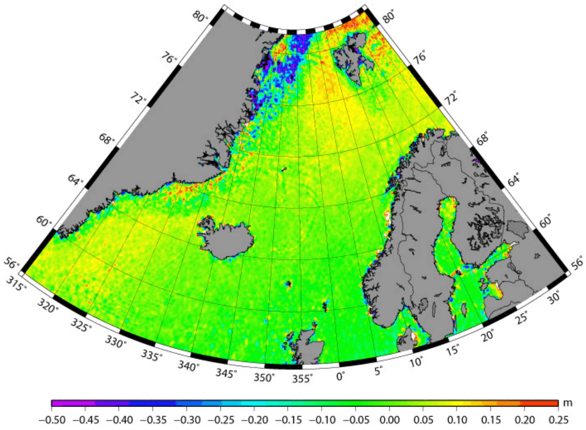

Figure 5. The differences between the NTNU and KMS04 MSS models.

One method for the determination of a MDT model is the 'synthetic' calculation. Synthetic MDTs (SMDT) are simply determined by combining a MSS and a geoid model, i.e. subtracting the MSSH from the geoid height (SMDT = MSS -- Geoid = MSSH -- N). The NTNU SMDT was derived for the study region by combining the NTNU MSS and the OCTAS04 geoid models. In order to provide clear patterns of the ocean currents (to be comparable with the OMDTs), the SMDT was filtered (i.e. spatial smoothing to filter out noises) by a suitable wavelength (150 km half width). Fig. 6 depicts the NTNU SMDT (ranges from -80 cm to 30 cm), which at a glance shows the general scale of the ocean currents over the study area quite similar to the OCCAM OMDT (see Fig. 7). The OMDT models in principle should resemble the SMDT. Therefore, to assess the compatibility of the NTNU MSS model and the geoid field with the OMDT models, residual analysis was carried out by comparison of the SMDT and OMDTs.

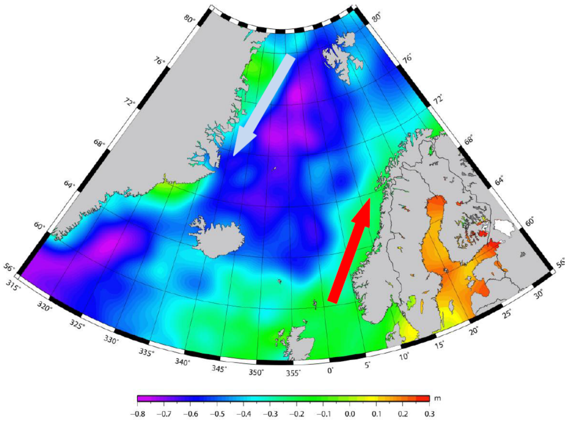

Figure 6. The SMDT derived from the NTNU MSS and OCTAS04 geoid.

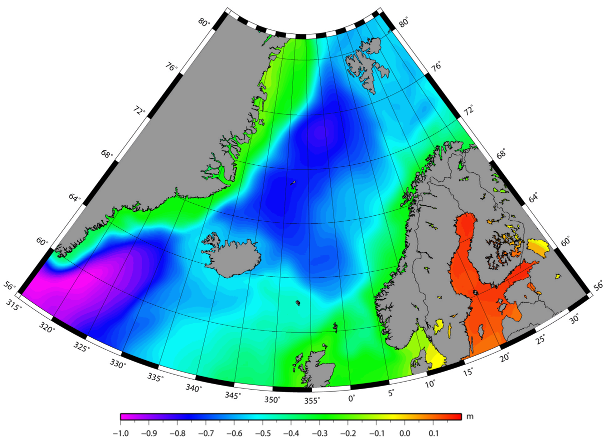

Figure 7. The OCCAM OMDT over the study area.

$$R = SMDT - OMDT = MSS - geoid - OMDT \approx 0 \qquad (8)$$

In order to perform the residual analysis, Eq. (8), combination of the different MSS (NTNU and KMS04), geoid (OCTAS04 and ArcGP) and OMDT (OCCAM and MICOM) models were used.

Note that the MICOM model, that was applied in this study, is NERSC (Nansen Environmental and Remote Sensing Center, Norway) version of the climate MICOM (Miami Isopycnic Coordinate Ocean Model) MDT (Lohmann et al., 2009); and the ArcGP geoid (ϕ>64°) is an output from the Arctic Gravity Project (see e.g. Forsberg and Skourup, 2005).

The residual analysis results (after removing outliers for the confidence interval of 3σ) are summarized in Table 4, and for comparison between the residuals derived from the NTNU and KMS04 MSS models one can refer to Figs. 8 and 9.

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

Table 4. The statistics of the residual analysis.

Models used for the residual analysis			mean (cm)	SD (cm)
MSS	Geoid	MDT		
NTNU	OCTAS04	OCCAM	10.1	13.1
KMS04	OCTAS04	OCCAM	9.3	13.3
NTNU	OCTAS04	MICOM	11.6	14.1
KMS04	OCTAS04	MICOM	10.4	14.4
NTNU	ArcGP	OCCAM	10.2	13.9
KMS04	ArcGP	OCCAM	8.9	13.1

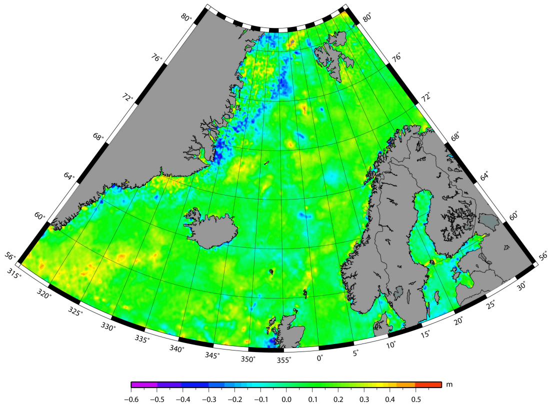

Figure 8. The residuals derived from the NTNU – OCTAS04 – OCCAM models.

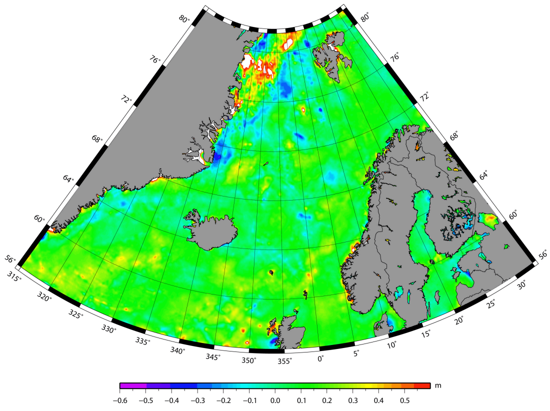

Figure 9. The residuals derived from the KMS04 – OCTAS04 – OCCAM models.

Considering the fact that the MSS and MDT models refer to different time periods residuals cannot be zero (assuming the geoid as a time invariant parameter within this period); see Eq. (8), $R \approx 0$. In addition, OMDT models do not usually refer to a well-defined geodetic datum, whereas the MSSH and geoid height are referenced to the same reference ellipsoid.

3.5. Analysis of the surface geostrophic velocity extracted from the SMDT

Geostrophic flow is a major component of the ocean surface currents, and is a function of wind forcing, tidal forces, the Earth's rotation and gravity. The geostrophic current is the result of balance between the pressure gradient and Coriolis force. Often in the deep ocean, a large percentage of the surface current is in the geostrophic balance, and it can be calculated as a function of the latitude and change in the SSH. Hence, satellite altimetry offers an accurate tool to observe the geostrophic current, exploiting the linear relationship between the geostrophic current and the SSH. Equations for the geostrophic balance are derived from the equations of motion assuming that the density (ρ) and gravity (g) are essentially constant in the upper few meters of the ocean. Therefore, two components (in the Cartesian coordinates) of the surface geostrophic current can be written as follows (see e.g. Stewart, 2006):

$$\begin{aligned} u &= -(1/f\rho)(\partial P/\partial y) = -(g/f)(\partial \zeta/\partial y) \\ v &= (1/f\rho)(\partial P/\partial x) = (g/f)(\partial \zeta/\partial x) \end{aligned} \tag{9}$$

where, 'u' and 'v' are respectively the north-south and east-west components, $f = 2\omega \sin \phi$ is the Coriolis parameter, ω is the angular velocity of the Earth's surface, ϕ is latitude and ζ is height of the sea surface above the geoid (i.e. dynamic topography). According to Eq. (9), the surface geostrophic currents are proportional to the slope of topography, a quantity that can be measured by the satellite altimeters if geoid height is known. In order to extract the geostrophic velocity components over the study region, the SMDT derived from the NTNU MSS and OCTAS04 geoid has been used. In addition, the KMS04 MSS and the OCCAM OMDT models were separately evaluated, then the differences between the geostrophic velocities derived from the NTNU and KMS04 MSS have been calculated, Figs. 10 and 11.

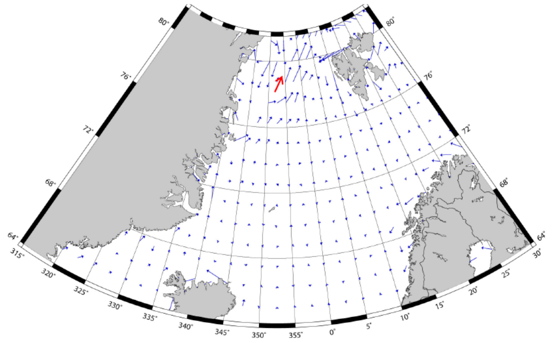

Figure 10. The geostrophic velocity differences between the NTNU and KMS04 → indicates 20 cm/s velocity.

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

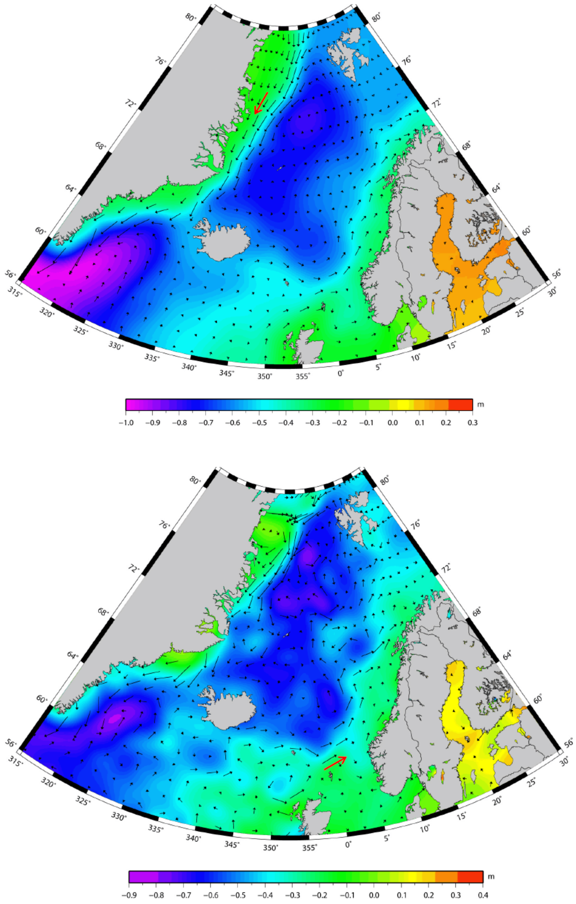

Figure 11. The geostrophic velocities from the OCCAM (upper) and the NTNU SMDT (lower) → indicates 20 cm/s velocity

4. Discussions

Determination of a high precision MSS model towards an improved MDT model over the Nordic Seas region is among the main goals of this study. Significant efforts have been made to avoid gaps in data over the sea ice area and to average out the ocean variability signals (annual, semi-annual, and sea surface trends). For this purpose, the SSHs were carefully evaluated to find the optimal SD (error estimate) for each satellite dataset individually, which mask the large error values over the sea ice and coastal areas. Afterward, corrections for the geoid gradients were taken into account and the ocean variability signals (see Table 1) were averaged out by applying the colinear analysis (see Sec. 2). The grid comparisons have been carried out to find the biases between the individual datasets (see Table 2), and by applying a four-parametric model, see Eq. (7) and Table 3, a combined gridded dataset was established for determination of the NTNU MSS model

Prior to the discussion about the validations (external comparison and the residual analysis, Sec. 3.4), one should pay attention that the absolute bias of TOPEX is known to be practically zero. Hence, this mission was chosen as a reference for the other altimeter missions and potential radar instrument biases between different satellites are removed using T/P data as reference (see e.g. Andersen et al., 2006). Furthermore, the comparison between different MSS models can be possible when they refer to the same reference; on the other hand the residual analysis results become more reasonable and meaningful.

Applying the best available MSS models over the area of interest, i.e. the KMS04 and CLS04, external comparisons indicate that the NTNU MSS model has good consistency with these models (the SD of the differences are 8.9 and 6.6 cm, respectively). It should be mentioned that compared with the NTNU, the KMS and CLS models have been determined employing different altimeter data which were referred to different time periods. Averaging period for the CLS04 was 1993-2001, and for the KMS04 was 1985-2003. In the determination of the KMS04, Geosat and ERS-1 GM (Geodetic Mission) data have been used, while for the CLS04 only ERS-1 GM was applied (for the NTNU none of them were used). More importantly, both the KMS and CLS were benefiting from the high accurate and long term data series of T/P and T/P-tandem (for the KMS about 10 years and for the CLS about 8 years). On the other hand, the NTNU MSS is one of the first MSS models that have utilized relatively long term of the ENVISAT data (about 4.5 years), which have not been used for the KMS and CLS. Hence, compared with the KMS and CLS, the NTNU model includes more SSH data over the high latitudes. As can be verified in Fig. 5, the differences between the NTNU and KMS are quite significant over the sea ice (especially in the northwest of the area along the Greenland coast). Also referring to the quality error estimations of the KMS04 and CLS04 (Ghazavi, 2008), one can testify that the NTNU model has shown relatively smaller error values, better coverage and quality over the sea ice (see Fig. 4). For the CLS a part of the sea ice area is not included in the model (i.e. $\phi<80^\circ$N, $\lambda<15^\circ$E). Regarding the applied correction for the above-mentioned MSS models, the most important differences are that the NAO.99b tide model (which is a global short-period ocean tide model) has been used for the NTNU MSS. This model is developed by assimilating nearly 5 years of the T/P altimeter data (cycles 10-198) into Schwiderski hydro dynamical model. On the other hand, the KMS04 was corrected for tide applying a modified version of the GOT00.2 model and for the CLS04, the GOT99.2 tide model was used (Hernandez et al., 2004 and Andersen et al., 2006). For many oceanographic applications it is desirable to remove the ocean static response to the atmosphere. Regarding this matter, another major difference in the applied corrections is the model that is used for the IB effect (Inverse Barometric). The KMS04 MSS has been corrected to account for this effect based on a constant global mean pressure of 1013 mbar, and for the CLS an ocean mean average pressure of about 1011 mbar was used (this generates approximately 2 cm bias on the mean profiles, which consequently appears as a constant height bias between them). For the NTNU, IB is presented

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

by a model that the mean pressure (calculated using the local mean sea level pressure) is adjusted for the temporal variations in the global mean ECMWF (European Centre for Medium-Range Weather Forecasts), as spatial average of the surface pressure over the global ocean. Applying this method (spatial averaging instead of a constant value) can lead to significant improvement for the IB correction.

The large current in the southwest corner of the region (Fig. 7) corresponds to the North Atlantic current within the sub polar gyre. This current and its small branches are important since they form the route by which relatively warm water (heat transport) travels northward into the Nordic Seas. The cold return flow in the east Greenland current (northwest of the region) is also well presented in the NTNU SMDT (see Fig. 6), although the quality estimates are relatively poor because of the sea ice.

Applying the OCTAS04 geoid and the OCCAM OMDT models, SD of the residuals for the NTNU and KMS04 MSS models are 13.1 and 13.3 cm (see Table 4), respectively. Also it can be verified that, the OCCAM has provided relatively better results than the MICOM (see Table 4). Comparing Figs. 8 and 9, the KMS04 residuals are slightly better southwest of Iceland, which benefiting from about 10 years of the precise T/P mean tracks should be the main reason. The differences can also be subscribed to the averaging of inter-annual sea level variations referred to the different time periods and also applying different tide and IB correction models. On the other hand, in the north and northwest part, over the sea ice, the NTNU MSS represents quite better results. This can be mainly due to utilization of the ENVISAT data, and also retrieving the SSH data with relatively good quality over the sea ice by scrupulous data editing. Numerical results of the residual analysis (see Table 4) showed that, applying the NTNU MSS (Fig. 3), residuals differ from a zero value by less than 3σ (i.e., $\approx \pm$40-45 cm) almost everywhere over the study area (see Fig. 8). This also gives some indication of the locations, which still bare some improvement to make the fields (MSS, OMDT and geoid) more consistent, i.e. in the northwest of the area over the sea ice.

Regarding the geostrophic velocity computations, it can be mentioned that the maximum values of the geostrophic velocity derived from the OCCAM OMDT, NTNU and KMS04 SMDTs are 18.2, 23.3, and 30.3 cm/s, respectively (see Fig. 11). Significant differences between the SMDT models and the OCCAM OMDT occur along the northeast coast of Greenland and mostly over the sea ice part. It can be verified that compared with the KMS04, the NTNU provides better results (especially over the sea ice). The maximum, mean and SD of the differences between the geostrophic velocities extracted from the NTNU SMDT and the OCCAM OMDT are 16.8, 4.97 and 2.94cm/s. Whereas, these values comparing the OCCAM with KMS SMDT are 23.1, 5.25, and 3.48 cm/s. Applying the OCTAS04 and ArcGP (ϕ>64°) geoid models, maximum differences between the NTNU and KMS04 are 13.9 and 22.6 cm/s, respectively, which are significantly large values (see Fig. 10). Note that the calculated geostrophic velocity values are dependent on the data smoothing process, i.e. using proper wavelength to filter out noises and provide the average mean geostrophic currents. Finally, it should be mentioned that the SMDTs cannot derive narrow boundary currents tightly attached to the continental boundaries (e.g. east coast of Greenland), because such boundary currents close to coasts are not well resolved with the altimeter data smoothed with a space correlation scale of about 150 km. Aside from this resolution problem, altimeter data over the shallow shelf and coastal regions are subject to greater tidal errors than the open ocean regions, therefore the SMDTs and thus their differences are much noisier over the sea ice. Disregarding the sea ice part, the differences reduce significantly (see Figs. 10 and 11).

Acknowledgments

Special thanks are due to C.K. Shum and Y. Yi (the Ohio State University) for providing satellite altimetry data and their valuable comments. O.B. Andersen and R. Forsberg (National Space Institute, Technical University of Denmark), are thanked for providing some models and GRAVSOFT software. D. Solheim and O.C.D. Omang (Statens kartverk, Norway) for providing the geoid models are acknowledged. The authors also wish to appreciate two anonymous reviewers for their comments and suggestions, which resulted in improved clarity of this contribution.

References

Andersen O.B., Vest A.L., Knudsen P. (2006): The KMS04 Multi-Mission Mean Sea Surface, Proceedings of the workshop: "GOCINA: Improving modeling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry" (13-15 April 2005, Luxembourg, Kirchberg), Cahiers du Centre Européen de Géodynamique et de Séismologie (ECGS) 2006, Vol. 25.

Chambers D.P., Tapley B.D., Stewart R.H. (1998): Reduction of geoid gradient error in ocean variability from satellite altimetry, Marine Geodesy, 1998, Vol. 21, 1: 25-39.

Chelton D.B., Ries J.C., Haines B.J., Fu L.L., Callahan P.S. (2001): Satellite Altimetry and Earth Sciences, Chapter one of a Handbook of Techniques and Applications, edited by Fu L. L. and Cazenave A., International Geophysics Series, Vol. 69, Academic Press, NY, USA.

Forsberg R., Skourup H. (2005): Arctic Ocean gravity, geoid and sea-ice freeboard heights from IceSat and GRACE, Geophysical Research Letters, 2005, Vol. 32, L21502.

Fox A.D., Haines K. (2003): Interpolation of Water Mass Transformations Diagnosed from Data Assimilation, Journal of Physical Oceanography, 2003, Vol. 33: 485-498.

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM

Ghazavi K. (2008): Satellite Altimetry derived Mean Sea Surface and its error analysis over OCTAS study area, PhD thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Hernandez F., Schaeffer P., Andersen O.B., Dorandeu J. (2004): Geoid Recent improvements in altimetry: how MSS and MDT can benefit from it in combination with GOCE geoid, 2004, Proceedings of the second International GOCE User Workshop (8-10 March 2004, Frascati, Italy), ESA SP-569, June 2004.

Hwang C., Hsu H.Y., Jang R.J. (2002): Global mean sea surface and marine gravity anomaly from multi-satellite altimetry: applications of deflection-geoid and inverse Vening Meinesz formulae, Journal of Geodesy, 2002, 76: 407-418.

Kruizinga G.L.H. (1997): Validations and applications of satellite radar altimetry, PhD thesis, University of Texas at Austin, USA.

Lohmann K., H. Drange, M. Bentsen (2009): A possible mechanism for the strong weakening of the North Atlantic sub polar gyre in the mid-1990s, Geophysical Research Letter, 2009, Vol. 36, L15602.

Omang O.C.D., Solheim D., Hunegnaw A., Lysaker D.I., Ghazavi K., Nahavandchi H. (2006): Ocean Circulation and Transport between the North Atlantic and Arctic Sea with a Focus on the Importance of a High Accuracy Geoid Model, 1st international Symposium of the international gravity field service, Gravity field of the Earth, 2006, Istanbul, Turkey.

Rapp R.H., Yi Y., Wang Y.M. (1994): Mean sea surface and geoid gradient comparisons with TOPEX altimeter data, Journal of Geophysical Research, 1994, Vol. 99, C12: 24,657-668.

Rapp R.H., Yi Y. (1997): Role of ocean variability and dynamic ocean topography in the recovery of the mean sea surface and gravity anomalies from satellite altimeter data, Journal of Geodesy, Vol. 71: 617-629.

Sandwell D.T., Zhang B. (1989): Global mesoscale variability from Geosat Exact Repeat Mission: Correlation with ocean depth, Journal of Geophysical Research, Vol. 94: 17,971-984.

Shum C.K., Braun A. (2004): Satellite Altimetry and Gravimetry, Lecture Series, Department of Civil and Transport Engineering, Geomatics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway, June 21-25, 2004.

Solheim D., Omang O.C.D., Drange H., Siegismund F., Nahavandchi H., Ghazavi K., et al. (2007): The OCTAS project, the Geoid, the Mean Sea Surface and the Mean Dynamic Topography, 2006, Proceedings of the third International GOCE User Workshop (6-8 November 2006, Frascati, Italy), ESA SP-627, January 2007, 27-34.

Stewart R.H. (2006): Introduction to Physical Oceanography, Department of Oceanography, Texas A&M University, USA.

Wang Y.M. (2001): GSFC00 mean sea surface, gravity anomaly, and vertical gravity gradient from satellite altimeter data, Journal of Geophysical Research, Vol. 106, C12: 31,167-174.

Yi Y. (2010): The Ohio State University Stackfiles for Satellite Radar Altimeter data, Report No. 495, The Ohio State University, USA.

Brought to you by | Universitetsbiblioteket I Trondheim NTNU Universitetsbiblioteket
Authenticated
Download Date | 8/26/19 2:31 PM