Updated OCTAS geoid in the northern North Atlantic - OCTAS07

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Abstract. A new gravimetric geoid (OCTAS07v2) is generated using Stokes' formula with gravity data as input. As local gravity data, a combination of land gravity data, new and old airborne gravity data, and adjusted marine gravity data has been used. All marine gravity data has been error screened and quality assured by removing dubious data and adjusting the data when necessary. Voids in the gravity data distribution were patched with gravity data from satellite altimetry.

The OCTAS07v2 geoid was estimated using the remove-compute-restore technique. The long-wavelength signal of the local gravity data was reduced using a Wong-Gore modified Stokes' function. The long-wavelength part was represented by a global gravity field model based on GRACE data.

The OCTAS07v2 geoid model was combined with the OCTAS07_MSS model to create a synthetic Mean Dynamic Topography (MDT) model. In comparison with the OCCAM MDT, our new synthetic MDT model gave a std. dev. of the residuals of 11 cm. A comparison to the main northern North Atlantic currents show many similar features.

Keywords. OCTAS, Geoid, MDT, MSSH, Adjusted Marine Gravity Data, New Airborne Gravity Data

1 Introduction

The Norwegian Ocean Circulation and Transport between the north Atlantic and the arctic Sea (OCTAS) Project, running from 2003 to 2008, focuses on the ocean circulation in the Fram Strait and adjacent sea with the main objective to improve the sea surface topography determination and to study the impact on ocean modelling, see Fig. 1. A central quantity for studying and understanding the ocean circulation is the MDT, which is the difference between the mean sea surface heights (MSSH) and the geoid. The MDT provides the absolute reference surface for the ocean circulation and is, in particular, expected to improve the determination of the mean ocean circulation. This, in turn, will advance the understanding of the role of the ocean mass and heat transport in climate change.

Up to the expected launch of GOCE, the gravimetric geoid is not known with sufficient accuracy to allow full use of the massive sea surface height information, which several satellite altimetry missions have regularly provided since the early nineties, in global ocean circulation analysis. However, in a few marine regions in the world, sufficient in-situ information about the Earth's gravity field exists to compute a more accurate geoid. The region covering the Norwegian and Greenland Sea between Greenland, Iceland, Norway and the UK, including the Fram Strait is one of these regions. One goal of the OCTAS project is therefore to determine an accurate geoid in the Fram Strait and the adjacent seas.

New airborne gravity measurements have been carried out. The marine gravity data have been adjusted and error screened based on the new airborne gravity data. Both, new airborne gravity data and adjusted marine gravity data will improve the quality of the gravimetric geoid. The new geoid is used together with an accurate MSSH to determine the MDT.

2 Airborne Gravity Survey

In a joint cooperation between Geoid and Ocean Circulation in the North Atlantic (GOCINA) and Ocean Circulation and Transport Between North Atlantic and the Arctic Sea (OCTAS), new airborne gravity data was collected during the summer 2003 in the Northern North Atlantic. In Fig. 2 the OCTAS part of the airborne measurement campaign is visible. For information about the airborne gravity data collected by GOCINA see e.g. Forsberg *et al.* (2004).

The airborne survey was carried out with an aircraft equipped with GPS receivers, laser altimetry, Inertial Navigation Systems (INS), and a modern LaCoste & Romberg marine gravimeter. The measure-

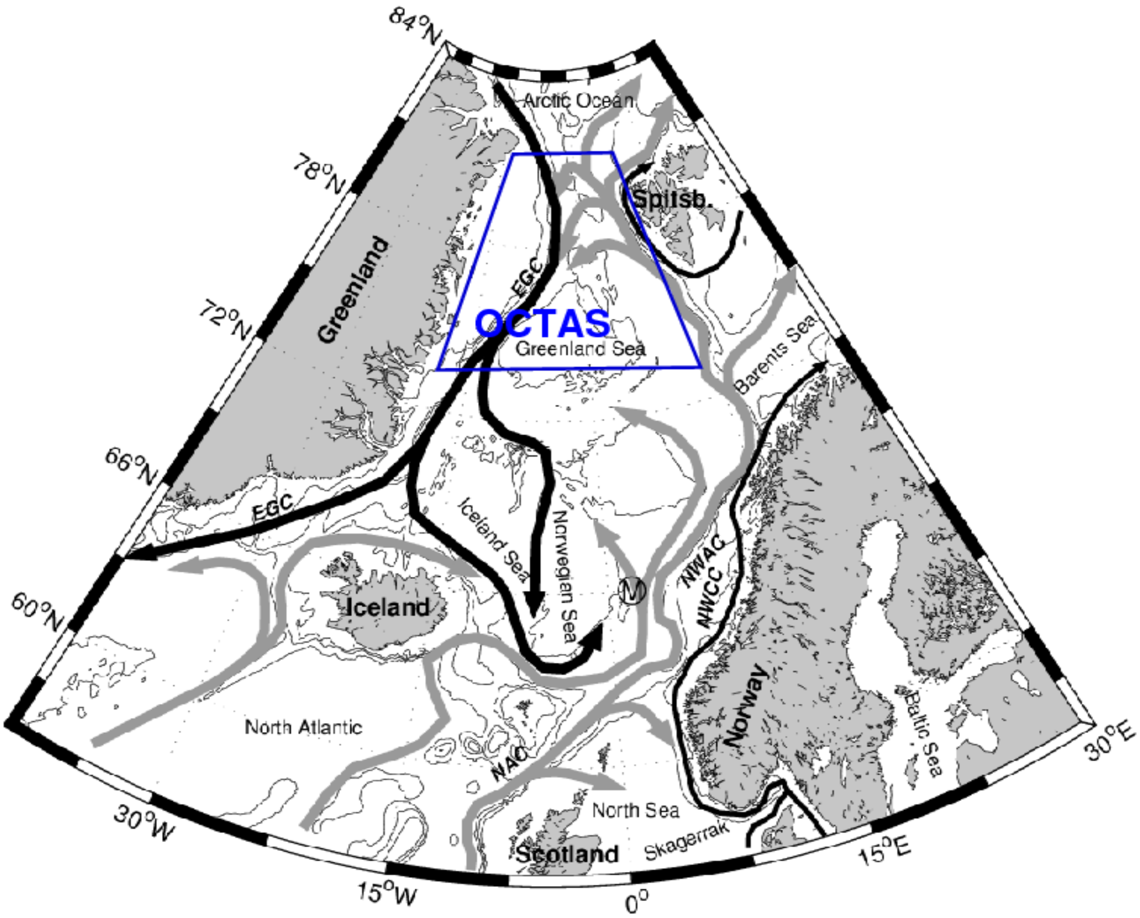

Fig. 1. OCTAS study area

ments were done around Greenland, Svalbard, Jan Mayen and along the Norwegian coast. This additional survey (including the GOCINA measurements from Greenland over Iceland to Norway) was particularly important since it ties in as many of the different marine surveys as possible, allowing a data check and improvement by crossover adjustment as well as filling of some major data voids.

A total of 9222 measurements divided into 35 profiles of airborne gravity tracks have been processed. An internal cross-over computation (airborne gravity data only) shows a RMS of 1.6 mGal, while the comparison with the original marine data gives a RMS of 4.51 mGal, see Table 1.

3 Marine Gravity Data

The main marine gravity data set used in this study has been acquired from BGI, NGDC, Norwegian Mapping Agency (NMA), and from international and national oil companies. The data set was recently improved with a major airborne gravity survey campaign performed in 2003 under the scope of the GOCINA and OCTAS project, see Sect. 2.

Marine gravity measurements are, in principle, very precise; military tests with the BGM-3 sea gravimeter, now commercially available, achieved RMS cross-over errors of only ± 0.38 mGal (Bell and Watts, 1989). For a variety of reasons, the accuracy of the available marine gravity anomalies does not match this precision. Some relate to measuring gravity on an im-

	N	Mean	Min	Max	RMS
Internal	15	0.71	-2.87	3.79	1.58
Marine	548	0.44	-27.44	20.54	4.51

Table 1. Statistics of the cross-over computations for the airborne data (internal: airborne data only; marine: cross-overs with marine data). Values in mGal

perfectly stabilised platform, while others are due to systematic instrument errors, loosing reference to an absolute gravity datum and uncertainties in the navigation system in terms of course, speed, and position errors, affecting the Eötvös correction. Wessel and Watts (1988) review these problems in depth.

Our strategy involves pre-processing the raw gravity data followed by a network adjustment. Pre-processing aims at reducing the dynamical errors associated with courses changes, smoothing out high-frequency noise, and removing spikes and blunders. Network adjustment aims at removing the systematic effects of datum offsets, different gravity reference systems and drifts in the gravity meter zero.

The basic component of our pre-processing algorithm is the *line-segment*. A line-segment is a component of a survey where the ship's course is adequately straight. Point-to-point vectors are compared with chosen criteria for breaking surveys into line-segments: a break can be triggered by a large change in course azimuth or an excessive gap between points. For each line-segment, we represent the a long-track free-air anomaly as well as the eastings and northings, defining the ship's position, by a continuous function. Chebyshev polynomials represent our best estimate for the true shape of the gravity anomaly profile, smoothing out point-to-point noise. Statistics derived from the residuals between the fitted curve and the point data are used to estimate the stationary random component of the data errors. The subsequent network adjustment is to suppress the remaining systematic errors.

The network adjustment model fits an independent datum shift parameter to each survey or survey leg. For any survey with a sufficient number of crossing points, a drift is included as an additional parameter. The adjustment estimates these model parameters by minimising the cross-over errors in the least squares sense, weighting the observed free air anomaly at the crossing according to the standard deviation of the polynomial curve fit for that line-segment.

For the approximately 45000 cross-over points in the northern Atlantic Ocean, the network adjustment reduces the standard deviation of the cross-over errors from 4.13 mGal to 1.64 mGal. Similarly, the difference between KMS02 altimetry anomalies and shipborne and airborne data improved, with the adjustment reducing the standard deviation of the differences from 8.15 to 6.07 mGal. The differences between marine free-air anomalies before and after adjustment are shown in Fig. 3. The figure shows that the network adjustment has identified datum shifts for several surveys, probably resulting from bad harbour ties.

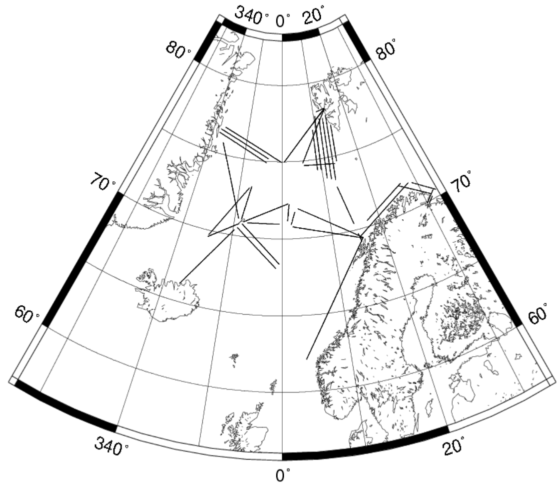

Fig. 2. New airborne gravity data measured by OCTAS during 2003

4 Global Geopotential Model

In the computation of the updated geoid (OCTAS07v2) we have used the global geopotential model (GGM) EIGEN-GL04S1 from GFZ. It is a satellite-only gravity field model based on GRACE data from Februar 2003 - July 2005, excluding Jan 2004, and LAGEOS data from Februar 2003 - Februar 2005. The tide system is tide-free. The model is complete to degree and order 150. For more information see GRACE science results at http://www.gfz-potsdam.de/pb1/op/grace/results/grav/g006_eigen-gl04s1.html.

5 Geoid determination

To obtain a gravity coverage without large gaps, a combination of several different data sets has been used. Covering the Nordic and Baltic countries, and parts of the European continent, gravity data were obtained from the Nordic Geodetic Commission (NKG) gravity data base, while over Greenland, Iceland and Svalbard data were selected from the Arctic Gravity Project (ArcGP). The marine areas were covered by a combination of adjusted marine gravity data (see Sect. 3), new and old airborne measurements (see Sect. 2), and gravity data from satellite altimetry [KMS-02, (Andersen and Knudsen, 1998)]. Voids in the marine and airborne gravity data were patched with KMS02 data.

The combined gravity data set was build up of complete Bouguer anomalies on land and free-air ano-

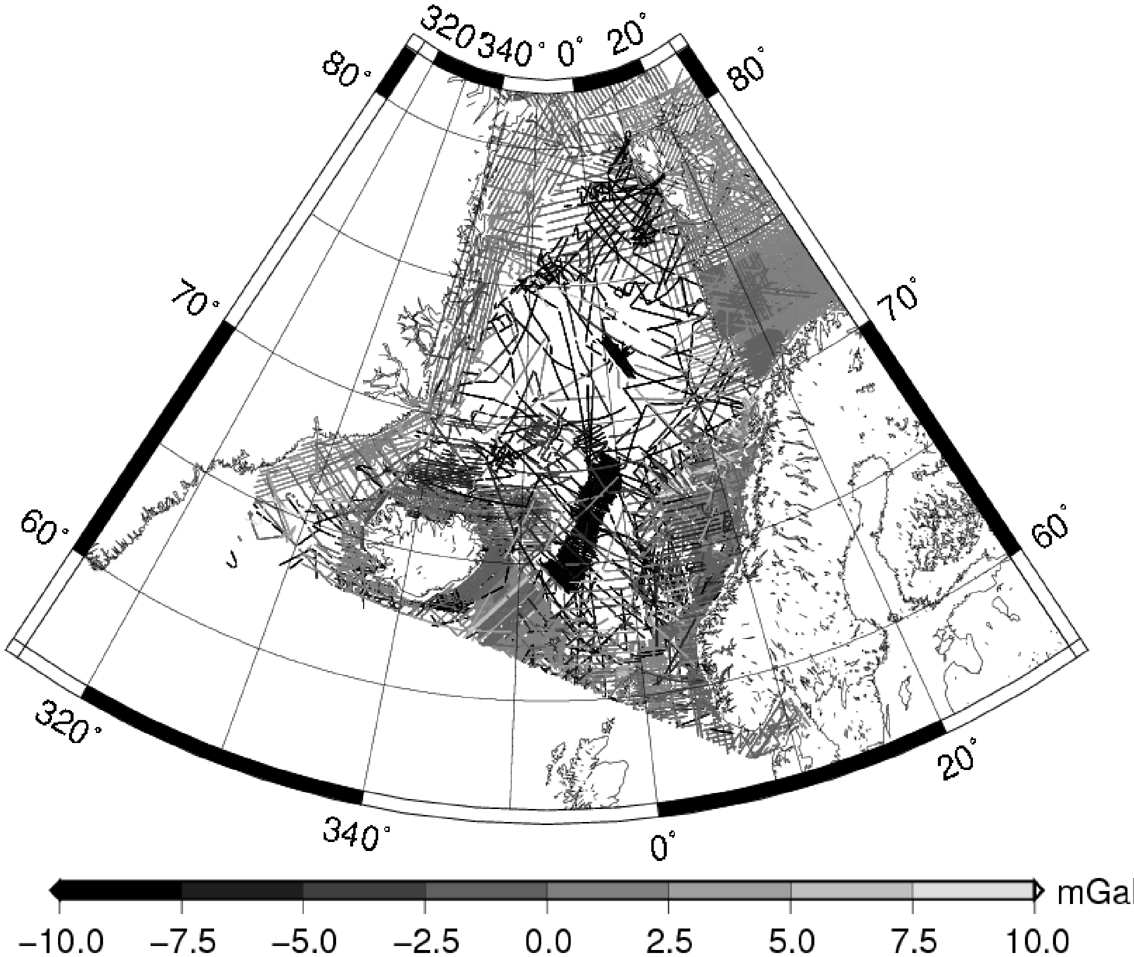

Fig. 3. Illustrated is the change in marine gravity data due to error screening and adjustment of the data

malies at sea. We are using the remove-restore technique in combination with the residual terrain model (RTM)/Helmert method (Forsberg, 1984; Omang and Forsberg, 2002).

The heights are averaged into a smooth reference surface h_{ref} with a resolution of approx. 50 km. A Bouguer plate approximation is used to obtain the reduced anomalies by

$$\Delta g_{\mathrm{red}} = \Delta g + 2\pi G \rho h_{\mathrm{ref}} - \Delta g_{\mathrm{ggm}}, \qquad (1)$$

where Δg_{ggm} is the global geopotential model. As GGM we used the EIGEN-GL04S1 as described in Sect. 4. The reduced gravity data Δg_{red} is gridded and Faye anomalies, Δg_{faye}, are obtained after restoring the RTM terrain effect $2\pi G \rho (h - h_{\mathrm{ref}})$. The residual quasigeoid is estimated using the multi-band spherical 2D-FFT (Forsberg and Sideris, 1993) approach

$$\zeta_{\mathrm{res}} = F^{-1}[F(\Delta g_{\mathrm{faye}}) F(S^{\tau}(\psi))], \qquad (2)$$

where F and F^{-1} are the Fourier and the inverse Fourier transform, respectively.

$S^{\tau}(\psi)$ is the Wong-Gore modified Stokes' function (Wong and Gore, 1969)

$$S^{\tau}(\psi) = \sum_{n=\tau}^{\infty} \frac{2n+1}{n-1} P_n(\cos\psi), \qquad (3)$$

where τ is the truncation degree, and P_n is Legendre polynomials. As Eq. (3) indicates, the Wong-Gore modification gives a kernel function, summing up only terms from degree τ to infinity. The long wavelength part of the signal is thereby not taken into account, and the changing of τ compares to some degree to the selection of different capsizes.

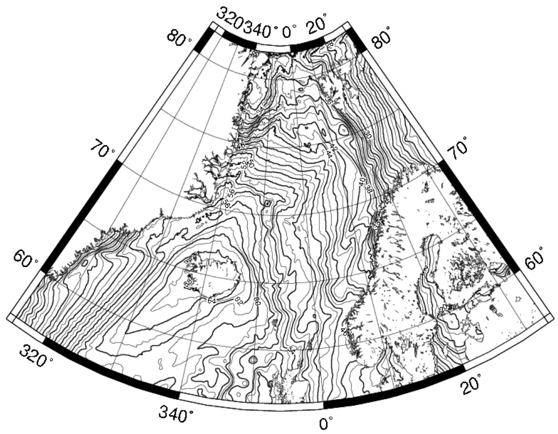

Fig. 4. The OCTAS07_MSS model

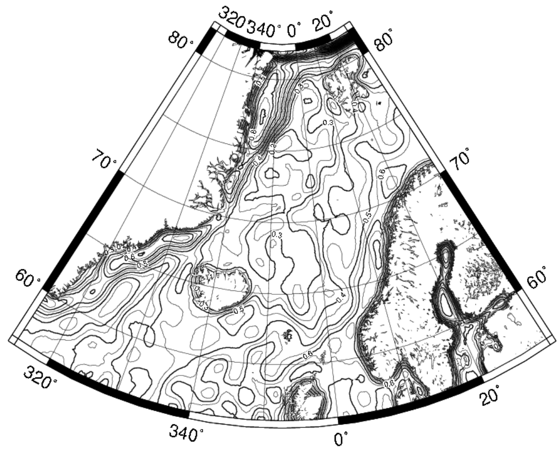

Fig. 5. A synthetic MDT derived from OCTAS07_MSS and OCTAS07v2 geoid model. MDT is low-pass filtered.

Restoring the GGM gives the quasigeoid,

$$\zeta = \zeta_{\mathrm{res}} + \zeta_{\mathrm{ggm}} \tag{4}$$

Over sea, or where the height equals zero, the quasigeoid ζ equals the geoid, N. The new geoid model is referred to as OCTAS07v2.

In Fig. 7 the effect of using adjusted marine gravity data instead of unadjusted data in the geoid computation is illustrated, compare to Fig. 3. As shown there are differences up to more than 50 cm, and several surveys give large changes in the geoid, e.g. a survey along latitude 75° N. Also changes do occur due to the fact that several points have been deleted.

6 OCTAS07 MSSH

Multiple high-latitude observing satellite radar altimetry data, including ENVISAT (cycles 10-52), ERS-2 (cycles 1-85), ERS-1 ERM (phases C and G) and GFO (cycles 37-168) data, are used to determine the MSS model, called OCTAS07_MSS. These data have been cross-validated using the multiple altimetry data base (the so-called stack files), generated at the Ohio State University. In this study, several experimental models have been derived and their consistency and accuracy have been evaluated, respectively. The OCTAS07_MSS model is developed with the mean tracks of TOPEX/POSEIDON as a reference. In this model, the annual, semi-annual as well as sea surface trends were removed. The resolution of the OCTAS07_MSS model is 3 minutes in latitude and 6 minutes in longitudes. The OCTAS04v1 geoid model is used later on for the comparisons and MDT computations and it is not used directly in the MSS computations. Note that OCTAS04v1 is a gravimetric geoid computed in the region in 2004. The long-wavelength portion of this geoid model is determined from the global geopotential model GGM01C up to degree and order 200. The OCTAS04v1 is calculated using the remove-restore technique and the Wong-Gore modified Stokes's function with truncation degree 80. The OCTAS07_MSS model ranges between 15 and 70 m in the study region. The internal consistency or the quality estimate for the OCTAS07_MSS model ranges from 2 to 5 cm over the study region. This quality estimate is output from the interpolation of the data using least-squares collocation. The OCTAS07_MSS model was also further validated using available global and regional models (KMS01, KMS03, KMS04, CLS01, CLS04, GSFC00, OCTAS-06_MSS and OSU95).

The mean and standard deviation of differences between the OCTAS07_MSS and KMS04 MSS models are 0.5 cm and 10.4 cm, respectively. These values are 0.8 cm and 7.2 cm, respectively, when the OCTAS07_MSS and the OCTAS06_MSS models are compared. The model OCTAS07_MSS is illustrated in Figure 4.

7 Synthetic MDT

A synthetic MDT model was computed from a combination of the OCTAS07v2 geoid, the OCTAS07_MSS and the OCCAM MDT (Webb *et al.*, 1998), mathematically given as,

$$MDT = OCTAS07\_MSS - OCTAS07v2. \tag{5}$$

The synthetic MDT was smoothed, to remove short scale features, using a Gaussian shaped filter with a resolution of 1 degree, i.e. a low-pass filter.

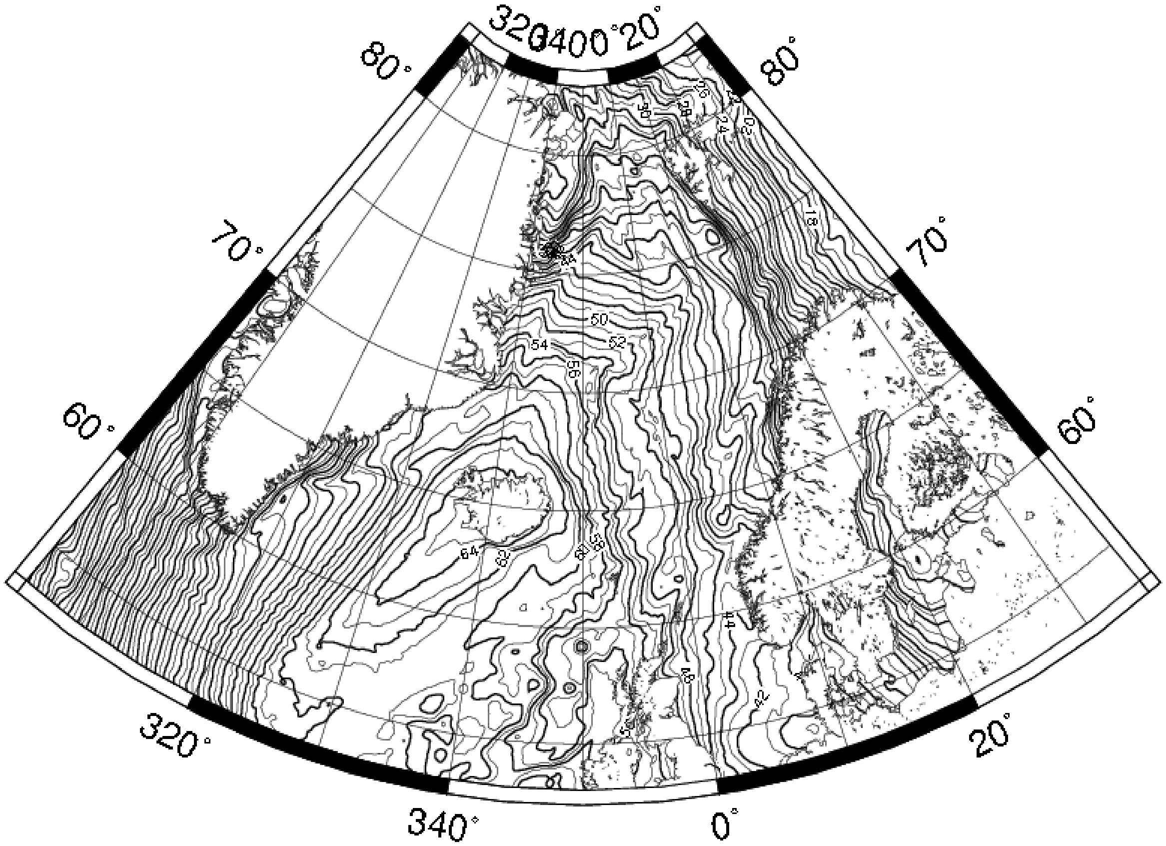

Fig. 6. The OCTAS07v2 geoid model

Table 2. Standard deviation of the residuals (ϵ = OCTAS07_MSS - Geoid - OCCAM MDT) are listed. All values in meter

Geoid	OCTAS07_MSS$_{sea}$	OCTAS07_MSS$_{ice}$
OCTAS03	0.297	0.129
OCTAS04v1	0.299	0.114
OCTAS04v2	0.298	0.122
OCTAS05	0.295	0.113
OCTAS06	0.292	0.117
OCTAS07v1	0.281	0.112
OCTAS07v2	0.281	0.111

In Fig. 5 our synthetic MDT, derived from OCTAS07v2 geoid and the OCTAS07_MSS model, is illustrated.

The synthetic MDT is labeled *synthetic* since it is not based on any oceanographic data.

8 Discussion

A new geoid model, OCTAS07v2, was calculated using adjusted marine gravity data, airborne data, ArcGP gravity data and EIGEN-GL04S1 as GGM, see Fig. 6. In Table 2 the new geoid model and all older OCTAS geoids are used in the computation of the residuals

$$\epsilon = MSSH - Geoid - OCCAMMDT, \quad (6)$$

where MSSH is OCTAS07_MSS. The subscript *sea* and *ice* indicates that the land areas are removed in the first case, while in the latter also areas north of Svalbard and along the east Greenland coast (where sea-ice is located) has been removed from the OCTAS07_MSS model.

As illustrated in Table 2 the residuals of Eq. (6) has decreased since the first OCTAS geoid model, to a level of approximately 28 cm or 11 cm if all sea area is included or if areas north of Svalbard and along the northeast coast of Greenland is excluded, respectively. In theory, however, the residuals, ϵ, of Eq. (6) should equal zero.

A synthetic MDT was generated using OCTAS07v2 geoid and OCTAS07_MSS model. From the synthetic MDT an velocity field was generated by taking the derivative with respect to ψ and λ. The estimated

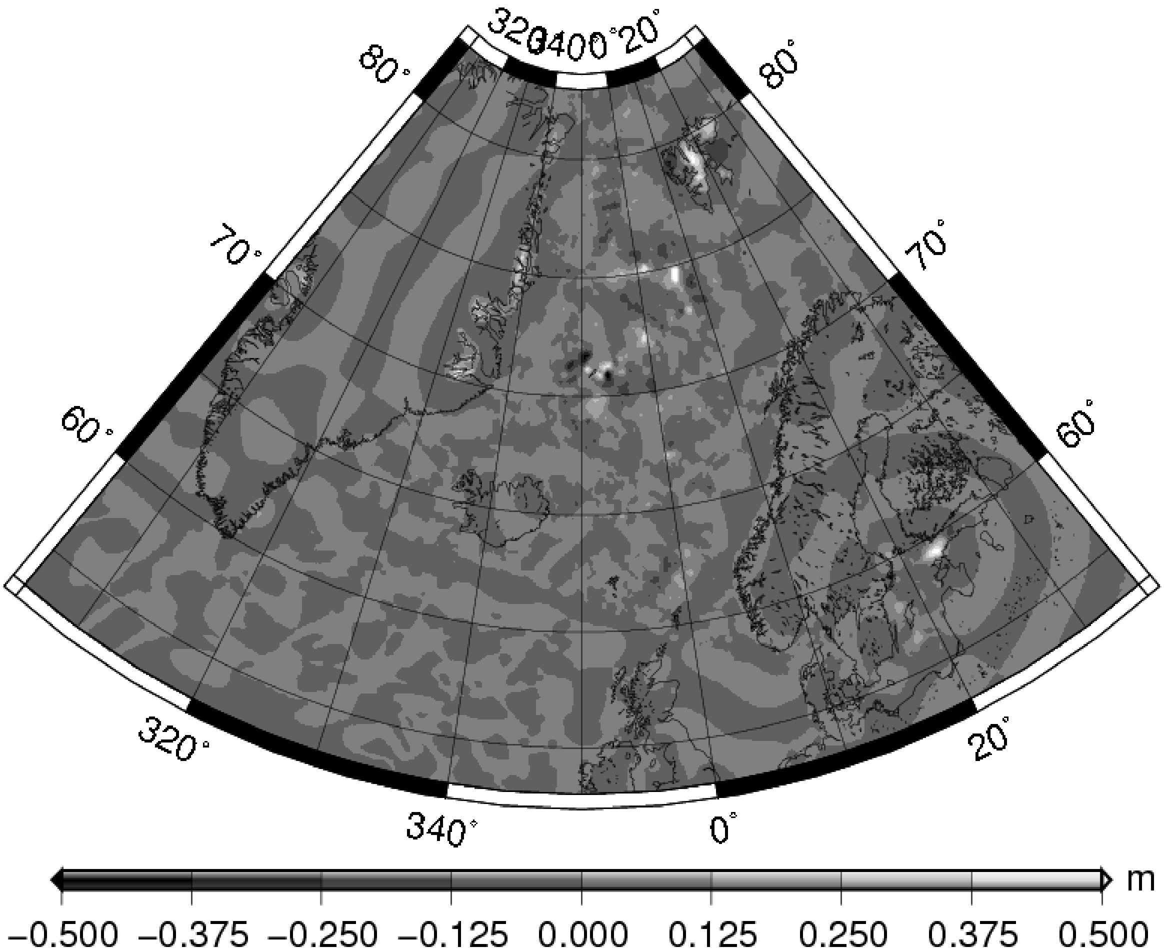

Fig. 7. Difference between geoid with adjusted marine data and one without

velocity field of the synthetic MDT, illustrated in Fig. 8, show similar oceanographic features of the North Atlantic current as Fig. 1. Especially, along the coast of Norway, the splitting west of Trondheim (65°N, 5°E) and west of Lofoten (70°N, 10°E), and the current north in direction of Svalbard. The current from Artic basin and southwards along the Greenland coast is also clearly visible. Main problem areas are especially north of Svalbard and close to the coast (e.g. northeast cost of Greenland). This is due to sea ice in the north and MSSH models having problems determining the correct sea height along the coastlines.

9 Conclusions

The marine gravity data in the Northern North Atlantic has been error screened and adjusted using new airborne gravity data. The standard deviation of the cross-over errors for the marine gravity data was reduced from 4.1 mGal to 1.6 mGal.

A new geoid was computed based on adjusted marine gravity data and EIGEN-GL04S1. The new geoid model OCTAS07v2 show a small improvement compared to the older versions of the OCTAS geoids.

A new synthetic MDT was computed by combining OCTAS07v2 geoid and OCTAS07_MSS model. The velocity field of the synthetic MDT give a good representation of the major oceanographic features/-currents in the Northern North Atlantic.

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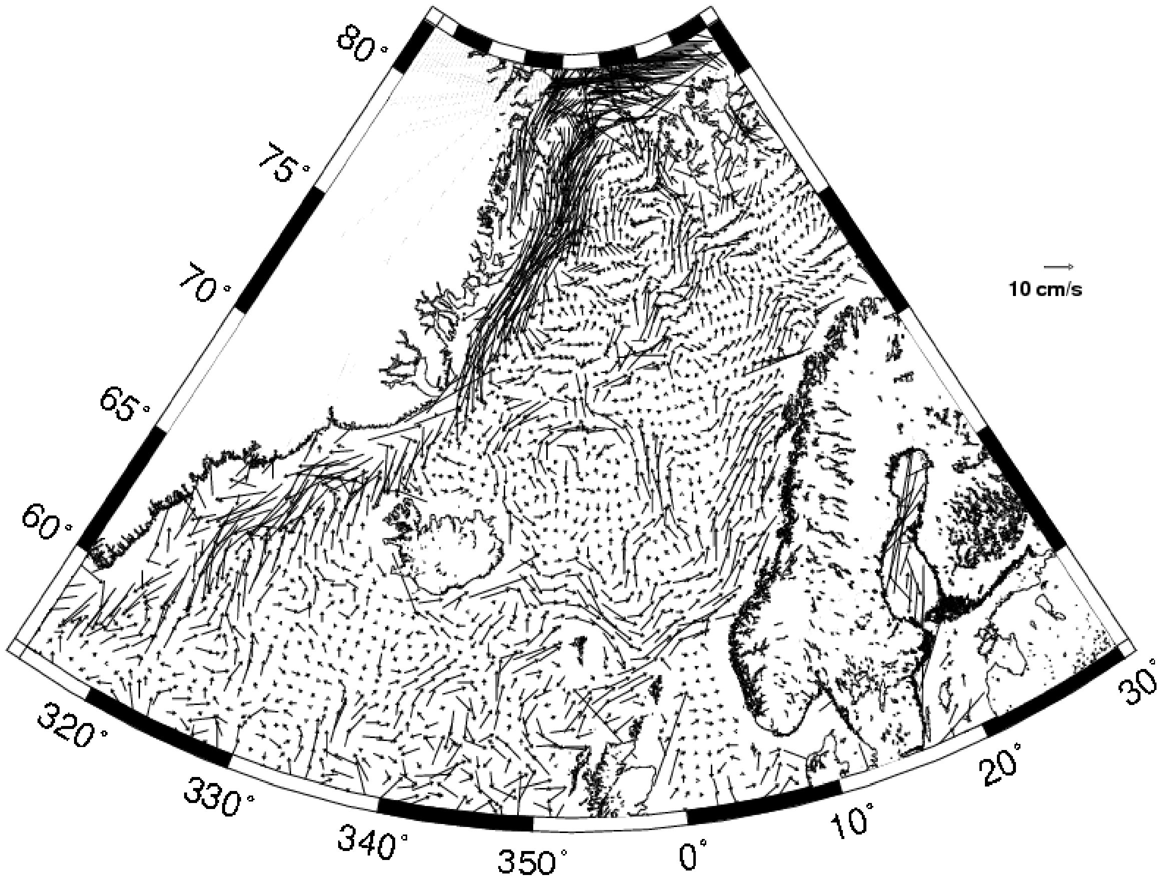

Fig. 8. An MDT derived from OCTAS07_MSS and a geoid model based on adjusted marine gravity data. MDT is low-pass filtered. Velocity is added

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