Consistent Combination of Gravity Field, Altimetry and Hydrographic Data

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Abstract The ocean's mean dynamic topography as the difference between the mean sea surface and the geoid reflects many characteristics of the general ocean circulation. Consequently, it provides valuable information for evaluating or tuning ocean circulation models. However, the determination of the mean dynamic topography from satellite based gravity field and altimetric observations as well as in-situ data is not straightforward. We developed a rigorous combination method where both instrumental errors and omission errors are accounted for, including the determination of optimal relative weights between the observation groups. This method allows the direct determination of the normal equations of the mean dynamic topography on arbitrary grids. In this paper we focus on the preprocessing steps of the in-situ data. We show results for the North Atlantic Ocean based on a combined GRACE/GOCE gravity field, altimetric sea surface height observations from Jason-1 and Envisat and in-situ observations of salinity, temperature and pressure from Argo floats.

Keywords Mean dynamic topography · GRACE · GOCE · altimetry · consistent combination

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1 Introduction

The determination of the mean dynamic topography from satellite-based gravity field and altimetry data is not straightforward, as the data types differ in their representation and spatial resolution. While the accepted gravity field models are provided as a band-limited series of spherical harmonics, the altimetric observations are given as point values over the ocean. Usually, dedicated filter approaches are introduced to overcome this difficulty (see e.g. Becker et al., 2012; Becker, 2012). In our recently developed approach the usage of a particular filter is avoided. The geoid and the mean dynamic topography are simultaneously assessed. Special attention is paid to the complete modeling and the consideration of the complete variance/covariance information of the observation groups within the model to provide the mean dynamic topography along with its consistent (inverse) covariance matrix or the normal equations on arbitrary grids respectively. Within inverse ocean modeling a cost function is minimized, which contains different contributions from quadratic model-data differences (e.g. temperature, salinity, mean dynamic topography) weighted by the particular inverse error covariance matrix. In case of the mean dynamic topography the derived normal equation matrix represents the appropriate weight matrix.

Complementary, hydrographic data can also be used to obtain information about the mean dynamic topography. The consistent integration of these data sets into the model requires a special data handling and the use of an additional bias parameter. The focus of this paper is on the preprocessing of hydrographic data sets – these are profile measurements of salinity, temperature and pressure of the Argo floats – and its rigorous combination with the satellite data. The different observation groups are combined in terms of normal equations. In order to provide an optimal estimation of the mean dynamic topography we implemented a rigorous variance component estimation to determine relative weights between the diverse observation groups. Additionally, we consider the impact of the different observation groups on the parameters of the mean dynamic topography. The focus of this study is on the North Atlantic Ocean.

The paper is organized as follows. The observations used in this study are briefly introduced in Section 2. The processing steps of the Argo float measurements are described in Section 3. In Section 4 we summarize the combination method of the different observation groups. Subsequently the obtained results are shown in Section 5. The paper closes with the discussion and an outlook in Section 6.

2 Data types

2.1 Gravity field model

We use the static part of the GRACE gravity field model ITG-Grace2010 (Mayer-Gürr et al., 2010) which is expanded as a sum of spherical harmonics up to degree and order 180 and the GOCE gravity field model GOCE_EGM_TIMrelease3 (Pail et al., 2011) with a maximum spherical harmonic degree of 250. Both gravity field models are provided with the full covariance matrix of the potential coefficients so that the normal equations can be reconstructed.

2.2 Altimetry

To derive a profile of mean sea surface heights for the North Atlantic Ocean we consider corrected sea surface heights from Jason-1 and Envisat between October 2002 and February 2009. During the whole preprocessing steps a rigorous error propagation was implemented based on empirical covariance functions along the satellite tracks in order to determine the full covariance matrix of the resulting mean sea surface profile. We used monomission along track data sets provided by AVISO (`http://www.aviso.oceanobs.com`). Details of the processing steps of the altimetric data can be found in Becker (2012).

2.3 Argo floats

The Argo project provides profile measurements of salinity, temperature and pressure. We used observations between October 2002 and February 2009 for the North Atlantic Ocean according to the considered altimetric observation period. The data used in this study were obtained from the French data centre Coriolis (`http://www.coriolis.eu.org`). Only delayed mode measurements which passed the quality controls (Wong et al., 2010) were used. The particular processing steps for the in-situ data are described below.

3 Processing of Argo float measurements

3.1 Dynamic heights

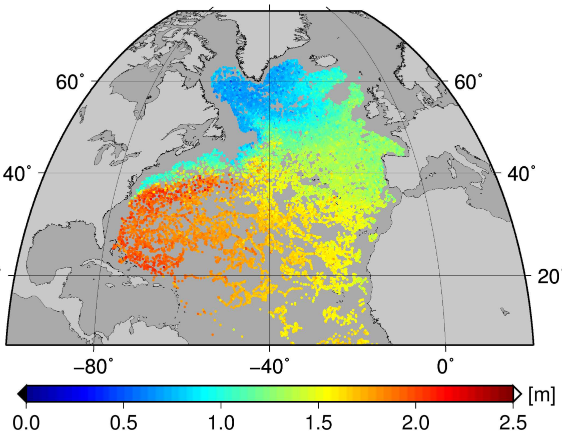
Initially, density values ρ are derived from the salinity s, temperature t and pressure p measurements for different depths (see e.g. Fofonoff and Millard, 1983). Based on these density profiles dynamic heights are calculated

$$\mathrm{DH} = \frac{1}{g} \int_{\zeta}^{P} \left(\frac{1}{\rho(s,t,p)} - \frac{1}{\rho(35,0,p)} \right) \mathrm{d}p \;, \tag{1}$$

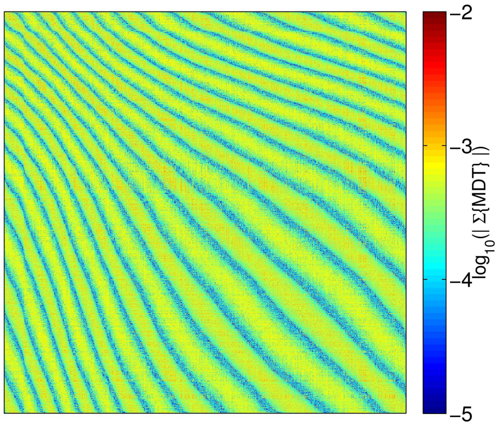
which reflect surface currents due to horizontal density variations relative to a presumed level of no motion P (see e.g. Gill, 1982). According to this, the dynamic heights represent the baroclinic part of the ocean's dynamic topography from the level of no motion up to the surface ζ. We assume a level of no motion P corresponding to a depth of 1500 m in this study. This choice turned out to be reasonable due to the amount of available data. Comparisons to dynamic heights relative to a depth of 1950 m have shown an almost constant shift and no significant change in the horizontal gradients can be expected.

The derived dynamic heights **DH** are dependent on time and space. In order to model the stochastic behavior we computed a two-dimensional empirical autocovariance function (see e.g. Sansó and Schuh, 1987) depending on the temporal distance Δt and spatial distance Δs. For this purpose we first subtract a space dependent deterministic trend from the dynamic heights **DH** and analyze the residual signal afterwards. The obtained covariances either dampen or amplify in space and can be modeled by the sum of two exponential functions with the coefficients c_1 and c_2. In the time domain the empirical covariances show an annual cycle which can be modeled by a cosine function with the coefficient a and the frequency b. The spatial and temporal dependencies are separated from each other and we use a product spatial-temporal covariance model

$$C(\Delta t, \Delta s) = a\cos(b\Delta t)\left[\frac{1}{2}e^{-c_1\Delta s} + \frac{1}{2}e^{-c_2\Delta s}\right] \tag{2}$$



(a)



(b)

Fig. 1 Quasi in-situ observed mean dynamic topography **MDT** and its corresponding covariance matrix $\boldsymbol{\Sigma}\{\mathbf{MDT}\}$.

to approximate the empirically derived covariance function. Subsequently the covariance matrix $\boldsymbol{\Sigma}\{\mathbf{DH}\}$ of the dynamic heights **DH** can be assembled.

3.2 Time variable content

As we are only interested in the time averaged dynamic topography the time variable part contained in the dynamic heights **DH** must be removed. The time variable component of the dynamic topography is represented by the sea level anomalies – the differences between the actual sea surface and the mean sea surface. In the following, we assume that the sea level anomalies also represent the time variable component of the dynamic heights **DH**. The required quantities are derived by linear interpolation of the altimetric determined sea level anomalies along the satellite tracks in time and space onto the observation times and positions of the Argo float measurements. Within this interpolation procedure we implemented a rigorous error propagation yielding the covariance matrix $\boldsymbol{\Sigma}\{\mathbf{SLA}\}$ of the required sea level anomalies **SLA**. Finally we subtract the time variable part from the dynamic heights **DH** to compute mean dynamic heights **MDH**

$$\mathbf{MDH} = \mathbf{DH} - \mathbf{SLA} \tag{3}$$

with the covariance matrix

$$\boldsymbol{\Sigma}\{\mathbf{MDH}\} = \boldsymbol{\Sigma}\{\mathbf{DH}\} + \boldsymbol{\Sigma}\{\mathbf{SLA}\} \ . \tag{4}$$

3.3 Modeling of the missing part

As already mentioned the information obtained from the hydrographic data only represents the baroclinic part of the dynamic topography from the surface down to the assumed level of no motion of 1500 m. To achieve a complete modeling and enable a consistent combination with the altimetric and gravity field data, the missing baroclinic part from the level of no motion down to the ocean bottom and the barotropic component must be considered. Denoting the missing component by $\Delta\mathbf{MDT}$ it can be written as

$$\Delta\mathbf{MDT} = \mathbf{MDT} - \mathbf{MDH} \ . \tag{5}$$

In the following the missing signal content is considered as random variable $\Delta\boldsymbol{\mathcal{MDT}}$ which is characterized by its expectation $\boldsymbol{E}\{\Delta\boldsymbol{\mathcal{MDT}}\}$ and the covariance $\boldsymbol{\Sigma}\{\Delta\boldsymbol{\mathcal{MDT}}\}$. These quantities are now determined by comparisons with external estimates of the mean dynamic topography. Here we used the CLS09 (Rio et al., 2011), DTU10 (Andersen and Knudsen, 2009) and Maximenko/Niiler (Maximenko et al., 2009) model and computed the particular differences between the three models and the derived mean dynamic heights **MDH**. Because we cannot prefer any of the models the mean values of the different deviations are analyzed to describe the expectation and covariance of the missing component. The mean value of these averaged differences is nearly zero so that the expectation $\boldsymbol{E}\{\Delta\boldsymbol{\mathcal{MDT}}\}$ is assumed to be zero and

$$\Delta\mathbf{MDT} = \mathbf{0} \ . \tag{6}$$

In order to model the covariances of the missing signal we determined the empirical autocovariance function depending on the spherical distance d. This shows a fast decrease to negative values and damped oscillations. Accordingly, the empirical autocovariance function is approximated by the following combination of finite covariance and Bessel functions

$$
\begin{aligned}
C(d) = \Bigg[& \frac{1}{3}R_1^6\pi - \frac{1}{2}R_1^4 d^2\pi + \frac{1}{3}\left(R_1^4 d + \frac{4}{3}R_1^2 d^3 - \frac{1}{12}d^5\right) \\
& \sqrt{R_1^2 - \left(\frac{d}{2}\right)^2} + \left(R_1^4 d^2 - \frac{2}{3}R_1^6\right)\arcsin\frac{d}{2R_1}\Bigg] \\
& \Bigg(2R_2^4\pi - 4R_2^4\arcsin\frac{d}{2R_2} - \left(6R_2^2 d - d^3\right)\sqrt{R_2^2 - \left(\frac{d}{2}\right)^2} \\
& + \sum_{i=1}^{4} a_i J_0(k_i d)\Bigg) \ .
\end{aligned}
\tag{7}
$$

The first term is a finite covariance function according to Sansó and Schuh (1987), where the parameter R_1 defines the half length of the support. The second term is composed of a finite covariance function according to Koch et al. (2010) with the half length of the support R_2 and a linear combination of four Bessel functions J_0 of first kind and order zero with the coefficients a_i and the frequencies k_i. This part models the fast decrease of the covariances to negative values by the finite covariance function according to Koch et al. (2010) and the oscillations by the Bessel functions. Additionally, the functions are multiplied with the finite covariance function according to Sansó and Schuh (1987) to describe the dampening of the oscillations.

The covariance matrix $\boldsymbol{\Sigma}\{\Delta\mathbf{MDT}\}$, describing the missing part, is assembled and we obtain quasi in-situ observations of the mean dynamic topography

$$
\mathbf{MDT} = \mathbf{MDH} + \Delta\mathbf{MDT} = \mathbf{MDH} + \mathbf{0} \tag{8}
$$

with the covariance matrix

$$
\boldsymbol{\Sigma}\{\mathbf{MDT}\} = \boldsymbol{\Sigma}\{\mathbf{MDH}\} + \boldsymbol{\Sigma}\{\Delta\mathbf{MDT}\} \ . \tag{9}
$$

Figure 1 shows the in-situ mean dynamic topography observations and its corresponding covariance matrix.

4 Combination method

The three different observation groups are combined in terms of normal equations. If only gravity field and altimetry observations are considered in our model, the unknowns of the model are the geoid represented by spherical harmonics and the mean dynamic topography parameterized by a linear combination of finite element base functions. The base functions can be linear or quadratic piecewise polynomials for example so that the unknowns of the mean dynamic topography parameterization are directly the mean dynamic topography and possibly its derivatives at the nodal points of the finite elements. According to this the altimetric mean sea surface is separated into the geoid and the mean dynamic topography. Within the model, different frequency domains of the observations are considered, so that the vector of the unknown gravity field parameters is separated into different subdomains. Special attention is paid to model the omission domain within the altimetric observation equations based on a priori information. In addition, we introduce smoothness conditions according to the Hilbert Space H_Γ^1 (Schuh and Becker, 2010). We use Kaula's rule of thumb (Kaula, 1966) as a first guess to fix the unknown coefficients. A detailed description of the developed method for combining gravity field and altimetry observations in a rigorous way can be found in (Becker et al 2012).

In theory, the satellite data and the quasi in-situ mean dynamic topography data provide the same information about the mean dynamic topography or its horizontal gradients respectively. However, the signals have different reference levels or mean values. Here, we assume a constant shift between satellite and in-situ information. Thus, we introduce an auxiliary bias parameter accounting for different reference levels, if in-situ data is introduced in the model. Denoting the gravity field parameters with $\boldsymbol{x}_{cs}$, the parameters describing the finite element mesh of the mean dynamic topography with $\boldsymbol{x}_{FE}$ and the bias parameter with x_c, the combined normal equations can be written as

$$
\begin{bmatrix}
\boldsymbol{N}_{cs}^{\mathrm{G}} + \boldsymbol{N}_{cs}^{\mathrm{MSS}} + \boldsymbol{N}_{cs}^{\mathrm{s}} & \boldsymbol{N}_{cs,FE}^{\mathrm{MSS}} & \mathbf{0} \\
\boldsymbol{N}_{FE,cs}^{\mathrm{MSS}} & \boldsymbol{N}_{FE}^{\mathrm{MSS}} + \boldsymbol{N}_{FE}^{\mathrm{MDT}} & N_{FE,c}^{\mathrm{MDT}} \\
\mathbf{0} & N_{c,FE}^{\mathrm{MDT}} & N_{c}^{\mathrm{MDT}}
\end{bmatrix}
\begin{bmatrix}
\boldsymbol{x}_{cs} \\ \boldsymbol{x}_{FE} \\ x_c
\end{bmatrix}
=
\begin{bmatrix}
\boldsymbol{n}_{cs}^{\mathrm{G}} + \boldsymbol{n}_{cs}^{\mathrm{MSS}} \\
\boldsymbol{n}_{FE}^{\mathrm{MSS}} + \boldsymbol{n}_{FE}^{\mathrm{MDT}} \\
n_c^{\mathrm{MDT}}
\end{bmatrix}
\tag{10}
$$

or in short

$$
\left(\boldsymbol{N}^{\mathrm{G}} + \boldsymbol{N}^{\mathrm{MSS}} + \boldsymbol{N}^{\mathrm{s}} + \boldsymbol{N}^{\mathrm{MDT}}\right)\boldsymbol{x} = \boldsymbol{n}^{\mathrm{G}} + \boldsymbol{n}^{\mathrm{MSS}} + \boldsymbol{n}^{\mathrm{MDT}} \tag{11}
$$

with the components for the gravity field (G), the mean sea surface (MSS), the smoothness conditions (s) and the in-situ observations (MDT).

Note, that in principle the in-situ data and the altimetric mean sea surface are correlated groups of observations because the subtracted time variable part **SLA** of the dynamic topography depends on the mean sea surface. However, the correlations are negligibly small so that we consider both normal equations separably.

4.1 Relative weighting – variance component estimation

Relative weighting of the different observation groups plays an important role in order to provide an optimal estimation of the parameters. We determine the relative weights $1/\sigma_i^2$ via a rigorous variance component estimation (see e.g. Koch and Kusche, 2002; Brockmann and

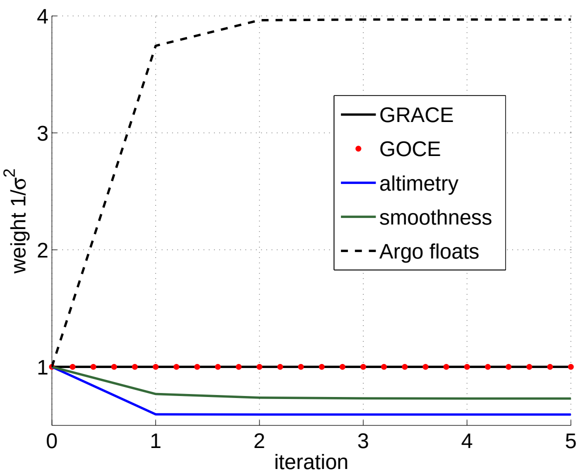


Fig. 2 Progression of relative weights between the observation groups resulting from variance component estimation.

Schuh, 2010) so that the combined normal equations (11) are rewritten as

$$\left(\sum_i \frac{1}{\sigma_i^2} \boldsymbol{N}_i\right) \boldsymbol{x} = \sum_i \frac{1}{\sigma_i^2} \boldsymbol{n}_i \ . \tag{12}$$

4.2 Contribution of different observation groups to the parameters

The overall solution $\tilde{\boldsymbol{x}}$ can be interpreted as weighted sum of the theoretical individual solutions $\boldsymbol{x}_i$ for the particular observation groups

$$\tilde{\boldsymbol{x}} = \boldsymbol{N}^{-1} \sum_i \frac{1}{\sigma_i^2} \boldsymbol{N}_i \boldsymbol{x}_i = \sum_i \boldsymbol{W}_i \boldsymbol{x}_i \ . \tag{13}$$

The weight matrices $\boldsymbol{W}_i$ sum up to the identity matrix $\boldsymbol{I}$, so that the main diagonal elements of the matrices $\boldsymbol{W}_i$ may be considered as the contribution of the individual observation group i to the overall estimation process of the parameters.

5 Results

The results shown here are obtained with the following model configuration. The nodal points of the finite elements were arranged on a regular triangulated $1^\circ \times 1^\circ$ grid. We used linear polynomials as base functions in order to represent the mean dynamic topography. Hence, the unknowns $\boldsymbol{x}_{FE}$ are the mean dynamic topography at the nodal points. The commission domain spans the spherical harmonics of degree $2-300$ and the omission

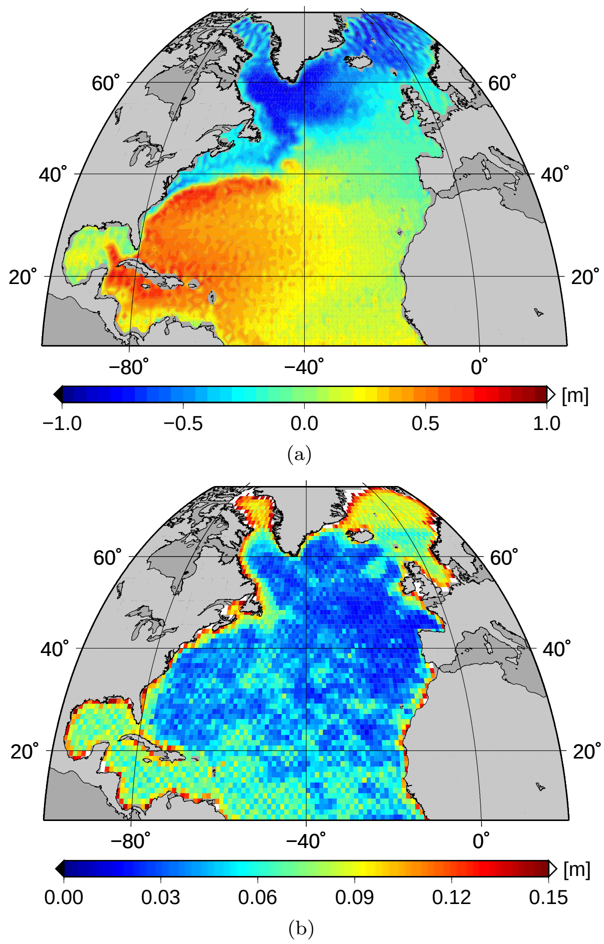


Fig. 3 Mean dynamic topography estimated on a $1^\circ \times 1^\circ$ grid and its associated standard deviations.

domain is described by a priori information provided by the EGM2008 (Pavlis et al., 2012) and Kaula's rule of thumb. See Becker et al. (2012) and Becker (2012) for details of the parameterization of the omission domain.

Figure 2 shows the progression of the relative weights of the different observation groups during the iterative variance component estimation process (see Section 4.1, (12)). The weights of the GRACE and GOCE observations remain at approximately $1/\sigma_{\mathrm{G}}^2 \approx 1$, while the impact of the smoothness conditions and the altimetric measurements decreases. The weight of the smoothness conditions reaches $1/\sigma_{\mathrm{s}}^2 \approx 0.7$ and the altimetric data is downweighted by $1/\sigma_{\mathrm{MSS}}^2 \approx 0.6$. In contrast, the relative weight of the Argo float measurements increases to $1/\sigma_{\mathrm{MDT}}^2 \approx 4$. This indicates that the empirical error modeling of the altimetric and in-situ measurements must be reconsidered, which is subject for further studies but beyond the scope of this study. In case of the altimetric data the covariance matrix is composed of two terms – the covariance of the mean sea surface and the covariance describing the omission domain. The omis-

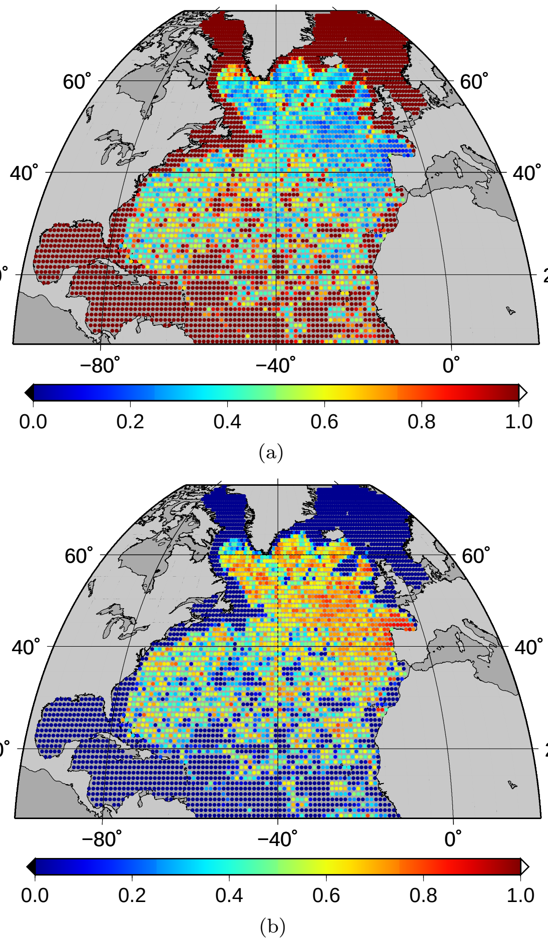


Fig. 4 Contribution of (a) the altimetric and (b) the Argo float measurements to the estimated mean dynamic topography.

sion error model includes the error degree variances of the EGM2008. We assume, that the downweighting of the altimetric data probably indicates that the EGM2008 errors are underestimated. The covariance matrix of the quasi in-situ mean dynamic topography is the sum of the empirically determined covariance matrix of the dynamic heights $\boldsymbol{\Sigma}\{\mathbf{DH}\}$, the covariance matrix of the time variable part $\boldsymbol{\Sigma}\{\mathbf{SLA}\}$ and the covariance matrix of the missing part $\boldsymbol{\Sigma}\{\Delta\mathbf{MDT}\}$. The increasing impact of the Argo float measurements on the estimated parameters suggests that the empirically derived error model of the dynamic heights implies a priori unrealistic large variances and must be reconsidered.

Figure 3 illustrates the resulting mean dynamic topography and its associated standard deviations. The mean dynamic topography shows some unrealistic short scale features especially at high latitudes. The standard deviation is 6.3 cm on average. It decreases to approximately 3.5 cm in regions where in-situ data is included in the computation and reaches its maximum at high latitudes greater than 66°N where only Envisat measurements are available and the oscillations of the mean dynamic topography are most pronounced. Closed-loop simulations have shown that these oscillations occur in case of insufficiently accurate information content of the integrated gravity field model at the defined spatial resolution of the finite elements. If the spatial resolution of the finite elements matches the frequency domain, in which the information content of the gravity field is highly accurate, the altimetry signal can be separated very well into geoid and mean dynamic topography and the combined model provides a smooth mean dynamic topography. In either case the characteristics of the mean dynamic topography are reflected by the associated error description and the method yields a consistent variance/covariance matrix. At high latitudes the spatial resolution of the finite elements increases so that the non-physical noise is amplified, while the standard deviations also increase.

The contributions of the altimetric mean sea surface and the Argo float measurements to the estimation of the mean dynamic topography parameters are shown in figure 4 (see Section 4.2, (13)). The largest impact of the in-situ data can be observed in regions where the observation density is high. In regions where both observation types are available for the computations the contribution of the altimetric measurements is 0.51 on average and the contribution of the in-situ data is accordingly 0.49.

6 Discussion and outlook

We developed an integrated approach to combine gravity field, altimetry and in-situ data in a rigorous way. With the presented method we are able to provide the normal equations of the mean dynamic topography on arbitrary grids or the mean dynamic topography and its consistent covariance matrix respectively. Hence, we have direct access to the target quantities required by ocean circulation models. Special attention is paid to the complete modeling of all observations including the omission domain and the consistent error description as well as its rigorous propagation. In addition we implemented a rigorous variance component estimation to determine optimal relative weights between the different observation groups.

The focus of the study is on the determination of the mean dynamic topography and its associated covariance matrix in the North Atlantic Ocean, but the approach also opens up the opportunity to improve the gravity field and the mean dynamic topography in a joint estimation. However, this requires the integration of additional observations like (global) ocean-wide altimetric data and terrestrial gravity data for example. Up to now the estimation process is completely unrestricted. No explicit smoothness conditions are applied to the mean dynamic topography. In order to improve the global gravity field and the mean dynamic topography additional constraints like e.g. energy minimization strategies can be considered and applied. Another possible extension of the method is the parameterization of the time variability of the ocean's dynamic topography within the estimation procedure. All these aspects are subject for further studies.

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