Considering ECMWF forecast data for GRACE de-aliasing

Henryk Dobslaw and Maik Thomas

Institute for Planetary Geodesy, Dresden University of Technology, Dresden, Germany

Abstract. Variations in atmospheric surface pressure and wind fields have a significant impact on ocean dynamics and corresponding mass redistribution. Since gravity field estimations directly obtained from satellite gravity missions like GRACE are aliased by high-frequency atmosphere and ocean mass signals, these variations have to be eliminated during the gravity field processing. Routinely, the European Centre for Medium Range Weather Forecasts (ECMWF) provides analysis and forecast fields describing the transient state of the atmosphere. By means of simulations with the Ocean Model for Circulation and Tides (OMCT) the impact of these different forcing fields on ocean mass redistribution is investigated. While differences in geoid height anomalies caused by forecast errors do not exceed 0.3 mm rms, and the effect of accumulated wind stress turn out to be insignificant, rms values due to doubled temporal resolution reach 0.6 mm in several oceanic regions. This indicates that 3 hourly forecasts of atmospheric pressure and wind fields contain significant additional semidiurnal variability causing a change in ocean mass redistribution which is well above the significance threshold of GRACE and have to be considered during the gravity field estimation process.

Citation. Dobslaw, H., Thomas, M.: Considering ECMWF forecast data for GRACE de-aliasing, Proc. Joint CHAMP / GRACE Science Team Meet. 2004, published online, www.gfz-potsdam.de/pb1/JCG, 2005.

1 Introduction

The Earth's gravity field undergoes changes due to mass exchanges between and mass redistribution within its subsystems. A significant contribution to the Earth's time-variable gravity field is caused by atmosphere and ocean dynamics. As these variable masses influence the gravity field estimation from satellite missions like the Gravity Recovery and Climate Change Experiment (GRACE), such signals have to be removed from the data in order to calculate a mean gravity field. By means of simulated gravity data, Wahr et al. (1998) showed that GRACE is expected to be sensitive to large scale ocean mass variations on annual timescales up to degree 37. Wünsch et al. (2001) additionally analysed high-frequency ocean mass variations, finding significant variability even on daily timescales which is well above the sensitivity threshold of GRACE. In order to reduce aliasing effects due to such short-term mass variations, atmosphere and ocean mass anomalies are reduced in standard GRACE gravity field processing using ECMWF analysis data and corresponding oceanic signals obtained from the barotropic ocean model PPHA (Hirose et al., 2001). Here, the impact of 3 hourly resolved ECMWF forecast fields on ocean mass variations is systematically analysed by means of numerical simulations using the baroclinic Ocean Model for Circulation and Tides (OMCT; Thomas, 2002). Typical effects of temporal resolution, forecast errors and wind representation on ocean mass variations are separated and discussed by means of instantaneous distributions as well as mean variabilities of resulting geoid height anomalies.

Correspondence to: H. Dobslaw (henryk.dobslaw@tu-dresden.de)

2 Atmospheric data

The European Centre for Medium Range Weather Forecasts (ECMWF) provides atmospheric data on an operational basis. The model currently in use has a spectral resolution of wave number 511 and 60 vertical layers. Every day, four global analyses are distributed describing the state of the atmosphere at 00, 06, 12 and 18 UTC. These analyses are obtained from two 4DVAR minimisation cycles (Klinker et al., 2000, and references therein) running from 03 to 15 UTC and from 15 to 03 UTC. By assimilating observational data for this time period an optimal transient state of the model atmosphere is determined. Instantaneous fields from these optimal fits, containing the best estimate of atmospheric state at a certain time step, are provided as analysis fields. These analyses are applied in the standard GRACE de-aliasing procedure.

Additionally, medium range forecast runs are performed following each 4DVAR minimisation cycle. Forecasts with a temporal resolution of up to 3 hours are distributed up to 10 days ahead the main synoptic hours at 00 and 12 UTC. These forecast fields contain information on instantaneous state quantities of the atmosphere like three-dimensional distributions of temperature, pressure, and wind speeds for the end of each forecast interval. In addition to instantaneous fields, forecasts provide accumulated information on evolving properties of the atmosphere, e.g., the amount of precipitation and evaporation as well as wind stresses accumulated over the forecast interval (Persson, 2003), which lead to representative mean values of these quantities for the considered time interval. Although forecasts are not constrained by data and consequently may contain forecast errors, the accumulated wind stress information and the doubled temporal resolution make forecasts potentially valuable also for post processing tasks. As new forecast sets become available every 12 hours, the first four forecasts steps at +3, +6, +9 and +12 hours have to be used. While instantaneous fields contained in each forecast are referenced to the end of the forecast interval, accumulated fields contain information from last analysis until the end of the forecast interval. Therefore, the ultimate preceding forecast field has to be subtracted in order to assess the information for the considered 3 hour interval only, which is then be used to calculate a representative mean.

To analyse the impact of atmospheric forecasts on numerical simulations of short-term ocean mass variations, different numerical experiments are performed in order to separate the impact of accumulated winds, temporal resolution and forecast induced errors. As a reference, analysis data will be used as in standard GRACE processing. To estimate the total effect of changing from analysis to forecast, an atmospheric data set is used containing 3 hourly resolved forecast fields with accumulated wind stresses. The impact of temporal resolution is analysed using a forecast dataset containing only the +6 and +12 hours forecasts. Effects of accumulated wind stresses are considered using instantaneous wind speed information provided with each forecast. With a resolution of 6 hours the last dataset is comparable to standard analysis and is used to estimate the impact of changing from analysis to forecast alone. For simplicity, analyses serve as reference fields and, thus, are assumed to be error-free in this study and all deviations from these reference state are considered as forecast errors. As we are primarily interested in analysing ocean mass variations, atmospheric mass anomalies are obtained simply from atmospheric surface pressure fields, which is sufficiently accurate for our intentions, as we are using mass anomalies above continents only for qualitative argumentation. In standard GRACE processing, however, atmospheric mass anomalies are derived using the vertical integral approach (see e.g., Flechtner, 2003).

3 Ocean model

The ocean's response to atmospheric conditions is obtained by means of simulations with the Ocean Model for Circulation and Tides (OMCT). The model was developed by adjusting the originally climatological Hamburg Ocean Primitive Equation Model (HOPE; Wolff et al., 1996, Drijfhout et al., 1996) to the weather time-scale and coupling with an ephemeral tidal model. Implemented is a prognostic thermodynamic sea-ice model (Hibler, 1979) that predicts ice-thickness, compactness and drift. Higher order effects such as nonlinearities are accounted for as well as the secondary potential due to loading and self-attraction (LSA) of the water masses.

In the present configuration, the model uses a time step of 30 minutes, a horizontal resolution of 1.875° and 13 layers in the vertical. Additional information on model physics can be found in Thomas and Dobslaw (2005, in the following labelled as TD05). In this study, the general ocean circulation due to temperature, fresh water fluxes, wind stress and pressure forcing has been simulated, and secondary effects like loading and self-attraction of a baroclinic water column have been accounted for.

To obtain mass anomalies, a temporal mean field from 2001 is subtracted. The prevailing bottom pressure anomalies are transformed into geoid height anomalies using Love's loading numbers (Dong et al., 1996, Farrel, 1972). To investigate differences with respect to atmospheric mass distributions represented by analysis and forecast data and corresponding resulting differences in oceanic mass distributions, simulations with different forcing conditions are performed: (1) analysis data as used in standard GRACE processing and as it has been used in TD05, (2) forecast data with 3 hours temporal resolution and accumulated wind stresses during the forecast intervall, (3) forecast data with 6 hours temporal resolution and accumulated wind stresses, and (4) forecast data with 6 hours temporal resolution and instantaneous wind stresses. Instantaneous wind speeds provided by ECMWF regularly within forecasts and analysis are transformed to wind stresses by means of a standard routine provided by ECMWF, which is consistent with the operational ECMWF forecast model (Beljaars, 1997). Fresh water fluxes due to precipitation and evaporation have been obtained from corresponding forecast fields for all simulations, since these data are not available from analyses.

Simulations have been performed for the period 2001-2004 using a common initial model state obtained from an initial spun up for 265 years with cyclic boundary conditions, i.e., climatological wind stresses according to Hellerman and Rosenstein (1983) and annual mean surface temperatures and salinities according to Levitus (1982) followed by a real-time simulation for the period 1958-2000 driven by wind stress components, 2m-temperatures, freshwater fluxes, and atmospheric surface pressure from ECMWF's 40 years re-analysis project ERA-40. Bottom pressure fields have been stored every 6 hours, corresponding to ECMWF analysis times.

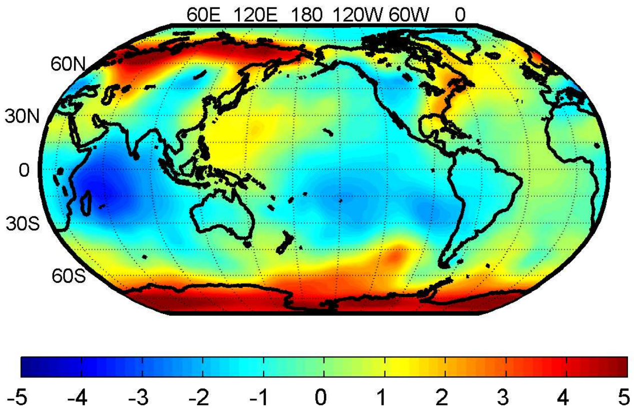

Fig. 1. Combined effect of atmosphere and ocean mass anomalies expressed in geoid height anomalies [mm] at 25 March 2004, 12:00 UTC, as obtained from ECMWF analysis data and OMCT simulation considering thermohaline, wind-, and pressure-driven circulation as well as loading and self-attraction.

4 Numerical results

To illustrate the dimensions concerned with in atmosphere and ocean de-aliasing, the combined effect of instantaneous mass anomalies from ECMWF analysis and corresponding OMCT simulation have been exemplarily displayed in Fig. 1. The largest anomalies can be found in continental regions, here with distinct high pressure systems above Antarctica and Russia. In oceanic regions geoid height anomalies up to 5 mm are typically found in the region of the Antarctic Circumpolar Current (ACC), which are mainly attributed to strong zonal dynamics both in atmosphere and ocean. Similar amplitudes can be found occassionally in the Arctic, where an immediate inverse barometric compensation of atmospheric pressure variations is partly prevented due to sea-ice presence. A distinct large scale anomaly pattern can be found in tropical oceanic regions, with negative anomalies in the Indic and south-east Pacific and positive anomalies in the eastern Pacific and, less pronounced, in the Atlantic. Obviously, the horizontal distribution of anomalies resembles well the pattern related to barometric tides published by Ray and Ponte (2003) indicating that high-frequency pressure changes are not fully compensated by a pure inverse barometric response of the ocean. Although, in general, semidiurnal signals in atmospheric pressure exceed diurnal variabilities, semidiurnal components are not adequately resolved by 6 hourly analyses. Thus, it will be targeting to analyse 3 hourly forecasts in order to fully resolve semidiurnal atmospheric pressure variability and corresponding oceanic responses.

The total impact on atmosphere and ocean mass anomalies caused by changes in atmospheric state representation has been displayed in Fig. 2a, according to differences from two OMCT simulations forced with analysis data and 3 hourly resolved forecast data with accumulated wind stresses. Differences above continents are rather small, approaching 0.3 mm above Africa and Australia. Distinctly higher signals approaching 1 mm geoid height anomaly can be found in wide regions of the world's ocean. Consequently, total differences in geoid height anomalies resulting from analyses and forecasts are expected to reach up to 30% of the original signal. These comparatively large differences are made up of three distinct amounts. According to Fig. 2b, solely forecast induced errors are derived from two OMCT simulations forced by analysis and forecasts, equally sampled at 6 hours temporal resolution with instantaneous wind fields. Signals are distinctly weaker compared to Fig. 2a and show a rather large scale pattern around 0.3 mm geoid height anomaly with tendentially lower values above continents. High signals can be found in the southern hemisphere and in arctic regions, but they are generally too weak to explain the total effect shown in Fig. 2a. The impact of accumulated wind stress is displayed in Fig. 2c. Signals are generally low in most of the oceanic regions; isolated high effects occur in small enclosed oceanic areas, which are, however, not very well resolved within a spatial resolution of 1.875°. The essential contribution to total differences has to be attributed to the doubled temporal resolution of 3 hours. OMCT simulations forced by forecasts with accumulated wind stresses sampled at 3 and 6 hours temporal resolution have been used to calculate the differences shown in Fig. 2d. A dedicated pattern can be found whose characteristics are easily recognised in Fig. 2a as well. The pattern is very regular, and shows distinctly steep spatial gradients.

In order to confirm the representativity of the instantaneous mass anomalies discussed above, monthly mean root mean square (rms) variabilities have been calculated according to

$$rms(\phi,\lambda) = \sqrt{\frac{1}{K-1}\sum_{k=1}^{K}\left(N(t_k,\phi,\lambda) - \bar{N}(\phi,\lambda)\right)^2}\,, \quad (1)$$

where K is the number of calculated sets of spherical harmonics per month, N the instantaneous and $\bar{N}$ the monthly mean geoid height anomaly at (ϕ,λ). According to Fig. 3a, rms-values due to total differences between analysis and forecasts generally confirm the results indicated by the instantaneous snap-shot displayed in Fig. 2a, with rms-values approaching 0.6 mm in some regions. Forecast errors alone cause distinctly weaker rms-values up to 0.3 mm in western Antarctica and Weddell sea, and some rather regional spots in the tropical Atlantic, Pacific and Indic (Fig. 3b). Apart from arctic regions, the northern hemisphere is much less affected. In general, mass distributions above continents resulting from analyses and forecasts show only marginal differences, except for Antarctica as mentioned above. The effect of accumulated wind stresses tends to be insignificant over most oceanic regions (Fig. 3c). However, some very local effects with rather high rms values up to 0.3 mm can be found in the Arctic and some enclosed oceanic areas like Black Sea, Mediterranean, and Yellow Sea. In most other regions the effects due to accumulated wind stress are well below 0.1 mm rms. Again, the essential contribution to monthly mean vari-

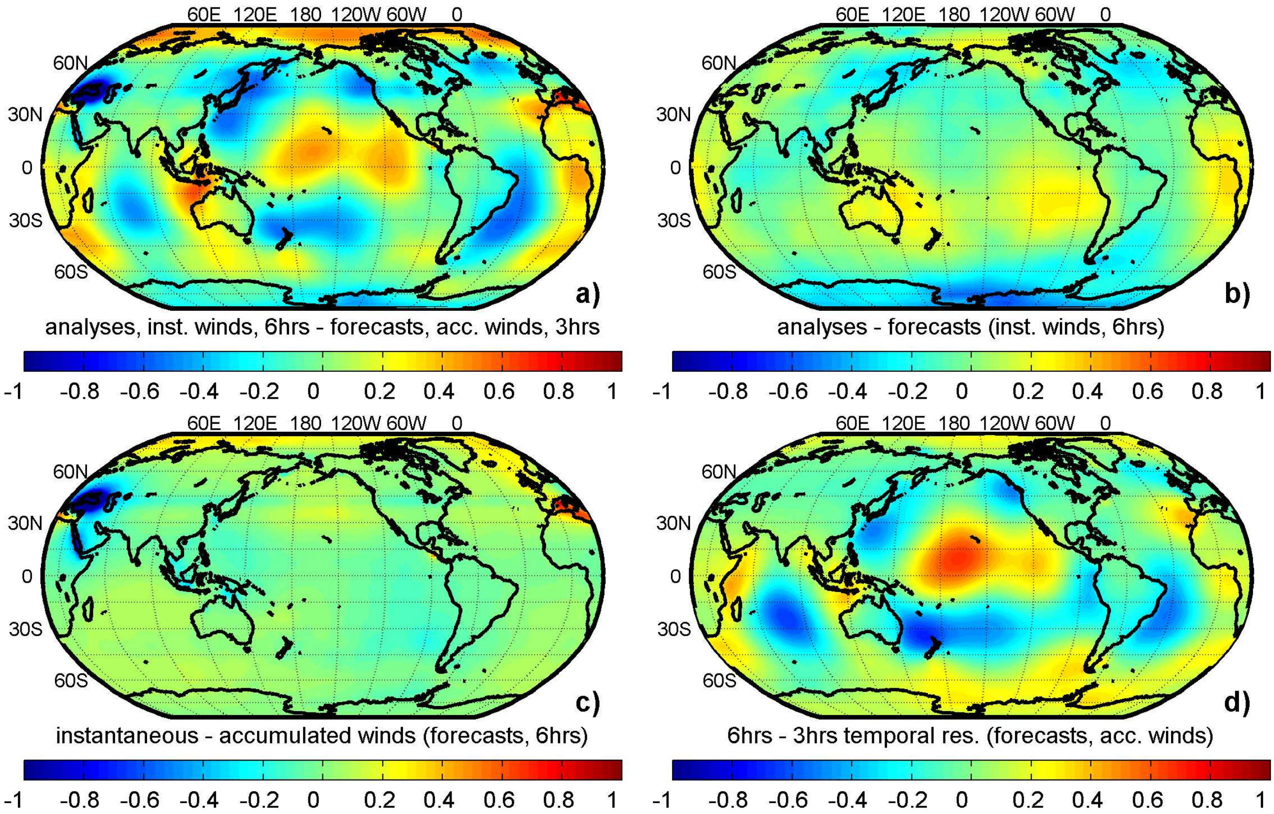

Fig. 2. Instantaneous atmosphere and ocean mass anomalies expressed in geoid height anomalies in [mm] on 25 March 2004, 12:00 due to (a) total effect of forecast versus analysis data, as well as separated into individual contributions due to (b) forecast errors, (c) accumulated wind stress, and (d) increased temporal resolution.

abilities has to be ascribed to the doubled temporal resolution with rms values exceeding 0.6 mm (Fig. 3d). In analogy to instantaneous anomalies shown in Fig. 2d, the very regular pattern in Fig. 3d indicates that significant variability on semidiurnal or even shorter timescales must be contained in the forecasts, which cannot be properly resolved within 6 hourly temporal resolution. In principle, both analyses and forecasts provided by ECMWF contain diurnal as well as semidiurnal signals (Janssen, 1999). Obviously, the proper resolution of semidiurnal atmospheric variability causes additional ocean dynamics, leading to a significant different mass distribution. As bottom pressure fields used to calculate rms distributions have been sampled at 6 hours in all simulations carried out for this study, this representation will alias exact semidiurnal variations. Additionally, variabilities above continents have been aliased as well, as bottom pressure fields (and consequently corresponding atmospheric pressure fields) have been stored and analysed every 6 hours concurrent with ECMWF's analyses. To overcome these limitations and to analyse in detail the behaviour of these high frequent variability contained in 3 hourly resolved forecast fields is beyond the scope of this paper and will be considered in a further study.

5 Conclusions

ECMWF routinely provides analysis as well as forecast data describing the transient state of the atmosphere. Although forecasts might be affected by errors, with 3 hours they provide a doubled temporal resolution compared to analysis data. Additionally, forecasts contain accumulated information on evolving properties of the atmosphere, like wind stresses at the surface, while analyses provide instantaneous wind speeds only. Differences between short periodic mass anomalies in atmosphere and ocean resulting from numerical simulations with OMCT forced with analysis and forecast data exceed 0.6 mm rms of geoid height anomalies in several oceanic regions. These rather high differences approaching almost 30% of the absolute signal are made up of three distinct contributions which were separated by numerical experiments with various forcing conditions. It turned out that different representations of wind forcing only marginally have an impact on oceanic mass distributions. Although forecast errors are responsible for rms values up to 0.3 mm, the essential contribution to overall differences in short periodic mass anomalies between analyses and forecasts has to be attributed by the increased temporal resolution of 3 hours, causing rms values up to 0.6 mm rms of geoid height anomalies.

For de-aliasing purposes during the GRACE gravity field estimation process it is necessary to remove short-term mass

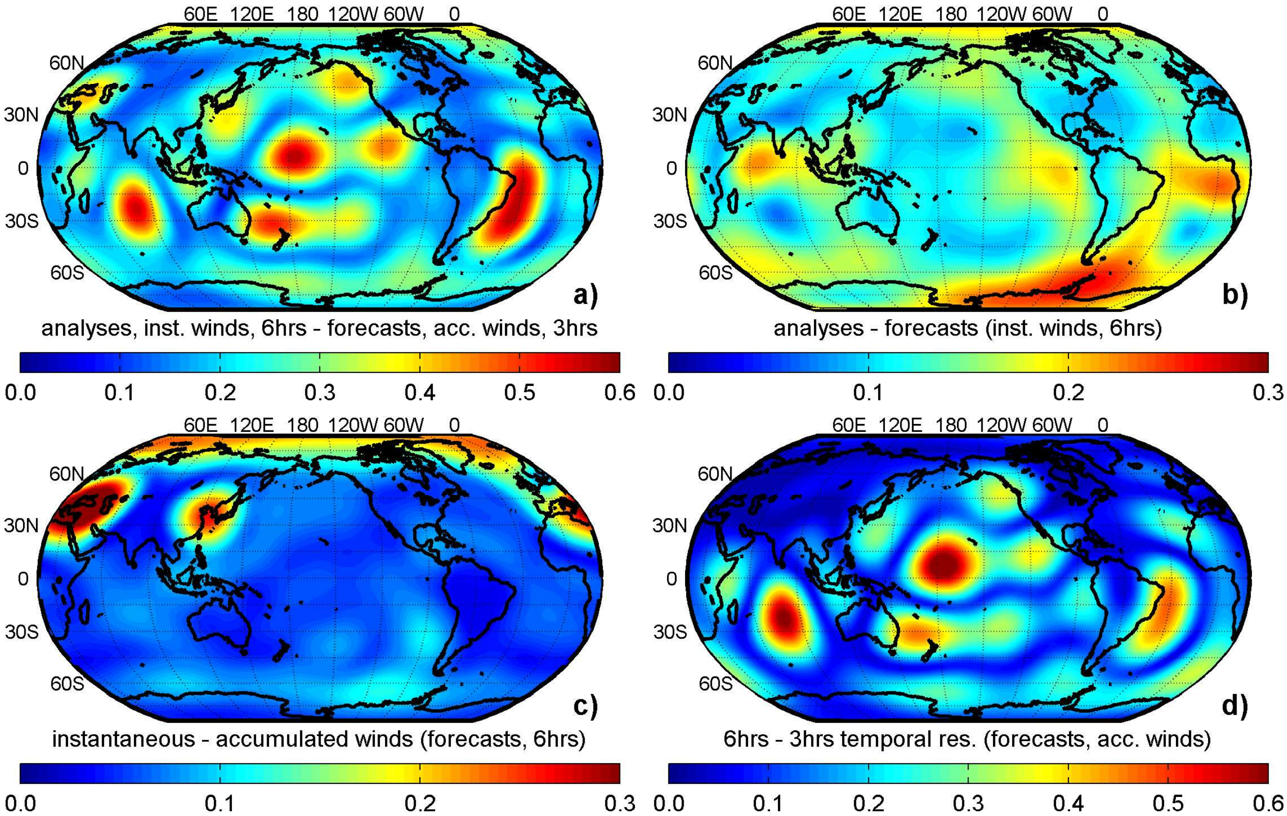

Fig. 3. Monthly mean rms-variabilities of geoid height anomalies in [mm] for March 2004, due to (a) total effect of forecast versus analysis data, as well as separated into individual contributions due to (b) forecast errors, (c) accumulated wind stress, and (d) increased temporal resolution.

variations as precise as possible. Since atmospheric analyses data from ECMWF are solely available with 6 hours temporal resolution, forecasts can be considered for de-aliasing purposes to take consistently into account diurnal and semidiurnal atmosphere and ocean mass redistribution, too. However, application of forecast fields comes along with accepting the quality degradiation due to forecast errors. On the other hand, analysis data can be used as in standard GRACE processing. In this case it is necessary to completely remove semidiurnal variability from the atmospheric data before calculating the combined effect of atmosphere and ocean mass variations and treating semidiurnal atmospheric tides and their corresponding oceanic responses with a separate reduction model.

Acknowledgements. Helpful comments by Anton Beljaars (ECMWF) on an early version of this manuscript are appreciated. We thank Deutscher Wetterdienst, Offenbach, Germany, and European Centre for Medium Range Weather Forecast, Reading, U.K., for providing data from ECMWF's operational forecast model. The OMCT simulations were performed on NEC SX6 of the Deutsches Klimarechenzentrum, Hamburg, Germany. This work was supported by the Deutsche Forschungsgemeinschaft under grant TH864/1-1.

References

Beljaars, A.C.M.: Air-sea interaction in the ECMWF model, ECMWF seminar proceedings on: Atmosphere-surface interaction, 8-12 September 1997, p. 33-52, Reading, U.K., 1997.

Dong, D., Gross, R. S., and Dickey, J. O.: Seasonal variations of the Earth's gravitational field: an analysis of atmospheric pressure, ocean tidal, and surface water excitation, Geophys. Res. Lett., 23, 725-728, 1996.

Drijfhout, S., Heinze, C., Latif, M., and Maier-Reimer, E.: Mean circulation and internal variability in an ocean primitive equation model, J. Phys. Oceanogr., 26, 559-580, 1996.

Farrell, W. E.: Deformation of the Earth by surface loads, Rev. Geophys. Space Phys., 10, 761-797, 1972.

Flechtner, F.: Short-term atmosphere and ocean gravity de-aliasing for GRACE, p. 45-47, in: GEOTECHNOLOGIEN, Science Report No. 3, "Observation of the system Earth from space", Status Seminar, Bavarian State Mapping Agency (BLVA), Munich, 12-13 June 2003, Potsdam: Koordinierungsbüro GEOTECHNOLOGIEN, 199p., 2003.

Janssen, P.A.E.M.: On tides in the ECMWF model, ECMWF, Tech memo, 284, Reading, U.K., 1999.

Hellerman, S., and Rosenstein, M.: Normal monthly wind stress over the world ocean with error estimates, J. Phys. Oceanogr., 13, 1093-1104, 1983.

Hibler III, W. D.: A dynamic thermodynamic sea ice model, J. Phys. Oceanogr., 9, 815-846, 1979.

Hirose, N., Fukumori, I., Zlotnicki, V. and Ponte, R.M.: Modeling the high-frequency barotropic response of the ocean to atmospheric disturbances: Sensitivity to forcing, topography and friction. J. Geophys. Res., 106 (C12), 30987-30995, 2001.

Klinker, E., Rabier, F., Kelly, G. and Mahfouf, J-F.: The ECMWF operational implementation of four dimensional variational assimilation. Part III: Experimental results and diagnostics with operational configuration. . Q. J. R. Meteorol. Soc. 126, 1191 1215, 2000.

Levitus, S.: Climatological atlas of the world ocean, NOAA Professional Paper, 13, 173 pp., U.S. Department of Commerce, 1982.

Persson, A.: User Guide to ECMWF forecast products. Meteorological Bulletin M3.2, European Centre for Medium Range Weather Forecasts, Reading, U.K., 2003.

Ray. R.D. and Ponte, R.M.: Barometric tides from ECMWF operational analyses. Ann. Geophys., 21, 1897-1910, 2003.

Thomas, M.: Ocean induced variations of Earth's rotation - Results from a simultaneous model of global circulation and tides, Ph.D. dissertation, University of Hamburg, Germany, 129 pp., 2002.

Thomas, M., Dobslaw, H.: On the impact of baroclinic ocean dynamics on the Earth's gravity field, Proc. Joint CHAMP / GRACE Science Team Meet. 2004, published online, www.gfz-potsdam.de/pb1/JCG, 2005.

Wahr, J., Molenaar, M., and Bryan, F.: Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, J. Geophys. Res., 103, 30205–30229, 1998.

Wolff, J.O., Maier-Reimer, E., and Legutke, S.: The Hamburg Ocean Primitive Equation Model HOPE, Technical Report No. 13, 103 pp., DKRZ, Hamburg, 1996.

Wünsch, J., Thomas, M., and Gruber, T.: Simulation of oceanic bottom pressure for gravity space missions, Geophys. J. Int., 147, 428-434, 2001.