Validation of GRACE Gravity Fields by In-Situ Data of Ocean Bottom Pressure

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1 Introduction

The GRACE (Gravity Recovery and Climate Experiment) satellite mission observes the gravity field of the Earth with unprecedented accuracy. Its potential to measure the temporal variability of the geoid due to mass redistribution on Earth's surface has opened the possibility to study mass trends of continental ice sheets and in the lithosphere, or the hydrologic cycle in monsoon regions.

Over the oceans, variability of the gravity field primarily represents oceanic and atmospheric mass redistribution. This corresponds to changes in ocean bottom pressure (OBP), which is an integral measure of the oceanic (and atmospheric) mass above any given location at the sea floor, explained by the hydrostatic equation:

$$p(-H) = g \int_{-H}^{0} \rho(z) dz$$

with pressure p at depth $-H$, acceleration of gravity g and density ρ as a function of depth z. For oceanographers, OBP is a relevant quantity to assess sea level and ocean currents. While satellite altimetry observes the actual sea level, the combination of altimetry and gravimetry allows to distinguish between thermal expansion (steric effect) and mass increase (which is captured by GRACE, and OBP). Further, temporal changes of the horizontal OBP gradient dp/dx correspond to abyssal geostrophic current velocity anomalies (chapter "On the Representation of Transport Variability of the Antarctic Circumpolar Current in GRACE Gravity Solutions and Numerical Ocean Model Simulations" by Böning et al., 2010). Hence, GRACE may provide a world-wide monitoring of changes of ocean circulation, at least on scales larger than ≈500 km and longer than months.

However, monthly mass variability over the oceans is much smaller than over the continents, where GRACE observes up to 15 cm of water column equivalent

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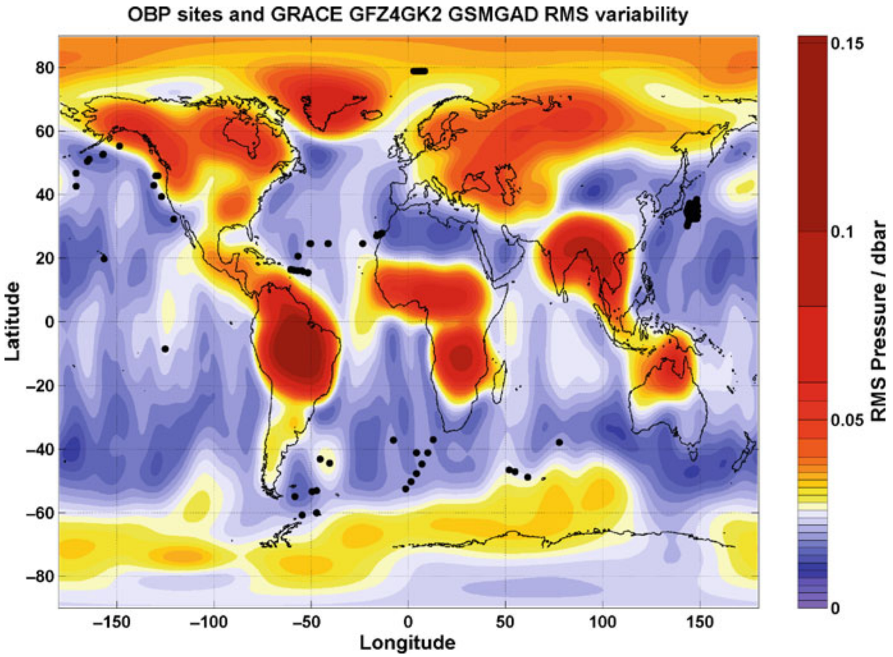

Fig. 1 RMS standard deviation of the monthly GFZ Release 04 GSM+GAD product. Note the high values over the continents, and in the Arctic and Southern Ocean. *Small black dots* mark positions of in-situ OBP observations used in this study

RMS variability in some monsoon regions. Typical monthly oceanic RMS variability ranges from about 1 cm in many tropical regions to 5 cm in the Arctic and Southern Oceans (Fig. 1). These comparatively small changes are close to the accuracy limit of the GRACE solutions. Further, large short-term variability, particularly tides reaching amplitudes of about 1 m in the open ocean, makes de-aliasing essential for realistic estimates of the monthly geoid, which is calculated from hundreds of satellite orbits. Meyer et al. (2007) showed, that even small modelling errors in ocean tide prediction significantly degrade the accuracy of the GRACE solutions.

Hence, a validation with in-situ OBP measurements is critical to assure that GRACE realistically captures oceanic mass redistribution. The main challenges in comparing satellite and in-situ OBP result from the differences in spatial and temporal scales: Due to the orbit height of the satellites, GRACE data represent spatial averages over several hundreds of kilometres. In contrast, in-situ time series depict OBP at a single point – which is not necessarily representative for the surrounding hundreds of kilometres. Particularly, close to oceanic fronts (like the Polar Front in the Southern Ocean) and in regions with highly localised variability (like close to some coastlines or western boundary currents) GRACE may show spatially smoothed variability not representative for local in-situ observations. Temporal short-term variability can be fully captured by in-situ instruments, thus the calculation of monthly means matching the time axis of GRACE data is not critical. If the same tide model is used as for GRACE data, errors from longer periodic tides should disappear. Nevertheless, the smaller sampling rate of the GRACE satellites (i.e. the less frequent overflights of a given region, compared to sampling rates of 15 s to 30 min for moored in-situ instruments) is the reason why de-aliasing of tidal and non-tidal short-term variability is critical to obtain realistic monthly gravity field solutions. Any discrepancies between GRACE and in-situ data can hence result from (a) differences in captured spatial scales, (b) errors in the numerical de-aliasing models used for the GRACE solutions, and (c) actual measurement errors in either in-situ pressure sensors or the GRACE satellites data.

During the last years, a number of studies compared GRACE and in-situ OBP time series provided by pressure sensors deployed on the sea floor at selected positions. These showed good agreement in some (Rietbroek et al., 2006; Morison et al., 2007; Park et al., 2008), but not all cases (Kanzow et al., 2005). Here, a global comparison at one hundred locations in all oceans is presented, which may allow first conclusions on the overall skill of GRACE to observe ocean mass variability. Significant differences between different GRACE solutions and different regions are discussed.

2 Data

2.1 In-Situ Ocean Bottom Pressure

OBP is measured in-situ by instruments deployed at the sea floor for time periods of up to several years. Typically, the resonance frequency of a piezo crystal which is deformed by the ambient pressure is measured and converted into pressure data. The widely used pressure sensors from Paroscientific, for example, achieve a resolution of 0.001 dbar (University of Rhode Island, 2006). (1 dbar $= 10^4$ Pa, equivalent to ≈ 1 m of water column). Thus, short-term pressure anomalies corresponding to a change of 1 mm in sea surface height are detectable. A significant issue is, however, the long-term stability of these pressure sensors. A sensor drift of 0.1 dbar, and in some cases up to 1 dbar, occurs in many deployments, and needs to be corrected to allow a proper comparison with GRACE, which will be explained below.

For this study, all available in-situ OBP time series were collected from cooperating institutes and fed into an OBP database at AWI. At present (February 2009), the database comprises 168 data sets from 152 deployments at about 100 different locations, covering the mission period of GRACE from 2002 to present. The length of most time series is between 1 and 2 years; in total, about 200 years of OBP observations are available. Table 1 gives an overview of the data; the positions are shown in Fig. 2 in the following section.

Most deployment sites primarily serve oceanographic purposes, e.g. observation of meridional overturning circulation (MOVE, RAPID), monitoring of ocean current variability (e.g. in Drake Passage or the Kuroshio extension) and inter-basin fluxes (e.g. Fram Strait), or detection of tsunami waves (DART). In a few projects, a 2-dimensional layout of the mooring sites was specifically chosen to aid

Table 1 Data inventory of the in-situ OBP database at AWI. The site number and time span refers to the data presently available in the database; in some cases, more recent data are not yet publicly available and will be included later. An "x" in the timespan marks ongoing projects where further data is expected in the future. References are either project websites or relevant publications

Project	Area, number of deployment sites, duration	Institution, contact person; reference
GRACE/AWI	ACC, 2D-array, 9 sites, 2002–2008 + x	AWI, Olaf Boebel
DAMOCLES	Fram Strait, 79°N, 6 sites, 2003–2008 + x	AWI, Agnieszka Beszczynska-Möller
KESS	Kuroshio Extension, 2D-array, 46 sites, 2004–2006	URI, Randy Watts; Park et al. (2008); http://uskess.org/
"Kerguelen"	Southern Ocean near Kerguelen, 2 sites, 2002–2004	CNES, Pascal LeGrand; Rietbroek et al. (2006)
MOVE	Atlantic at 16°N, 2D-array, 6 sites, 2002–2008 + x	IFM-GEOMAR, Johannes Karstensen; SIO, Uwe Send; Kanzow et al. (2005)
DART	Pacific tsunami early warning system, 15 sites, 2002–2005 + x	NOAA, Christian Meinig; http://www.ndbc.noaa.gov/
POL/ACCLAIM	Drake Passage and ACC, 10 sites, 2002–2005	POL, Chris Hughes; http://www.pol.ac.uk/psmsl/programmes/acclaim.info.html
RAPID	Atlantic at 24–27°N, 10 sites, 2004–2005 + x	NOC, Stuart Cunningham, Robin McCandliss; http://www.noc.soton.ac.uk/rapid/rapid.php

the comparison with GRACE, since a 2-D array captures large-scale coherent OBP variability (which is observed by GRACE) better than single points or lines of moorings. Namely the MOVE, KESS and AWI/ACC arrays represent this dedicated 2-D pattern.

So far, the database is used in this project for GRACE/in-situ OBP validation, as well as for validation of ocean tide and ocean circulation models (see next chapter in this volume). For the future, public access to the database is planned.

An essential issue before using the in-situ for an automatic correlation analysis with all GRACE products is a homogenization of the many different data formats, and quality control to eliminate measurement errors. Following, all steps that were performed before the GRACE validation are explained:

(1) *Data format:* The OBP time series from different institutes come in all kinds of formats. The data were converted to a uniform format allowing an automatic data processing of all deployments.

(2) *Quality control*: Outliers and other obvious errors like zero values from the surface at begin and end of a deployment, were removed. The most critical issue, however, is the sensor drift introduced above (Fig. 2). Typically, the drift is largest during the first weeks and months of a deployment, and reduces to a slower drift during later part of a time series. The nonlinear trend prohibits a

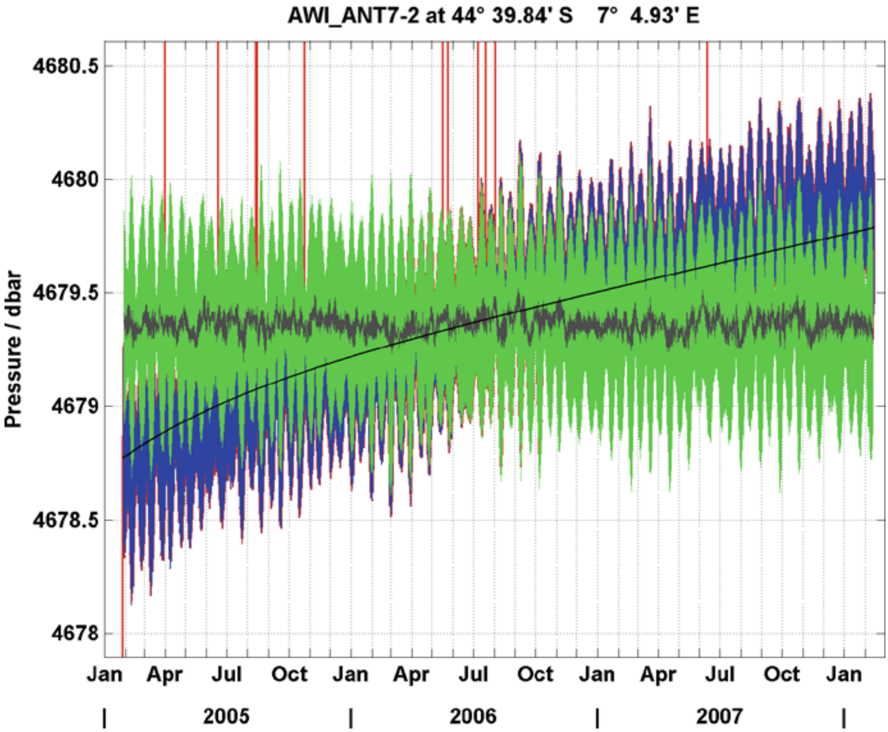

Fig. 2 Example of in-situ ocean bottom pressure, here at location ANT7 in the AWI-operated ACC array at 45°S 7°E. *Black* shows uncorrected raw data, with single outliers. A drift of 1 dbar over the period of 3 years is visible. The *black line* depicts the empirical fit function and *light grey* the resulting de-drifted time series. *Dark grey* marks the de-drifted and de-tided time series used to calculate monthly averages for GRACE validation

linear interpolation between pre- and post-deployment calibrations (if these are available at all). Therefore, sensor drift was eliminated by an exponential-linear fit function empirically determined with a least squares fit (e.g. Kanzow et al., 2006; Park et al., 2008), after the time series were first de-tided evaluating the FES2004 tide model (Lyard et al., 2006) at the deployment location. Finally the tides were re-added to retain the originally observed short term tidal variability. The de-tiding, however, avoids the possibility that the fit function itself is influenced by tides. A downside of the drift correction is, that information of longperiodic pressure signals and trends is lost. Hence in most cases no conclusions about interannual oceanic variability or deformation of the ocean floor related to e.g. Glacial Isostatic Adjustment can be obtained from in-situ OBP observations, since normally the sensor drift is much larger (0.1–1.0 dbar/year).

Small gaps in the time series (shorter than the periods of the semidiurnal tides) and other short-term errors were interpolated. Longer gaps often imply that the remaining time series are effectively separated, since "jumps" in the pressure values can be related to either sensor drift in the meantime, or real, e.g. seasonal variability, or both. Time series too short to calculate several consecutive monthly means are hence not compared with GRACE, since the correlations become insignificant with only 2 or 3 data points.

(3) *Final time series:* For a comparison with GRACE, the FES2004 tides are subtracted from the de-drifted in-situ time series. From this data set, monthly averages are calculated over the same time periods as in the GRACE data set. Tides need to be removed since GRACE represents monthly averages of a de-tided ocean (see next subsection). Instead of an empirical tidal fit (which could easily be calculated from any in-situ data), the FES2004 model was used here, since FES2004 is also used for de-tiding in GRACE data processing (chapter "The Release 04 CHAMP and GRACE EIGEN Gravity Field Models" by Flechtner et al., 2010a). Any errors in the tide model would influence GRACE, but not the in-situ data if these were de-tided with a "perfect" empirical fit. Nevertheless, tides may still have different effects on in-situ and GRACE data: Due to the frequent sampling of in-situ instruments, short period tides are perfectly averaged in monthly means, only long-periodic tides (fortnightly and longer) may cause aliasing if not properly modelled by FES2004. In contrast, the short period tides play a major role for GRACE, which has a lower sampling rate (see below).

2.2 GRACE

The GRACE gravity field solutions analysed here are provided by the SDS data centres CSR, GFZ and JPL as well as ITG and GRGS as monthly (or shorter) temporal averages. The science data system (SDS) "standard" products consist of a monthly geoid GSM, and the monthly averages of the non-tidal de-aliasing models GAx. For ocean bottom pressure, GAC, and – in newer releases – the special OBP-optimized GAD product which mostly eliminates land signals is recommended (Flechtner, 2007). Ocean tides, that produce large, but regular short-term OBP fluctuations and hence orbit disturbances, are de-aliased by the FES2004 tide model (chapter "The Release 04 CHAMP and GRACE EIGEN Gravity Field Models" by Flechtner et al., 2010a). Thus, the full solution for bottom pressure in a tide-free ocean is given by

$$\mathbf{OBP} = \mathbf{GSM} + \mathbf{GAC/D}$$

The GAC/D values represent monthly averages of the OBP variability predicted by the non-tidal de-aliasing OMCT model (Dobslaw and Thomas, 2010; chapter "Improved Non-tidal Atmospheric and Oceanic De-aliasing for GRACE and SLR Satellites" by Flechtner et al., 2010b). The residual de-tided variability measured by the satellites which is not explained by the FES2004 and OMCT models constitutes the GSM field.

Both the GSM+GAx and the GSM or GAx fields alone, respectively, were compared with in-situ OBP to evaluate the skill of GRACE to capture oceanic mass redistribution realistically. This allows also to assess whether good (or poor) agreement between in-situ and GRACE measurements at a specific location is a result of good (or poor) de-aliasing models, or the actual satellite observations given by the sum of GSM and GAx fields. The comparison of earlier and more recent releases allows to quantify advances made due to improved data processing and de-aliasing model. Further, in months with poor GRACE data coverage, both constrained and unconstrained solutions are analysed.

Additionally to the CSR, GFZ and JPL fields, GRACE solutions from ITG and GRGS were analysed. The ITG fields represent a different computational approach with gravity fields calculated from short arc intervals instead of modelling the satellite orbit over longer timespans. Further, the ITG Spline solution describes the temporal variability using smooth quadratic spline functions instead of monthly means (Mayer-Gürr et al., 2006). Here, however, monthly averages of the spline functions are taken, reducing the effects of potential errors from short term tide-de-aliasing in both GRACE and in-situ data. The GRGS fields, finally, are provided in 10-day intervals, using overlapping weighted 30-day means (Lemoine et al., 2007). The higher temporal resolution allows to capture shorter-term OBP variability, although the reduced number of satellite orbits may potentially increase the noise level, and tide de-aliasing becomes more critical.

For a complete overview, all GRACE products used in this study are listed in Table 2.

Table 2 GRACE products included in this study. In all cases, all available combinations, i.e. GSM only, GAC/D only, GSM+GAC and GSM+GAD were evaluated. For references, see text

Data centre	Releases	Products	Remarks
CSR	01, 02, 04	GSM, GAC, GAD (Rel. 04 only)	Monthly means
GFZ	03, 04	GSM, GAC, GAD (Rel. 04 only)	Monthly means
JPL	02, 04, 04.1	GSM, GAC, GAD (Rel. 04.1 only)	Monthly means
GRGS	2006, 2007		10-day timeaxis
ITG	02, 03	GSM, GAC, GAD (Rel. 03 only)	Monthly means, rel. 03 based on quadratic splines

For a uniform representation, all GRACE fields were expanded from degree and order 2 to 50 (ITG: 2–40). A 750 km Gauss filter was applied to mostly eliminate meridional striping and other unrealistic artifacts. This spatial filter scale represents a reasonable compromise between high resolution and noise-reduction, and is comparable with filter scales used in other studies comparing GRACE and in-situ OBP (Kanzow et al., 2005; Rietbroek et al., 2006).

A full analysis that would include the effects of different degree and order expansions, Gauss filter radii and advanced non-isotropic (Swenson and Wahr, 2006) and pattern filters (Böning et al., 2008), is planned for the near future (Böning and Macrander, in preparation). That study will also include fine step temporal evolution of the ITG Spline solutions, Mascon solutions provided by JPL which represent a completely different approach, modelling discrete mass concentrations on Earth's surface, and the recent weekly fields provided by GFZ (chapter “The Release 04 CHAMP and GRACE EIGEN Gravity Field Models” by Flechtner et al., 2010a), which may better capture short-term variability.

3 Methods

The skill of GRACE to realistically capture OBP variability was assessed with a correlation analysis. The de-tided in-situ OBP time series were time-averaged corresponding to the considered GRACE product, and correlated with GRACE. For averaged estimates over several in-situ sites, correlations were weighted with time series length, since longer time series attain higher significance levels of correlations while correlations calculated from short time series spanning a few months only are hardly meaningful. Additionally to the correlations, the amplitude of variability was compared, since particularly in regions with a significant seasonal cycle, correlations can be high, even though GRACE may greatly overestimate the actual variability.

4 Results

A first view on the comparison of in-situ OBP with GRACE reveals moderate to good correlations at many, but not all locations of the OBP database. Figure 3 shows the results for the recent GFZ release 04 GSM+GAD solution. Particularly in the tropical Atlantic, coastal northern Pacific and in Drake Passage, some sites with weak or negative correlations are found, whereas in higher latitudes correlations are normally higher than 0.5, reaching values of up to 0.9.

Following, the different regions will be considered in more detail, including both correlation and amplitudes of variability for different GRACE solutions. Characteristic features will be shown in selected time series which are typical for each region, before an integrated comparison of all sites with all GRACE solutions is discussed.

(1) *Southern Ocean*: The Antarctic Circumpolar Current (ACC) is the largest current of the oceans, carrying about 130 Sv ($1\ \text{Sv} = 10^6\ \text{m}^3/\text{s}$) around the Antarctic Continent (Orsi et al., 1995; Swart et al., 2008). Its strong barotropic component, and coherent OBP variability observed along the Antarctic coast (Hughes et al., 2003; chapter “On the Representation of Transport Variability of the Antarctic Circumpolar Current in GRACE Gravity Solutions and Numerical Ocean Model Simulations” by Böning et al., 2010) imply a high signal amplitude to be detected by GRACE. In fact, GRACE GFZ release 04 GSM+GAD and other GRACE solutions display increased oceanic RMS variability in the Southern Ocean, reaching 0.05 dbar (corresponding to 5 cm of sea level change) on monthly timescales (Fig. 1), which is comparable with in-situ observations.

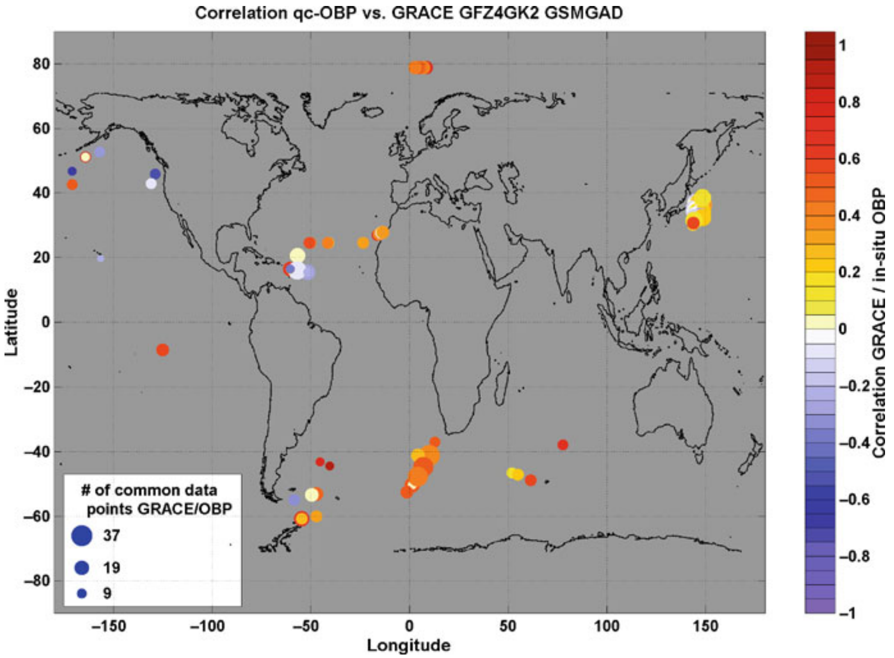

Fig. 3 Correlation of in-situ OBP with GRACE GFZ Release 04 GSM+GAD; constrained GRACE solutions were used for months with incomplete GRACE raw data. Colour of *dots* depicts correlation level, the dotsize corresponds with the length of the time series in months. Correlations with in-situ time series shorter than 5 months are not shown

Since 2002, up to 9 pressure sensors were deployed by AWI in the Atlantic sector of the Southern Ocean in a 2-dimensional pattern to detect large scale coherent OBP variability which was also found in the numerical FESOM ocean model (chapter "On the Representation of Transport Variability of the Antarctic Circumpolar Current in GRACE Gravity Solutions and Numerical Ocean Model Simulations" by Böning et al., 2010). The region is also far away from continents, where leakage effects from the hydrological cycle might degrade the GRACE solutions.

Indeed, both phase and amplitude of GRACE agree comparatively well with the in-situ time series (Fig. 4a shows an example from site ANT7). Further, some advances are evident for the recent GFZ release 04 (GSM+GAD; correlation coefficient $r = 0.56$) vs. release 03 (GSM+GAC; $r = 0.50$). The GAD de-aliasing model alone, however, shows much smaller variability than actually observed both by GRACE and the in-situ instrument and a lower correlation ($r = 0.31$).

Comparing the correlations of all GRACE products with all ACC array moorings (Fig. 4b), CSR performs slightly better than GFZ solutions. While for the GFZ products, the weighted average correlations changed

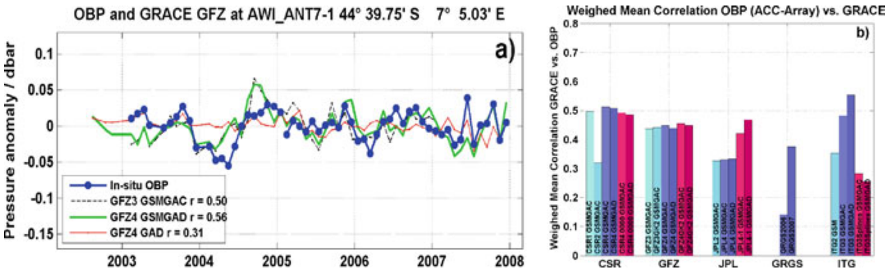

Fig. 4 (**a**) In-situ OBP time series at site ANT7 (45°S 7°E) in the ACC array (*blue*), and different GRACE GFZ products (*dashed black*: release 03 GSM+GAC; *green*: release 04 GSM+GAD; *red*: GAD only). Correlation coefficients are 0.50, 0.56 and 0.31, respectively. (**b**) Averaged correlations for all ACC array moorings, grouped according to GRACE products. From *left* to *right*: CSR: releases 01, 02 GSM+GAC (*light blue*); release 04 GSM+GAC, GSM+GAD (*blue*); release 04 with constrained solutions GSM+GAC, GSM+GAD (*magenta*). Similarly, the second group depicts GFZ rel. 03 and 03 constrained (*light blue*), 04 GSM+GAC, GSM+GAD (*blue*), 04 constrained GSM+GAC and GSM+GAD (*magenta*). Third group JPL rel. 02 (*light blue*), 04 (*blue*), 04.1 (*magenta*). Fourth group: GRGS (2006, 2007). Last group ITG rel. 02 (*blue*), 03 (monthly means) GSM+GAC, GSM+GAD (*magenta*)

little from release 03 to 04 (the improvements here are mainly due to reduction of noise amplitude; not shown), the JPL solutions improved significantly from releases 02 and 04 to 04.1. Recent GRGS and especially the monthly averages of the ITG release 03 spline solutions perform quite well in this region. At some individual sites – depending on their position relative to oceanic fronts which separate different regions of coherent OBP variability – correlations reach 0.7 for 750 km Gaussian filter. Advanced filtering techniques like the ocean-model derived pattern filter achieve even better correlations (Böning et al., 2008). The generally good agreement of GRACE and in-situ OBP time series of the ACC array is corroborated by a study of Rietbroek et al. (2006) in the Kerguelen region, which showed high correlations, here for the 10-day GRGS solutions.

(2) *Fram Strait*: Located between Greenland and Svalbard, Fram Strait represents the deepest connection between the Atlantic Ocean and the Arctic Mediterranean. GRACE observes strong OBP variability (O(0.05 dbar)) in the Arctic (Fig. 1). At 79°N, several pressure sensors are operated since 2003 to monitor the exchange of water masses between both basins. From all regions analysed in this study, Fram Strait exhibits by far the best agreement between in-situ OBP and GRACE.

During 4 years of mooring deployments at the F8 site, GRACE GSM+GAC/D closely follows the observed in-situ OBP (Fig. 5a). In this example, the average correlation is 0.73 (GFZ release 03), but over individual deployments in the entire Fram Strait array, correlations better than 0.9 are reached regularly.

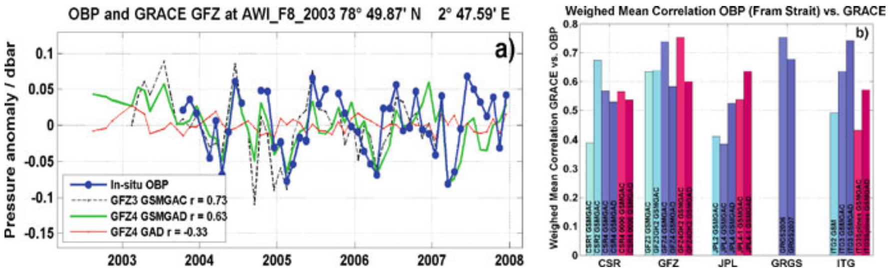

Fig. 5 (**a**) In-situ OBP time series at site F8 (79°N 3°E) in Fram Strait (*blue*), and different GRACE GFZ products (*dashed black*: release 03 GSM+GAC; *green*: release 04 GSM+GAD; *red*: GAD only). Correlation coefficients are 0.73, 0.63 and –0.33, respectively. (**b**) Averaged correlations for all Fram Strait moorings. For explanation, see legend of Fig. 4b

The figure shows also, that the GAC/D de-aliasing models alone do not capture the observed variability – hence, the actual satellite measurements are necessary, and not just good models.

The high correlation is found for all GRACE solutions (Fig. 5b), with the best results obtained by the GFZ RL04 GSM+GAC, GRGS and ITG RL03 GSM+GAD solutions. As in the Southern Ocean, the JPL solutions exhibit the largest improvements from early to recent releases. Interestingly, the GSM+GAC fields of GFZ (but not CSR and JPL) are slightly better than the OBP-optimized GSM+GAD solutions – obviously GAD does not always improve the results. Nevertheless, GRACE shows almost perfect skill to observe oceanic mass variability in Fram Strait; this agrees also with central Arctic Ocean OBP studied by Morison et al. (2007).

(3) *Subtropical north Atlantic*: As part of the MOVE and RAPID projects, several of OBP sensors are deployed at 16°N and 26°N to monitor the Atlantic meridional overturning circulation. The MOVE array was extended to a 2-dimensional layout to capture coherent OBP variability, which is observed by GRACE. Kanzow et al. (2005) showed that GRACE greatly overestimated the annual cycle of OBP. These findings are still true: Despite unrealistic annual cycles were significantly reduced in some recent GRACE releases (e.g. from GFZ, less so in e.g. JPL), the correlations of GRACE with in-situ OBP are still small (Fig. 6). In some cases, the GAC/D de-aliasing models alone perform even better than the full GSM+GAC/D solutions. Apparently, the small signal amplitude (O(0.01 dbar)) and the wider spacing of satellite groundtracks in low latitudes make realistic observations of oceanic mass variability with GRACE more challenging. A particular artifact of many GRACE solutions (especially CSR, JPL, ITG) is a northward extension of the hydrologic signal from South America. Its annual cycle is evident in e.g. the JPL solutions shown in Fig. 6b.

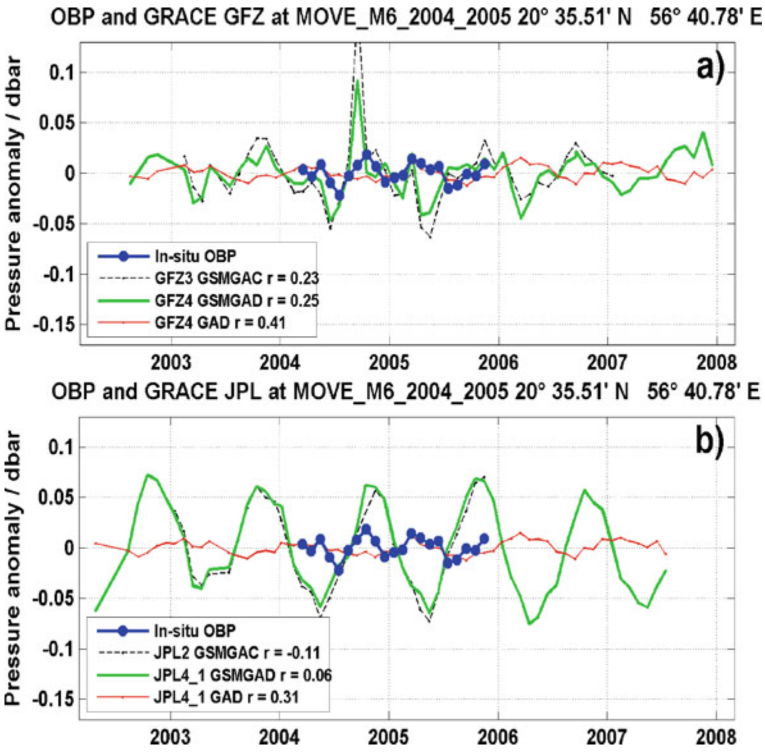

Fig. 6 (**a**) In-situ OBP time series at site M6 (near 21°N 57°W) of the MOVE array (*blue*), and different GRACE GFZ products (*dashed black*: release 03 GSM+GAC; *green*: release 04 GSM+GAD; *red*: GAD only). Correlation coefficients are 0.23, 0.25 and 0.41, respectively. (**b**) As above, but for JPL releases 02 and 04.1. Correlations are –0.11, 0.06 and 0.31, respectively. Note the large annual cycle in the JPL GSM+GAx solutions, which is likely affected from South America hydrology

At 26°N (RAPID array), correlations appear to be somewhat better (not shown, but c.f. Fig. 7 later), but here, only 1-year long time series were investigated in this study, with some higher correlations resulting from annual cycles of both in-situ and satellite data in phase, even though amplitude and short-term variability are still quite different.

(4 and 5) *Coastal north east Pacific; Drake Passage*: In these regions covered by the DART tsunami early warning system, and oceanographic moorings collected in the POL database, respectively, GRACE/in-situ OBP correlations differ from one station to the next. Some time series are in excellent agreement, suggesting, that GRACE generally captures OBP variability also in these regions quite well. Nevertheless, these regions require further investigations since at some positions GRACE data might be influenced by leakage of continental signals, and some positions in areas with highly localized variability may be not well sampled with the 750 km

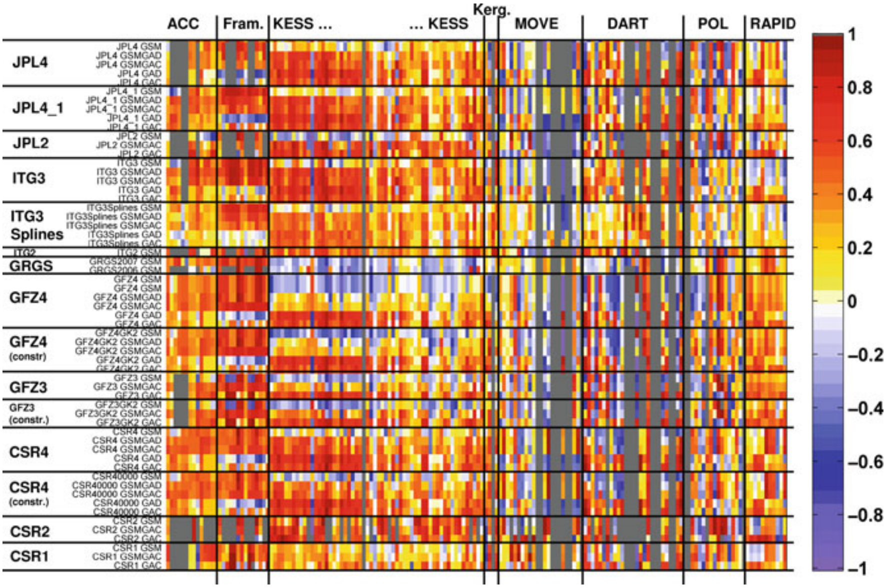

Fig. 7 Checkerboard plot showing correlation of in-situ OBP (x axis) with all different GRACE products (y axis). OBP sites are grouped according to Table 1. Only time series with more than 5 common data points with at least one GRACE solution are plotted. For clarity the 155 individual site names of these time series are not shown here. GRACE products are grouped into data centre/release. In each group, GSM-only constitutes the *top row*, followed by GSM+GAC (and GSM+GAD in recent releases) as "official" OBP products. The *bottom rows* of each group are the GAC (and GAD) de-aliasing models alone. Colour denotes correlation from +1 (*dark red*) to –1 (*blue*). *Grey* fields mark where GRACE and in-situ time series have not enough overlap (less than 5 common data points). This is the case where early GRACE releases are discontinued before the start of certain OBP time series, or in case of some short-term deployments or data gaps due to instrument problems

Gaussian filter used in this study. Böning et al. (2008) showed significant improvements using an ocean-model derived pattern filter technique to select the region for which each in-situ instrument is representative. Finally, all in-situ time series need to be cross-checked again to ensure that all measurement errors are corrected as good as possible.

(6) *Kuroshio extension*: In this highly energetic western boundary current, an extensive array of pressure sensors was deployed in the framework of the KESS experiment. Park et al. (2008) found good agreement between in-situ and GRACE data (GFZ, and especially CSR, JPL), particularly in the northern and western part of the array. This underlines that a point measurement (in-situ) may or may not be representative for a larger region sampled by the spatially averaging GRACE data.

Overview: Space does not allow here to discuss each of the 168 in-situ time series and the 53 GRACE products and combinations in detail. After the introduction of six characteristic regions sampled by in-situ instruments, an overview of the comparison of all in-situ data with all GRACE data is given below. At first glance, the full picture showing all correlations (Fig. 7) is somewhat confusing, but it shall be attempted to indentify the key features: In the high-latitude ACC and Fram Strait arrays, all GRACE releases agree well with the in-situ observations. Generally, the best correlations are achieved by the GSM only, or the GSM+GAC/D fields, suggesting that the monthly oceanic variability is mostly captured by the satellites, but not the de-aliasing models. This is particularly the case in the 79°N Fram Strait array. In contrast, the de-aliasing models are clearly necessary in the Kuroshio extension, where almost all GRACE GSM+GAC/D solutions perform well, but not the GSM-only fields. The GFZ solutions are the only ones in the Kuroshio extension that show considerably lower correlations – whereas in the subtropical Atlantic at 26°N (RAPID) GFZ provides the comparatively best solutions. North east Pacific (DART) and Drake Passage (POL) reveal mixed results as discussed above. Nevertheless, JPL and ITG appear to be slightly better in the north east Pacific, while GFZ better captures Drake Passage.

5 Summary and Conclusions

Summarizing the results of the comparison of all different GRACE products with all OBP time series, some characteristic features can be found, whose background (e.g. de-aliasing, spatial scales of OBP variability) require further investigations. The key findings are:

(1) Recent vs. early GRACE product releases: Generally, more recent GRACE releases appear to be better than early ones. This is mostly evident in the reduction of unrealistically large annual OBP cycles and leakage effects of continental variability into the oceans. Nevertheless, the increase in actual correlation between in-situ time series and GRACE is often small. Further, the OBP-tailored GAD product does not always improve the correlations when compared with GAC.

(2) "Good regions": In some regions, particularly in the Southern Ocean (ACC array, Kerguelen) and the Arctic Ocean (Fram Strait), all GRACE solutions agree well with in-situ observations both in amplitude and phase. Further, the high correlation levels of GSM+GAx vs. in-situ OBP are mainly achieved by the GSM contribution, and not by the GAx de-aliasing models alone. This implies, that the actual satellite observations are necessary to determine the real oceanic variability. Generally, GRACE appears to realistically capture OBP variability in higher latitudes.

(3) "Partially good regions": In other parts of the oceans, correlations in-situ OBP vs. GRACE disagree among different GRACE products. For example, in the subtropical Atlantic at 26°N (RAPID array), GRACE solutions from GFZ generally reach the best correlations. The same holds for several GAC/D de-aliasing models, but *not* for the GSM geoids. Obviously, the numerical models capture

at least some of the OBP variability in low-latitude regions (e.g. the annual cycle), but the actual satellite observations degrade the final solution. This is in marked contrast to the high-latitude regions mentioned above. Another example is the Kuroshio extension in the Pacific Ocean – here, JPL and CSR perform quite well, but not GFZ (Park et al., 2008). Further, the GRGS solutions, which show excellent skill in the ACC array, Kerguelen region (Rietbroek et al., 2006) and Fram Strait, attain only weak or even negative correlations in the Kuroshio extension.

(4) "Problematic regions": All GRACE solutions exhibit low correlations with in-situ OBP in the tropical Atlantic at 16°N (MOVE, Kanzow et al., 2005) where signal amplitudes are very small, and leakage from South America hydrology is found in many GRACE solutions. Also in areas with strong small-scale variability like in parts of the Drake Passage or different sites close to coastlines in the Pacific (DART), correlations are either weak, or completely different from one site to the next.

The good skill of GRACE in high latitudes conforms with the denser sampling pattern due to the polar satellite orbits, and the generally higher signal amplitudes in polar oceans, which are mostly barotropic, in contrast to lower latitudes, where OBP variability is smaller, with warm surface and abyssal layers mostly decoupled. The poor skill in some areas with localized variability and coastal regions can be attributed to the small spatial scales which are not captured by GRACE. More challenging, however, are the remaining, "partially good" regions: Obviously, data processing and de-aliasing models play a major role in defining the skill of GRACE to realistically observe OBP variability. But, the "best" solution or model does not exist so far – products that perform well in one region, are poor in another part of the ocean, where a different GRACE product is better. The irregular distribution of "good" and "poor" regions makes it also impossible to guess how realistic a particular GRACE solution is elsewhere in the ocean, where no in-situ ground truth observations exist.

A continued global validation of GRACE offers the perspective to further improve GRACE data processing, and, in particular, tidal and non-tidal de-aliasing. Therefore, the AWI OBP database is continuously extended as more recent observations become available. Automatic validation tools are under development to allow a rapid assessment of improvements or degradations achieved by new GRACE products. A full analysis of GRACE/in-situ OBP correlation will include the effects of different degree/order expansions, recognition of characteristic geographic or temporal patterns in the correlations, and their dependence on tidal de-aliasing and filtering mechanisms such as Gaussian, anisotropic and ocean-circulation model aided pattern filter (Böning et al., 2008). Also, a validation of the temporal evolution of spline solutions, "Mascon" solutions of GRACE, which are based on a completely different approach to gravity field variations, and weekly GRACE solutions, which capture more short-term variability while reducing spatial resolution, will provide interesting results.

Until a GRACE solution is found which shows good skill at all ground-truth sites OBP remains a challenge for GRACE, and hence the validation of GRACE with in-situ observations is essential for realistic estimates of oceanic mass redistribution.

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