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Analysis of gravity field variations derived from Superconducting Gravimeter recordings, the GRACE satellite and hydrological models at selected European sites

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If we restrict the spatial resolution to a half-wavelength of about 1500 km and the temporal resolution to 1 month, GRACE-derived temporal gravity variations can be resolved within the μgal (10^{-8} m/s^2) range. A comparison with ground gravity measurements from selected Superconducting Gravimeter (SG) stations forming the Global Geodynamics Project (GGP) provides an independent validation. For this study, five European SG-stations were selected that both cover a large test field and allow closely located SG-stations to be studied. Prior to this comparison, GRACE and SG data sets have to be reduced for the same known gravity effects due to Earth and ocean tides, pole tide, and atmosphere. After these reductions, the remaining part can be mainly attributed to mass changes in terrestrial water storage. For this reason, gravity variations derived from global hydrological models are included in the comparison of SG and GRACE results. Conversely, the hydrology models can be checked by gravity variations determined from GRACE and SG observations. For most of the SG locations investigated here, the comparison based primarily on computed correlations shows quite a good agreement among the gravity variation derived from the three different kinds of data sets: SG, GRACE, and hydrology models. The variations in SG gravity (point measurements) prove to be representative for a large area within the μgal accuracy range, if local gravity effects are removed correctly. Additionally, a methodology for an analysis of dominant common features based on the EOF-technique is proposed and illustrated. The first principal component shows strong periodicity, and the search for arbitrary periods confirms a strong common annual component, which reduces the total signal content considerably. The first eigenvector reveals common features and differences between distinct SG stations. Discrepancies between SG, GRACE, and hydrology models at individual SG stations, detected by both methods, may provide valuable hints for further investigations of respective data series.
Key words: Superconducting gravimetry, GRACE, temporal gravity variations, hydrological models, cross validation, correlation, EOF.

1. Introduction

The new-generation satellite gravity mission GRACE (Tapley and Reigber, 2001) shows a gravity resolution in the μgal (10^{-8} m/s^2) range at a half wavelength $\lambda/2$ spatial resolution of about 1500 km for a temporal resolution of 1 month (Schmidt *et al.*, 2005). Because of this remarkable recovery of temporal Earth gravity field variations, the comparison of satellite-derived temporal variations in gravity with ground gravity measurements is of fundamental interest. Since the time variations contained in the GRACE solutions range from 1 month to the life time of GRACE, terrestrial gravity measurements must have a long-term stability, which can be fulfilled only by Superconducting Gravimeters (SG) (Goodkind, 1999).

The recovery of GRACE-derived gravity variations is based on monthly averages of the time-varying gravitational potential (see Section 2.1). A special method for calibrating formal errors of monthly solutions is applied (Schmidt *et al.*, 2005). Figure 1 shows these calibrated errors as functions of the degree of spherical harmonic coefficients. With increasing degree, the spatial resolution becomes finer, but the error increases. Comparing the magnitudes of the calibrated errors of the monthly GRACE solutions with the signal amplitudes of monthly gravity variations derived from a hydrological model shows that the cumulated error (Fig. 1, dotted lines) reaches the level of the hydrology signal at about degree $\ell = 16$, and the error per degree (solid line) reaches the level of the hydrology signal per degree at $\ell = 10$. Hence, to ensure that the GRACE errors are smaller than the expected hydrology effect, the GRACE and hydrology models have to be filtered appropriately. Table 1 summarizes roughly the GRACE parameters for spatial resolutions of 500 km and 2000 km in comparison with the SG.

High-precision gravity measurements on the Earth's surface are carried out with SGs of the Global Geodynamics Project (GGP) network (Crossley *et al.*, 1999). These mea-

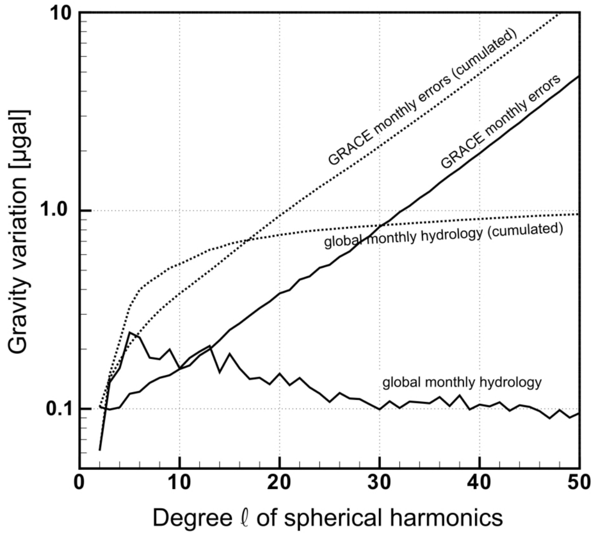

Fig. 1. Calibrated errors of the GRACE monthly solutions and gravity variations derived from the hydrology model (WGHM) (Döll *et al.*, 2003) as functions of degree ℓ of spherical harmonics. Errors of monthly solutions per degree (solid line) and as function of maximum degree (dotted) are shown.

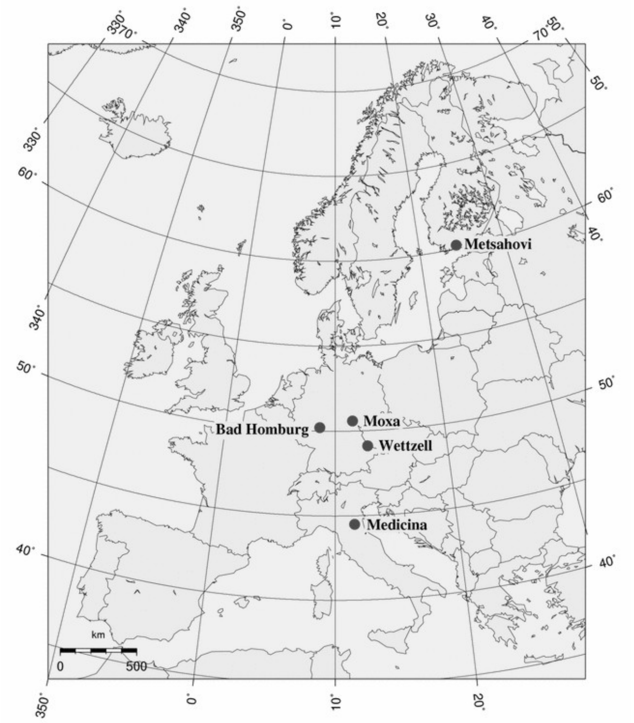

Fig. 2. Location of the considered Superconducting Gravimeter (SG) sites.

Table 1. Performance parameters of GRACE and Superconducting Gravimeter (SG).

	GRACE		SG
Gravity resolution	10 μgal	0.5 μgal	0.1 μgal
Spatial resolution $\lambda/2$	500 km	2000 km	Point
Sph. harm. coefficient	$\ell_{\max} = 40$	$\ell_{\max} = 10$	—
Temporal resolution	1 month		10 sec
Long term stability (drift)	no drift		$\sim$3 μgal/year

surements have a gravity resolution of about 0.1 μgal in the time domain and a linear drift of some μgal per year (Table 1).

For a comparison of satellite-derived temporal gravity variations with ground-measured ones, both data sets (after pre-processing and the reduction of known gravity effects) should represent the same sources of gravitation at the same spatial resolution. One question to be answered is "How representative are the SG point measurements for an area with a diameter of approximately 1500 km, which is the spatial half-wavelength resolution of the GRACE satellite-derived temporal gravity variation?". Previous comparisons between temporal gravity variations derived from SG and CHAMP satellite observations (Neumeyer *et al.*, 2004a) inferred that the SG gravity variations are valid for a large area within the μgal accuracy if the local gravity effects are carefully removed. Subsequent studies confirmed the quality of gravity field variation measurements with SGs in Europe (Crossley *et al.*, 2005). With the increasing gravity and spatial resolution of GRACE solutions (Reigber *et al.*, 2005; Schmidt *et al.*, 2005), this kind of comparison is being studied in more detail with a worldwide selection of SG-stations (Neumeyer *et al.*, 2006).

The study reported here presents a comparison with time-series of the SG GGP network during a period of 3 years; this network covers a large test field and also enables closely located SG-stations to be studied. Underground stations from the GGP network were not included because of the difficulty in modeling the local hydrological effects above the gravimeter (with one exception, the Moxa station, to illustrate the problem). For this study, five European SG-stations were selected (see Fig. 2) that both cover a large test field (maximum distance between two SG-stations of almost 2000 km) and allow closely located SG-stations (minimum distance less than 200 km) to be studied. The selected stations are:

- Medicina/Italy (MC): $\phi = 44.5219°$, $\lambda = 11.645°$, $h = 28$ m
- Bad Homburg/Germany (BH): $\phi = 50.2285°$, $\lambda = 8.6113°$, $h = 190$ m
- Moxa/Germany (MO): $\phi = 50.645°$, $\lambda = 11.616°$, $h = 455$ m
- Wettzell/Germany (WE): $\phi = 49.144°$, $\lambda = 12.878°$, $h = 580$ m
- Metsahovi/Finland (ME): $\phi = 60.217°$, $\lambda = 24.396°$, $h = 56$ m.

A comparison between satellite-derived temporal gravity variations and ground-measured ones requires representative data sets with the same sources of gravitation and comparable spatial resolutions. This can be achieved by:

- reducing the same known gravity effects in both data sets using the same models
- adapting the SG gravity variations to the spatial resolution of the satellite
- considering the effects that are unique to each method.

When located on the Earth's surface, a SG measures, in addition to the gravitational mass attraction, the gravity effect due to elastic deformation (vertical surface shift) (e.g. Pick *et al.*, 1973; Vanicek and Krakiwsky, 1982) and the deformation potential (mass redistribution due to vertical surface shift). In contrast, a satellite is not coupled to the Earth's surface and hence only sensitive to the change in potential. The part resulting from the change of location of the SG due to a deformation is sensed by the SG only. The reductions of the Earth tides and pole tide, as well as the loading effects of the atmosphere and hydrosphere, are different for SG and GRACE; body Love numbers and load Love numbers, which describe the height variations, are only relevant for the processing of SG data.

After the known effects have been reduced, the spatial resolution for the remaining gravity variations is still different for SG (point measurements) and GRACE (spatial resolution of between 1000 km and 2000 km used in this study). The SG measurements include all gravity variations from short- to long-periodic spatial distribution. For comparison purposes, only the gravity variations related to the spatial resolution of GRACE should be taken into account. The present approach for adapting the remaining SG gravity variations to the spatial resolution of GRACE consists of removing the local gravity effects, mainly induced by local hydrology, from SG data.

The following data sets were used for this study: GRACE monthly gravity field solutions, SG recordings, three-dimensional (3D) air pressure variations, groundwater level variations measured at SG sites, and gravity variations derived from hydrology models within the time period from February 2003 to December 2005.

The aim of this study is the validation of the GRACE results, checking of the SG data pre-processing and reduction procedures, checking of gravity variations derived from hydrological models, and an analysis of the dominant common features of all three data sources.

2. Preparing the Gravity Variations for Comparison

Before SG- and GRACE satellite-derived gravity variations can be compared, the measurements must be reduced for the same gravity effects that have been applied in the GRACE data processing. These effects are:

- Earth tides
- pole tide
- gravity variations induced by the atmosphere
- ocean tidal loading.

The same models are used for both sets of gravity variations to reduce these effects. Additionally, the load-induced height variations contained in the SG measurements are added to the monthly GRACE solutions (see Section 2).

2.1 Improved monthly gravity field solutions from GRACE

In this study, the recent time-series of monthly GRACE-only models provided by GFZ Potsdam is used (available at GFZ Information System and Data Centre (ISDC; http://isdc.gfz-potsdam.de/grace) or at the International Centre for Global Earth Models (ICGEM; http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html)). This series is labeled Release 03 (RL03) in the product history of monthly GRACE-only gravity field models generated at GFZ. It currently consists of 41 monthly models in the period February 2003 to August 2006 (used in this study until January 2006). The fields for June 2003 and January 2004 are missing due to limitations in the amount of useable data in these 2 months. The available models are expanded up to degree and order 120.

General aspects of the gravity recovery from GRACE can be found in Reigber *et al.* (2005), Schmidt *et al.* (2005), and Neumeyer *et al.* (2006). Here, we briefly highlight several major modifications that were made compared to the GFZ RL02 fields (see also Flechtner (2005) for full details on the processing of RL03 models):

- usage of the further improved EIGEN-CG03C (Förste *et al.*, 2005) as initial static gravity background model.
- migration from the FES2002 to the FES2004 ocean tide model (Lefevre, 2005) containing 17 waves (eight long periodic, four diurnal, five semi-diurnal) expanded to a maximum degree and order 80 (for some constituents).
- inclusion of atmospheric tides by means of an analytic tide model equivalent to ocean tides; we use amplitudes and phases for diurnal and semi-diurnal constituents from (Biancale and Bode, 2006) developed up to degree 8 and order 5.
- a change in the oceanic de-aliasing model from the barotropic model (Ali and Zlotnicki, 2003) to the baroclinic model OMCT (Ocean Model for Currents and Tides) from Technical University Dresden (Thomas *et al.*, 2001). In addition to previous oceanic de-aliasing products (AODs) used for gravity recovery from GRACE, this version of the AOD has been generated without the semi-diurnal (S2) variations in the atmospheric data fields when driving the baroclinic ocean model. Using this procedure, the double book-keeping of the S2-driven mass variations of the previous AOD releases of the short-term atmospheric-oceanic mass variation products was avoided, thus resulting in a much more consistent modeling.
- inclusion of the oceanic pole tide model from Desai (2002). Instead of the full model available up to degree and order 360, the coefficients were truncated at degree and order 30, which is considered to be sufficient here.
- improvements in the precise orbit determination (POD) of the GRACE satellites via significantly augmented ephemeris and clocks of the GPS sender constellations. These GPS sender constellations are generated in-house at GFZ to apply the two-step approach described in Reigber *et al.* (2005). The improvements for GPS sender orbits and clocks were obtained by introducing an ambiguity fixing method for the GPS ground station data. Comparisons to the precise GPS orbits independently generated at IGS show a decrease in the root mean square (RMS) of the differences in the positions from some 7 cm of the GFZ-generated GPS orbits used in the RL02 processing to an average value of about 5 cm used for the generation of RL03. This gain in the quality of the GPS constellation transfers

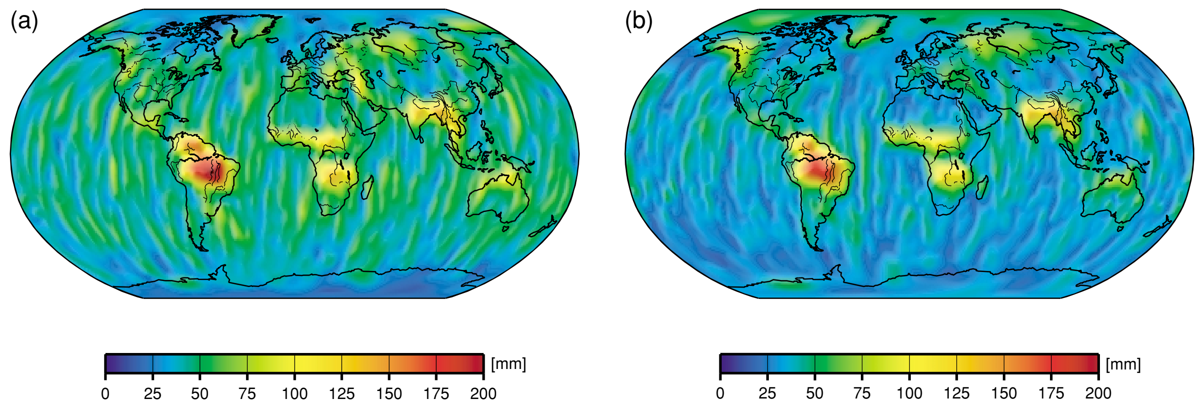

Fig. 3. (a) Root mean square (RMS) variability of the monthly gravity models from GRACE RL02. (b) RMS variability of the monthly gravity models from GRACE RL03.

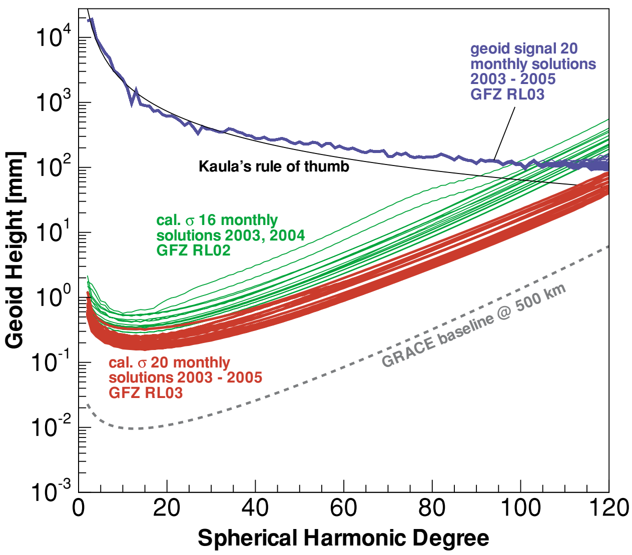

Fig. 4. Decrease in the model errors from GRACE RL02 to RL03.

into a further improved determination of the GRACE orbits.

Based on these refinements, the overall performance of the monthly GRACE-only models was improved significantly. The obtained gain in spatial resolution and accuracy of the models is illustrated in Figs. 3(a) and (b) and 4. Figure 3(a) shows the variability in the RMS of the monthly models from RL02 around their mean in terms of surface mass anomalies expressed as the equivalent height of water. Displayed are Gaussian averages of surface mass anomalies for a filter radius of 500 km. The same is shown for the RL03 models in Fig. 3(b). Along with the well-known features of the unreduced time-variable gravity signals from, for example, hydrology, one can see a significant reduction in the amplitudes of the spurious gravity variations (striping) for RL03 models.

Figure 4 shows the decrease of the model errors from RL02 to RL03. Displayed are the error degree amplitudes for geoid heights per spherical harmonic degree on the basis of calibrated errors for the RL02 and RL03 gravity fields. These calibrated errors were obtained for both releases using the method described in Schmidt *et al.* (2006) based on a degree-dependent scaling of the formal model errors. It can be seen that, compared to RL02, a gain in accuracy of a factor of about 2 has been achieved for RL03.

In addition to the direct gravity field variations, the SG also measures the gravity changes due to the load-induced variations of the radial position of the SG, whereas the satellite-derived models naturally do not contain this effect.

To compare the satellite-derived gravity variation with that measured by the SG, we add the height-induced loading part (changing of the SG's vertical position) (δg_{load}) measured by the SG to the gravity variations from GRACE (δg_{G}) as described in Eq. (1).

$$\begin{aligned}\delta g(\varphi,\lambda) &= \delta g_{\mathrm{G}} + \delta g_{\mathrm{load}} = \frac{GM}{R^2}\sum_{\ell=0}^{\ell_{\max}}(\ell+1-2h'_\ell)\\ &\quad\cdot\sum_{m=0}^{\ell}\left[\delta\bar{C}^{\mathrm{G}}_{\ell m}\cdot\cos(m\lambda)+\delta\bar{S}^{\mathrm{G}}_{\ell m}\cdot\sin(m\lambda)\right]\\ &\quad\cdot\bar{P}_{\ell m}(\sin\varphi) \qquad (1)\end{aligned}$$

where φ, λ are the spherical geocentric coordinates of the computation point (longitude, latitude), R is the reference radius (mean equatorial radius of the Earth), GM is the gravitational constant times mass of the Earth, ℓ, m are the degree and order of the spherical harmonics, $\ell_{\max}$ is the chosen maximum degree in practical calculations (any natural number, $\ell_{\max} < \infty$), h'_ℓ is the degree-dependent load Love number (Farrell, 1972; Zürn and Wilhelm, 1984; Hinderer and Legros, 1989). $\bar{P}_{\ell m}$ represent the fully normalized Legendre functions and $\bar{C}_{\ell m}$, $\bar{S}_{\ell m}$ are the fully normalized Stokes' coefficients. Superscript G is related to the spherical harmonic coefficients of GRACE gravity variations. More details can be found in Neumeyer *et al.* (2006).

Figure 5 shows the GRACE-derived gravity variations with and without height-induced loading effect at ME in Finland from February 2003 to December 2005.

The resulting monthly data sets of spherical harmonic coefficients have been used to calculate the gravity variations δgm_{G} (Eq. (1)) for the selected SG positions in the time span from February 2003 to December 2005. According to the expected signals from hydrology (on the one hand) and the errors of the GRACE-derived models (on the other

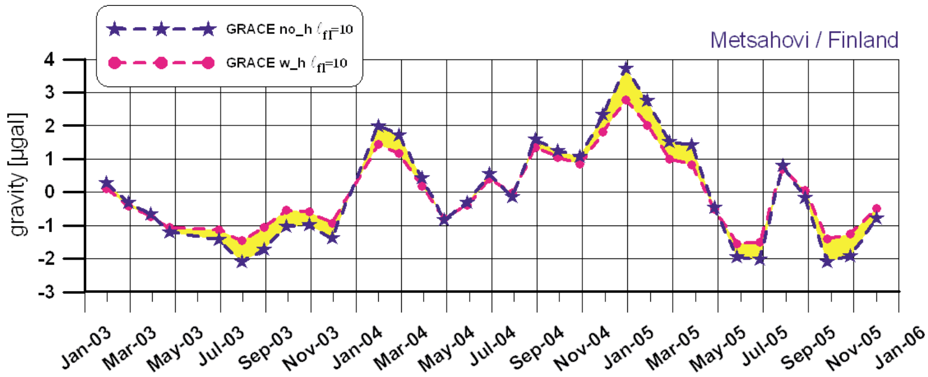

Fig. 5. GRACE-derived gravity variations with and without height-induced loading effect at ME in Finland from February 2003 to December 2005.

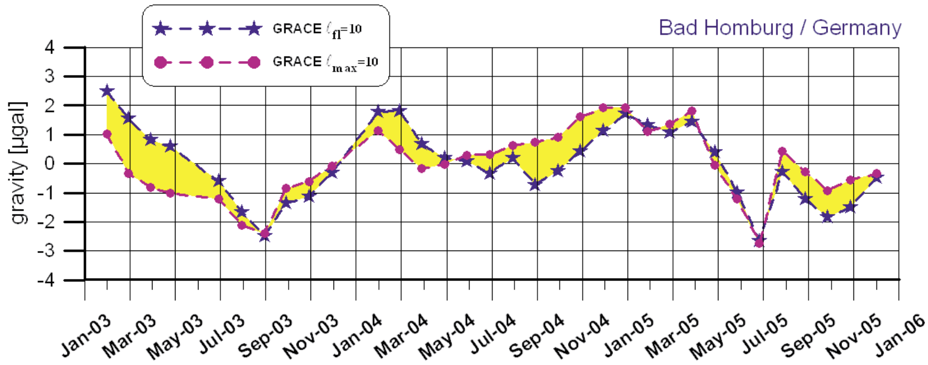

Fig. 6. GRACE-derived gravity variation filtered with a simple truncation ($\ell_{max} = 10$) and Gaussian filtering ($\ell_{fl} = 10$) of the spherical harmonic coefficients at BH in Germany from February 2003 to December 2005.

hand), both of which are shown in Fig. 1, the models have to be low-pass filtered. In Neumeyer *et al.* (2006), we simply truncated the coefficients at degrees $\ell_{max} = 10, 15, 20$, which corresponds to a spatial resolution of $\lambda/2 = 2000$, 1333 and 1000 km, respectively. More adequate than this hard truncation is a low-pass filtering by Gaussian averaging in the space domain, which corresponds to a damping of the spherical harmonic coefficients by a Gaussian bell-shaped function (Jekeli, 1981). Here, we used these damping functions in such a way that their values are 1/2 for spherical harmonic degrees $\ell_{fl} = 10, 15, 20$ in order to make them comparable to the truncation in Neumeyer *et al.* (2006). Figure 6 for the BH station shows that the differences between both methods may not be negligible.

2.2 SG gravity variations

In a pre-processing procedure, spikes and steps due to instrumental and other perturbations, such as earthquakes, are carefully removed from the raw SG recordings. Spikes larger than 0.2 μgal and steps that do not have their origin in atmosphere- or groundwater level-induced gravity variations have been removed. Of special importance is the correction of steps in the raw data which are associated with the instrument (e.g. liquid helium transfers or lightening strikes). This should be carried out with great care because steps in the data series directly influence the result of the comparison. The data are then low pass filtered with a zero phase shift filter (corner period 300 s) and reduced to a 1-h sampling rate. From these preprocessed gravity data (δg_{raw}), which include gravity variations of different sources, the same gravity effects are subtracted as in the GRACE data processing.

- Earth tides: the Earth tide reduction is performed with the Wahr-Dehant model (Dehant, 1987; Wenzel, 1996). The tidal parameters from this model were used to calculate the tidal gravity effect (ET) applied for semi-diurnal to long-periodic constituents (tidal frequencies 3.190895 cpd to 0.00248 cpd).
- gravity variations induced by the atmosphere (atmospheric pressure effect): for calculating the atmospheric pressure effect (δg_{air}), 3D atmospheric pressure data from ECMWF have been used. This gravity effect consists of both an attraction and deformation part. The calculation of the attraction term is performed with the program 3DAP (Neumeyer *et al.*, 2004b), while the deformation term is calculated according to the Green's function for atmospheric loading (Merriam, 1992; Sun, 1995).
- ocean tidal loading (δg_{ol}): based on the global ocean tide model FES2002 (Lefevre *et al.*, 2002; Le Provost *et al.*, 2002), the ocean loading for various waves in semi-diurnal, diurnal, and long periodic bands have been calculated using the GFZ program OCLO based on Francis and Mazzenga (1990). In addition, we have to consider the effect of the ocean currents according to the baroclinic model OMCT (Thomas *et al.*, 2001). The aliasing arising from this effect was reduced during the processing of GRACE (see Section 2.2). In the

SG processing, we considered only the reduction of the ocean tide effect. Unexpectedly, the calculation of the ocean current effect for the SG sites up to $\ell_{\rm fl} = 15$ and its reduction from the SG data resulted in lower correlations between SG and GRACE as well as between SG and hydrological models, especially at Metsahovi. This result can not be explained by physical reasons in a plausible way. When using the considered ocean circulation model to estimate gravity effects of ocean circulation at points located on the land very near to the coastline, it may be that the local uncertainties of the model strongly influence the result. Hence, the problem of applying a correction for the gravity effects of ocean circulation to the recordings at SG sites requires an extensive, serious and detailed investigation, which should be carried out in the future. Making an ocean circulation model comparable with gravity recordings is rather a complex process (see Sato *et al.*, 2001).

- pole tide for the rigid Earth (PT): the gravity effect of the polar motion is calculated for the SG-stations from IERS polar motion data according to Torge (1989).
- local groundwater level gravity effect ($\delta g_{\rm gwl}$) induced by water circulation in the surroundings of the SG causes variation in the gravitational attraction and deformation at the surface similar to that due to the atmosphere. Precipitation causes changes in soil moisture and groundwater level. The four SG-stations used in this study are currently equipped with boreholes for measuring variations in groundwater level. A good correlation between gravity and groundwater level variations has been shown in many cases (Kroner, 2001; Harnisch and Harnisch, 2002; Virtanen, 2001). The gravity effect of these variations is determined by regression analysis. This is a simple model, which does not reflect the true hydrological gravity signal very accurately. Separating local from regional/global environmental signals is a challenge for interpreting temporal gravity variations. Both soil moisture and groundwater level data reflect local effects as well as signals on regional or continental scale. Additionally, topography and local hydrological structure have a big impact on hydrological loading (e.g. Boy *et al.*, 2005; Kroner and Jahr, 2005; Meurers *et al.*, 2005). All of these facts restrict a clear separation of hydrological gravity contributions from different scales. In our study, we reduce the local hydrological gravity effect based on groundwater level variations near the SG-station, and we may also reduce a part of the global effect. For better modeling, a local hydrology model that considers the local hydrological cycle is necessary around the SG site. Input data for this model should be precipitation, soil moisture, and groundwater level variations measured at representative locations.
- the determination of the instrumental drift is based on polar motion measured by SG ($\delta g_{\rm SG\_pol} = \delta g_{\rm raw} - {\rm ET} - \delta g_{\rm air} - \delta g_{\rm ol} - \delta g_{\rm gwl}$) and calculated from IERS data (PT). It is simulated by a first-order polynomial $dr(t) = a_0 + a_1 t$, and the drift parameters a_0 and a_1 are determined by a linear fit of $\delta g_{\rm SG\_pol}$ and PT.

After these gravity effects have been reduced from the raw gravity data, the remaining part can be assumed to be mainly due to mass changes in terrestrial water storage $\delta g_{\rm SG}$.

$$\delta g_{\rm SG}(t) = \delta g_{\rm raw}(t) - {\rm ET}(t) - {\rm PT}(t) - \delta g_{\rm air}(t) - \delta g_{\rm ol}(t) - \delta g_{\rm gwl}(t) - dr(t). \quad (2)$$

Monthly arithmetic means $\delta gm_{\rm SG}$ are calculated from gravity variations $\delta g_{\rm SG}$ for comparison with those derived from GRACE and hydrological models.

3. Gravity Variations Derived from Global Hydrology Models

After the different gravity effects from the SG recordings and the GRACE solutions have been reduced, the remaining gravity variations can be attributed mainly to mass changes in continental water storage. Therefore, gravity variations derived from global hydrology models were compared with these "measured" hydrological effects (cf. Wahr *et al.*, 2004; Schmidt *et al.*, 2006; Neumeyer *et al.*, 2006).

Global hydrological models represent both the spatial distribution and the changes in continental water budget over time. It should be noted that any kind of redistribution of water masses induces changes in the Earth's gravity field. Therefore, an appropriate hydrological model for our purposes should represent all water resources, which are available as ground water storage, surface water, or soil moisture, contained in ice shields or existing in any other form. However, none of the existing models meets these requirements completely.

The water budget change (wbc) of all global hydrological models is based on precipitation (prec), runoff (roff) and evapotranspiration (evpt) expressed by the very simple fundamental relation:

$$\text{wbc} = \text{prec} - \text{roff} - \text{evpt}. \quad (3)$$

Nevertheless, the implementation brings difficulties, since the water stocks cannot be measured directly, and the same partly holds for the remaining variable quantities. Hence, the possibilities to validate a model through a direct check of Eq. (3) are very limited. Consequently, different hydrological models can be quite different, especially from the point of view of reflecting 100% the redistribution of water masses.

In our study, three global hydrological models have been considered:

- Water gap Global Hydrology Model (WGHM) (Döll *et al.*, 2003); data coverage from January 1992
- Leaky-Bucket Model (H96) (Huang *et al.*, 1996; Fan and Van den Dool, 2004); data coverage from January 1948
- Land Dynamics model (LaD) (Milly and Shmakin, 2002); data coverage from January 1980.

The output of these three models is available in form of grided data sets representing monthly averages of water storage expressed as equivalent water columns in millimeters or centimeters. The grid step in geographical latitude and longitude is 0.5° for the first two models and 1° for the

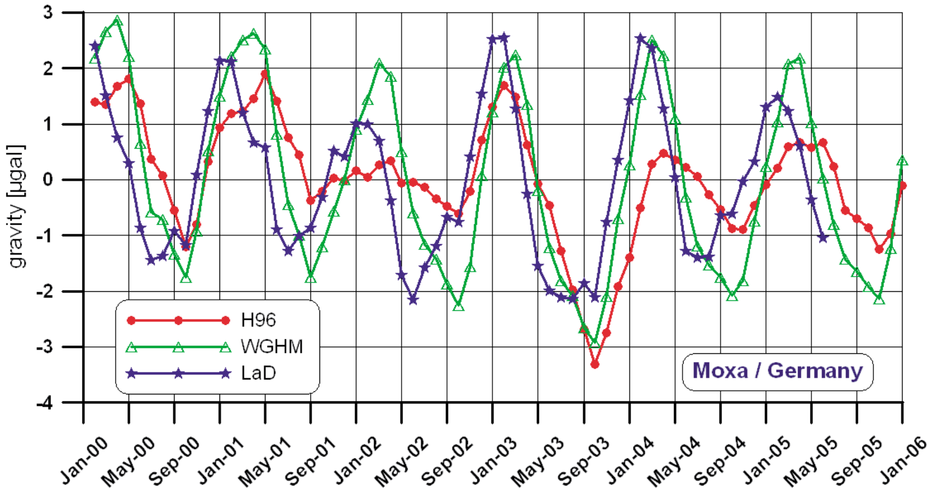

Fig. 7. Gravity variations derived from global hydrology models WGHM, H96 and LaD ($\ell_{\mathrm{fl}} = 10$) at the SG site MO in Germany from January 2000 to January 2006.

third one. The models are updated regularly so that current data are available with a delay of several months. It should be stressed that the depth of the considered ground water in different models differs, snow is taken into account only partially and in different ways, and the modeling of ice shields is, according to the authors, very incomplete and unreliable.

The main goal of this study is to compare temporal variations of the Earth's gravity field deduced from different sources. Prior to comparing variations deduced from global hydrological models with the respective variations resulting from GRACE or SG observations, it is necessary to derive some idea of how reliably this kind of information can be deduced from global hydrological models. Global comparison of the variations of geoid undulations deduced from two different hydrological models shows differences which lie almost in the same order of magnitude as the variations themselves, although the correlation coefficients are rather high (Abrikosov *et al.*, 2006; Schmidt *et al.*, 2006). However, in some regions (e.g. on the South American continent), the correspondence between the variability deduced from the three hydrological models is relatively good, and well-pronounced features, especially in large tropical river basins, are clearly visible in all three representations. In the context of our study, this means that the variations in the Earth's gravity field at some SG-stations deduced from global hydrological models may be quite realistic. However, the existing global hydrological models in their present form still have to be regarded as rather uncertain. The main possibilities to validate these models in an independent manner are to carry out comparisons with the gravity field determined either with satellite techniques, like GRACE, (Schmidt *et al.*, 2006) or with SG, as in Neumeyer *et al.* (2006) and this study.

The deviations of the three models (Fig. 7) illustrate a difficulty in modeling the gravity effect based on global hydrology models. A comparison between hydrology models, SG, and GRACE gravity variations does not indicate any hydrology model that fits best everywhere. Depending on the SG location, one of the models matches to SG and/or GRACE at best (Fig. 8).

3.1 Computation of the gravity variations derived from hydrological models

For our comparison of the observed variations of the Earth's gravity field with the variations deduced from global hydrological models, we have computed the component of the gravity field induced by the modeled water stocks for each epoch (i.e. month); the result is represented in spherical harmonics expansion with a GFZ analysis program based on Eq. (4). Equation (4) was derived based on the approach proposed by Wahr *et al.* (1998), and the procedure is described in Neumeyer *et al.* (2006).

The variation δr of the radial position of the SG-station caused by the load is considered in the same way as in the case of the satellite-derived gravity variations. The equation for gravity variations derived from hydrological model δg_{HM} takes the form:

$$\delta g_{\mathrm{HM}}(\varphi,\lambda) = \frac{GM}{R^2}\sum_{\ell=0}^{\ell_{\max}}(\ell+1-2h'_\ell)\sum_{m=0}^{\ell}\left[\delta\bar{C}_{\ell m}^{\mathrm{HM}}\cdot\cos(m\lambda) + \delta\bar{S}_{\ell m}^{\mathrm{HM}}\cdot\sin(m\lambda)\right]\cdot\bar{P}_{\ell m}(\sin\varphi) \quad (4)$$

for arbitrary $\ell_{\max}$, which is the same form as Eq. (1)

Degree-0 ($\ell = 0$) and degree-1 ($\ell = 1$) terms have not been used for comparisons, since the hydrological models contain neither mass conservation (which does not exist on the level of continental water budget alone) nor a consistent datum definition (which prevents a physical interpretation of geocenter variations derived from these data). Omitting the degree 0 and 1 terms and taking into account the filtering used (same as for the satellite-derived gravity variations), we can show that the contribution of δr amounts to approximately 1/4 of the variations of δg_{HM} in Eq. (1), compare Neumeyer *et al.* (2006), and the detailed discussion in Hinderer *et al.* (2006). Due to these necessary omission and filtering steps, the magnitude of δr cannot be compared directly with the data observed by GPS or any other technique.

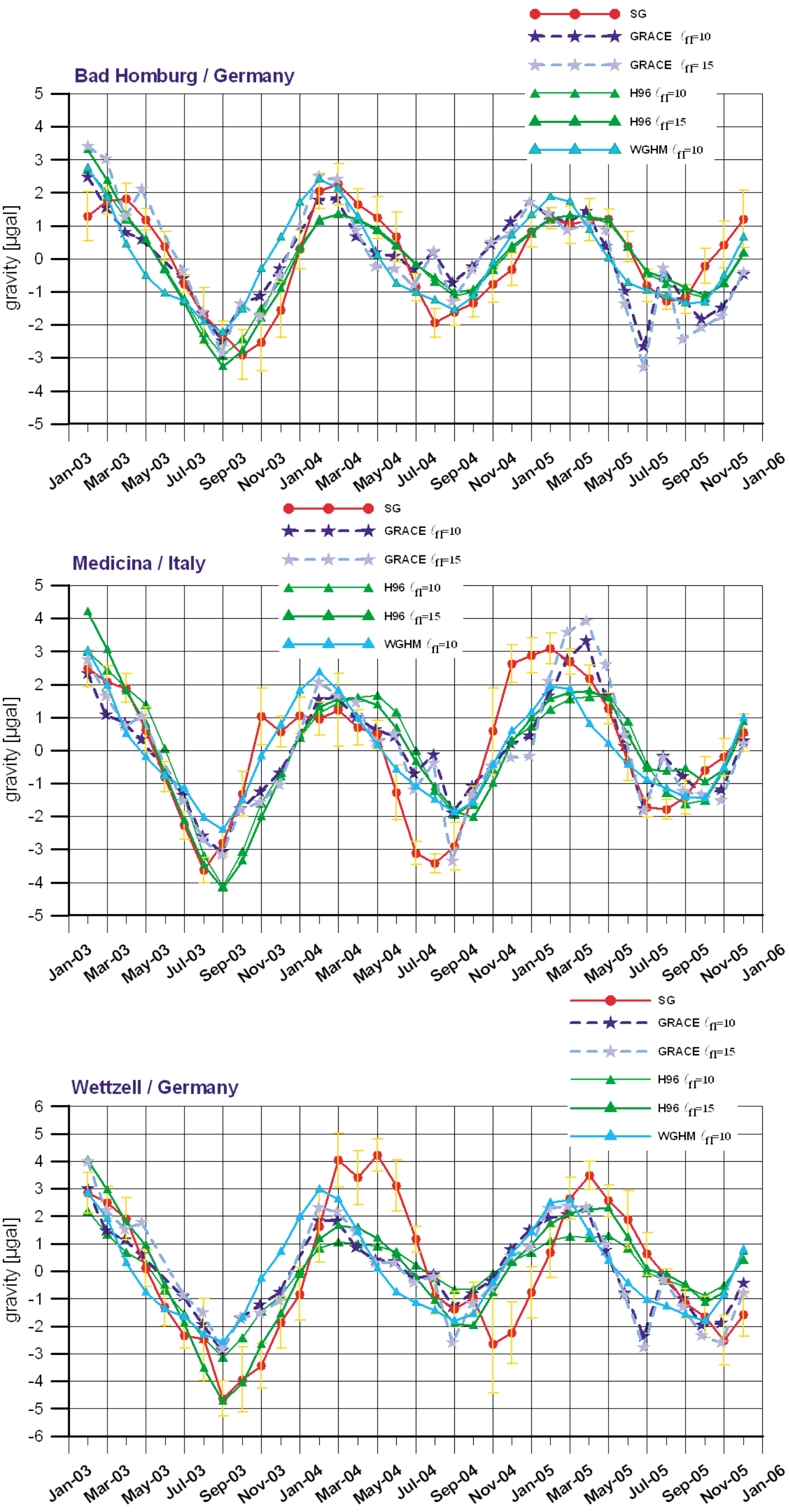

Fig. 8. Gravity variations from SG, GRACE, and global hydrological models H96 and WGHM at SG sites BH, MC, WE, MO, and ME from February 2003 to December 2005.

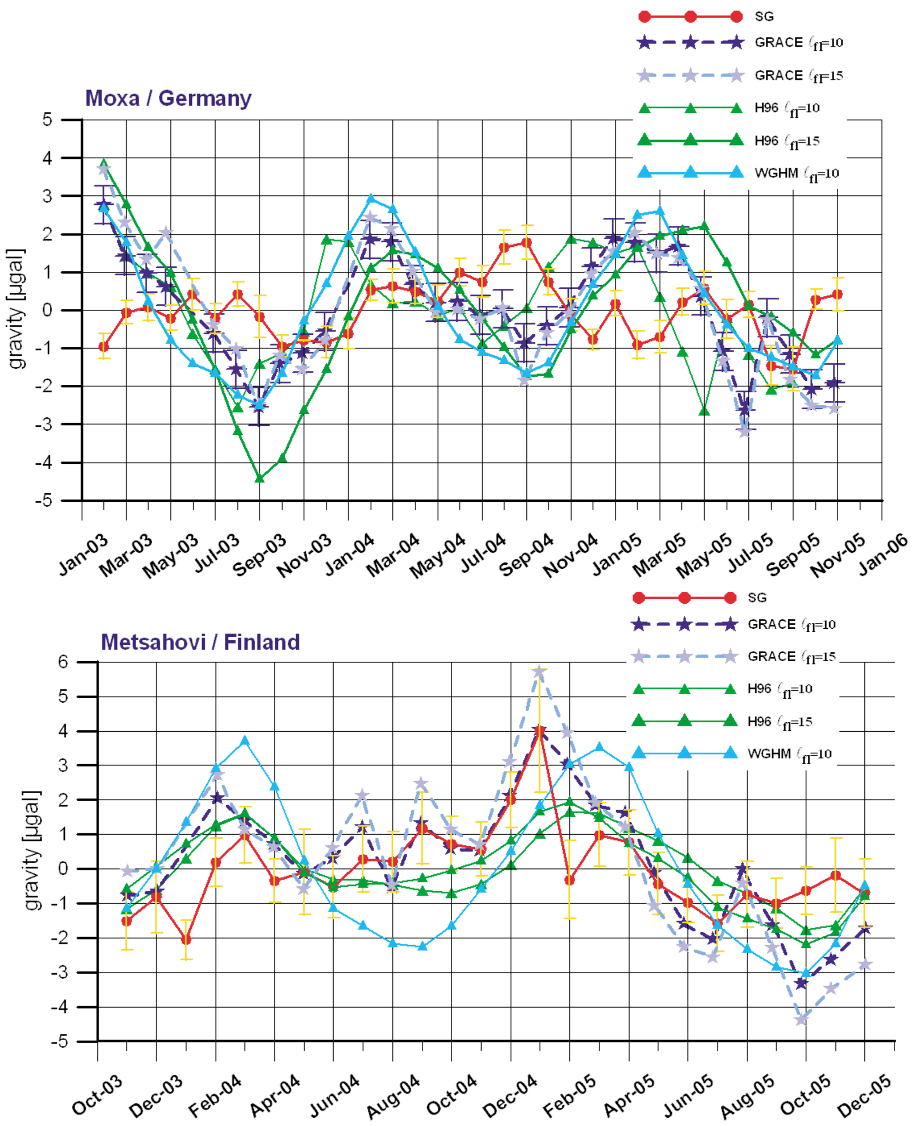

Fig. 8. (continued).

4. Comparison of SG, GRACE, and Hydrology Model Derived Gravity Variations

Within the time period from January 2003 to December 2005, SG gravity data were processed according to the procedure described in Section 2.2. For the MC, MO, WE, and ME sites the local groundwater level correction, δg_{gwl}, was performed. For the BH station, the available groundwater level data did not yield a suitable correction result when the usual simple regression method was applied. This may be due to the complicated hydrological structure at this site. Therefore, δg_{gwl} has not been performed at BH. For comparison purposes, the monthly averages of the gravity variations δgm_{SG} (Eq. (2)) are used. The assigned GRACE values, δgm_{G}, are taken from the monthly global gravity field solutions calculated for the coordinates of the selected SG sites (Eq. (1)). Because of the reduction due to Earth and ocean tides, pole tide, and atmosphere, the remaining time variable gravity effects are mainly caused by continental large-scale hydrology. For the SG sites hydrology-model-derived gravity variations, δgm_{HM} (Eq. (4)), have also been calculated. Figure 8 summarizes the results. The error bars on the SG gravity (δgm_{SG}) do not represent measurement errors; they show the variations of gravity within the respective month.

In order to demonstrate agreement between the different data series, we calculated correlation coefficients between SG, GRACE ($\ell_{\mathrm{fl}} = 15$) and the hydrological models ($\ell_{\mathrm{fl}} = 15$) H96 and WGHM (Table 2).

In the comparison shown in Fig. 8, it should be taken into account that the correlation computation is based on 35 (due to monthly resolution of GRACE solution) data points only. Hence, the computed values of the correlation coefficient should be considered to be rather insignificant in a statistical sense. However, they give an objective measure of how similar the two curves look (as opposed to a subjective estimate of a viewer).

According to Table 2, the correlation coefficients between the SG- and GRACE ($\ell_{\mathrm{fl}} = 15$)-derived gravity variations lie around the level of 0.8 at SG sites BH, MC, and ME. Similar correlation coefficients are obtained between SG and hydrological models, except for a smaller correlation for the WGHM model at stations WE (0.39) and ME

Table 2. Correlations between the gravity variations derived by the SG, GRACE ($\ell_{fl} = 15$), and hydrological models ($\ell_{fl} = 15$) for the SG sites BH, MC, WE, MO, and ME.

	SG-GRACE	SG-H96	SG-WGHM	GRACE-H96	GRACE-WGHM
BH	0.77	0.89	0.79	0.88	0.86
MC	0.74	0.75	0.82	0.91	0.79
WE	0.77	0.55	0.39	0.73	0.57
MO	−0.09	−0.02	−0.20	0.86	0.87
ME	0.74	0.85	0.64	0.92	0.89

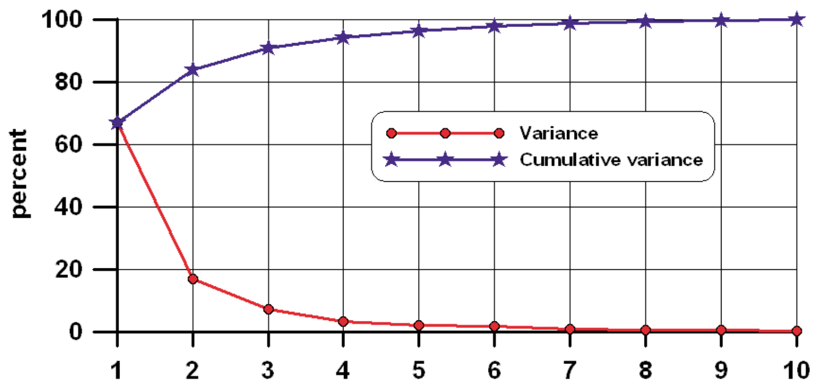

Fig. 9. Variances (eigenvalues in %) and cumulative variances for the first ten modes of the simultaneous Empirical Orthogonal Functions (EOF) analysis of GRACE, SG, and WGHM.

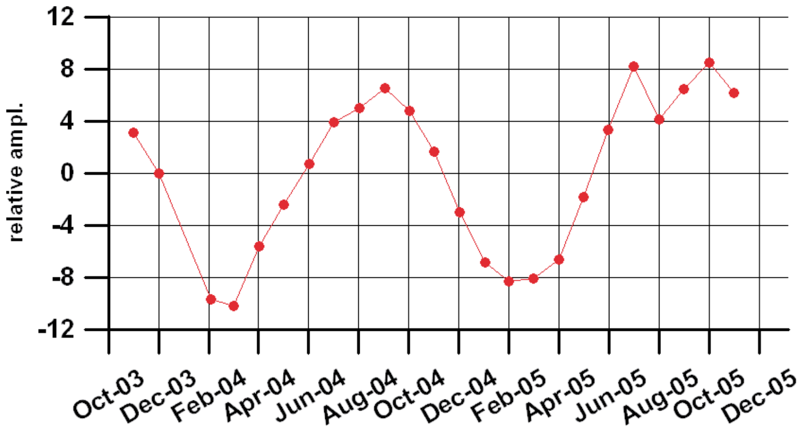

Fig. 10. Time variations of the first principal component computed simultaneously for GRACE, SG, and WGHM from October 2003 to October 2005.

(0.64) (compare also the result at ME in Boy and Hinderer (2006) for LaD). This result may be caused by uncertainties of the hydrological model. In the case of ME, there may be a large estimation error in the gravity effect of the snow in the hydrological models, which may contribute to the low correlation (cf. Sato *et al.*, 2006). The GRACE- and hydrological model-derived gravity variations fit well for all selected sites. They have correlation coefficients around 0.8. The highest correlation with the H96 model appears for the ME station (0.96) and the lowest for the WGHM model at the WE station (0.57). Practically no correlation can be detected at the MO station for SG-GRACE and SG-hydrological models (cf. Boy and Hinderer, 2006).

For the MO station, the SG data are also corrected for groundwater level changes. However, we could not consider a hydrological portion caused by rainfall and changing soil moisture above the SG because the site is located in a mountain tunnel. This portion influences the reduction of the hydrological signal (Kroner, 2001).

5. EOF Analysis of Dominant Common Features

Empirical Orthogonal Functions (EOF) analysis, known also as Principal Components Analysis, is an appropriate method for finding characteristic spatial and temporal patterns in time-series of physical fields. A review of the history, the theory, and typical applications in meteorology and oceanography can be found in Preisendorfer (1988) and Wilks (1995), among others. In the most common form of EOF, the use of SVD (Singular Value Decomposition) is involved.

In order to detect systematic parts of mass redistributions from GRACE and global hydrological models, EOF can be applied to time-series of global grids of mass anomalies derived from these data sources (Petrovic *et al.*, 2007).

Table 3. First eigenvector for GRACE ($\ell_{fl} = 15$), SG, and WGHM ($\ell_{fl} = 15$) for the five SG stations resulting from the EOF analysis.

	BH	MC	ME	MO	WE
GRACE	−0.24	−0.30	−0.33	−0.26	−0.29
SG	−0.17	−0.25	−0.09	0.01	−0.22
WGHM	−0.26	−0.23	−0.40	−0.28	−0.29

Table 4. Periods, amplitudes, and phases contained in the first principal component resulting from the simultaneous EOF analysis of GRACE, SG, and WGHM data.

No.	Period (year)	Amplitude	Phase (°)	RMS
original data				6.03
1	0.993	7.81	−164	1.73
2	0.501	1.24	172	1.39
3	0.387	1.15	28	1.14
4	0.323	0.93	60	0.98
5	2.008	0.73	−120	0.83

Table 5. Variances of original and reduced (annual signal subtracted) data.

	GRACE		SG		WGHM	
	orig	red	orig	red	orig	red
BH	1.69	1.06	1.36	0.75	1.62	0.43
MC	2.17	1.22	1.92	1.04	1.50	0.56
ME	3.06	2.69	1.21	1.14	2.51	0.77
MO	1.75	1.09	0.87	0.86	1.77	0.48
WE	1.88	0.95	2.35	1.93	1.84	0.54
Total	2.17	1.55	1.63	1.22	1.88	0.57

A first application of EOF to the results of the SG observations can be found in a very instructive article by Crossley *et al.* (2004). To apply the EOF technique, the results of SG recordings were first interpolated (and extrapolated) to a rectangular region covered by a uniform grid. This facilitates the application of EOF and enables the results to be presented in the form of contour maps. However, interpolating the data from the eight stations used in this study to more than 20000 grid points cannot increase the information content of the data as it still corresponds to the information content of eight irregularly distributed locations. This may lead to a false feeling for the significance of the results and to an overweighting of the conclusions drawn from the analysis. Nevertheless, the paper by Crossley *et al.* (2004) should be regarded as a pioneering work in the field of application of the EOF-technique to the results of SG recordings.

An alternative approach is proposed in this study. EOF-analysis does not require the data to be given on a uniform grid; they may be distributed arbitrarily. Hence, we apply EOF to the five SG-stations considered in this study, specifically to the data introduced, described, and analyzed in Sections 1–3. Since the number of SG-stations used is very limited, the conclusions drawn should be taken with extreme caution. The main purpose of the analysis is to illustrate the methodology, which could give more reliable results if applied to a greater number of stations and time epochs.

The EOF technique was applied simultaneously to all three data sets: GRACE-derived gravity field variations and those derived from SG recordings and from the global hydrological model WGHM. This means that the input consists of 24 monthly epochs (those, for which all kinds of data exist for all stations) and for each epoch of 15 values (three values at each of five stations). These 360 values have been arranged appropriately in a vector for input into the FORTRAN package from D. Pierce (Scripps Institution, La Jolla, CA), which is available on his internet home page (http://meteora.ucsd.edu/~pierce/eof/eofs.html). The computations were performed using covariance matrices.

First, the significance of individual modes is represented in Fig. 9. Mode 1 explains about two thirds of the complete signal contained in the data. The decrease in subsequent modes is very rapid.

Concentrating on mode 1, Fig. 10 presents the time variations of the first principal component, Table 3 presents the associated eigenvector.

An analysis of Table 3 reveals an obvious anomalous behavior of SG results for station MO, which is in concordance with the conclusions reported in Section 4; this behavior should be attributed to an incomplete reduction of local influences. This anomalous behavior was not detected by the EOF analysis performed by Crossley *et al.* (2004), probably because of the interpolation of the SG recordings to a rectangular grid, in the course of which the specific characteristics of MO (which is in the interior of the considered region) were smoothed out.

Figure 10 demonstrates a very pronounced periodic component contained in the first principal component. Hence, analyses of periodic parts of this principal component can be performed. It makes sense to search for arbitrary periods in order to determine which periods are really contained in the data. The possible general advantages of such an approach are explained in Mautz (2002) and Mautz and Petrovic (2005).

Table 4 lists the periods found in the first principal component. Taking into account the very limited number of data points used, the periods of 0.993 and 0.501 years can be regarded as almost perfect annual and semiannual waves, respectively, which were expected for physical reasons. However, only the annual wave, which explains about 70% of the variations of the first principal component, can be regarded as being truly significant. The dominating annual wave for the European SG-stations was also detected by Crossley *et al.* (2004), who applied an EOF analysis in a different way.

Now, when the phase of the annual variations is known, it is possible to determine a common annual wave (only the amplitude should be scaled to the respective kind of data at the respective station) and to subtract it from the original data. This approach differs essentially from the usual reduction of annual (or any other periodic) wave independently (with individual, independent phases) from each spherical harmonic coefficient or at each location of the space domain and may be physically more plausible. An application of this methodology to grid data preprocessed with EOF is currently being investigated, and the publication in preparation will contain more technical details on the method.

Subtracting the common annual wave from the data reduces the total signal, as shown in Table 5. The overall re-

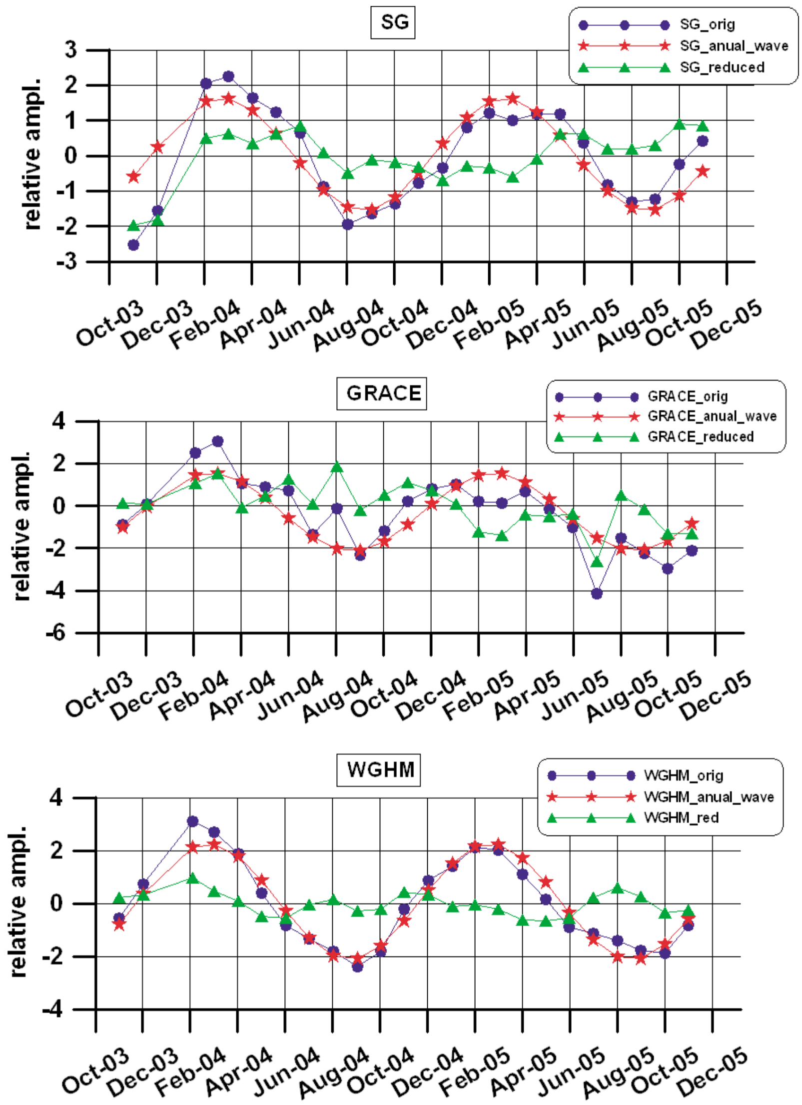

Fig. 11. Original data, annual wave, and reduced data (after subtracting the annual signal) for SG, GRACE, and WGHM at the BH site from November 2003 to October 2006.

duction is somewhat less than 40%; in the case of GRACE, it is about 30%; for SG, 25%; for WGHM, 70%.

Figure 11 illustrates the original data, the annual wave, and the reduced data for station BH.

The reduction of the power in all three data sets is considerable for BH. For MO, the reduction for GRACE and WGHM is very similar to that for BH, which is a logical consequence of the geographical closeness of both stations combined with the fact that the GRACE and WGHM data for the respective stations were computed from global representations. The essentially weaker data reduction for SG in MO can be attributed to the insufficient local corrections (discussed earlier).

A very high degree of signal reduction for global hydrological models after applying just a common annual wave is obviously a consequence of the present state of these models, which are still too coarse. A relatively small reduction for GRACE could partly be due to well-known problems with GRACE monthly solutions, which still show striped features. However, the processing of GRACE monthly solutions is steadily improving. Finally, the reduction of only 25% for SG can primarily be attributed to two SG-stations with known problems in local reductions. When only BH, MC, and WE are considered, the reduction of signal after subtracting the common annual wave for SG rises to 30%.

It is possible to further analyze the reduced data, for example, by applying the EOF technique again, this time to the reduced data. The significance of individual modes is shown in Fig. 12. Mode 1 explains almost a half of the complete signal. The decrease in subsequent modes is rapid, but not as rapid as for the original data.

In order to avoid an overestimation of the conclusions following from an application to a very sparse data set, we stop further elaboration at this point. However, we consider the proposed methodology for the analysis of the data first transformed in another representation by means of EOF as promising and plan to apply it to more complete data sets.

Nevertheless, even from this application to only five SG-stations, some preliminary conclusions can be drawn. The first eigenvector (Table 3) reveals both common and different behaviors, the first principal component (Fig. 10) shows an obvious periodicity, and the search for arbitrary periods

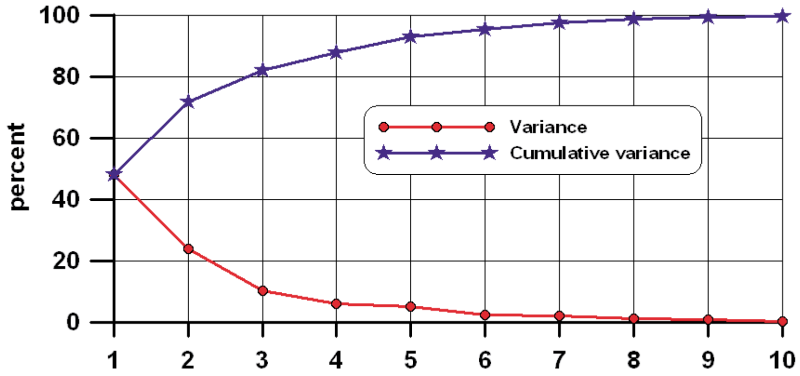

Fig. 12. Variances (eigenvalues in %) and cumulative variances for the first ten modes from the simultaneous EOF analysis of the reduced GRACE, SG, and WGHM data.

(Table 4) makes it possible to detect periods contained in the data. Finally, the constructed common periodic component (in this example, annual) proves to be realistic and reduces the total signal contents considerably.

6. Conclusions

For most of the selected SG locations the comparison based primarily on computed correlations shows quite a good agreement between gravity variations derived from SG, GRACE, and hydrology. However, the discrepancies that were detected are not negligible and may provide valuable suggestions for further investigations of individual data series.

A methodology for an analysis of dominant common features based on EOF is proposed and illustrated. The first principal component shows a strong periodicity, and the search for arbitrary periods confirms a strong common annual component, which considerably reduces the total signal content. The first eigenvector reveals common features and differences between distinct SG-stations.

Currently, the deviations in the different data sets, as detected by both applied methodologies, cannot be explained completely. However, we were able to show that SG measurements can be used for validating the GRACE- and hydrology model-derived gravity variations.

To answer all of the remaining questions in full, it will be necessary to carry out investigations on longer data sets and with better spatial coverage. For example, more significant results from the analysis based on the EOF technique could be obtained by including all European SG-stations and longer data series.

However, the example of the Moxa SG-station shows that only SG data satisfying the criteria of a reduction of all local gravity effects can contribute to a better comparison, validation, and understanding of the phenomena connected with time variations of the Earth gravity field. Hence, only SG sites where the local hydrological gravity effects can be well modeled can be recommended for validation of GRACE and global hydrology models. Therefore, it is necessary that:

- all SG sites should be equipped with groundwater table, soil moisture, and rain gauges for better modeling of the local hydrological gravity effect; and
- for each SG station, a local hydrology model based on real data should be developed.

In further validation experiments, field SG measurements should be carried out in areas with large or very small gravity variations; for example, in the Amazon area in South America, where seasonal gravity changes can be observed in the order of some 10 μgal, or in the Atacama Desert (Chile), where only a very weak hydrology signal is to be expected.

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References

Abrikosov, O., F. Jarecki, J. Müller, S. Petrovic, and P. Schwintzer, The Impact of Temporal Gravity Variations on GOCE Gravity Field Recovery, in *Observation of the Earth System from Space*, edited by J. Flury, R. Rummel, C. Reigber, M. Rothacher, G. Boedecker, and U. Schreiber, 255–269 and 304, Springer Berlin Heidelberg New York, 2006.

Ali, A. H. and V. Zlotnicki, Quality of wind stress fields measured by the skill of a barotropic ocean model: Importance of stability of the Marine Atmospheric Boundary Layer, *Geophys. Res. Lett.*, **30**(3), 1129, doi: 10.1029/2002GL016058, 2003.

Biancale, R. and A. Bode, Mean and Seasonal Atmospheric Tide Models based on 3-hourly and 6-hourly ECMWF Surface Pressure Data, *Scientific Technical Report STR06/01*, GeoForschungsZentrum Potsdam, ISSN 1610-0956, 2006.

Boy, J. P., J. Hinderer, and G. Ferhat, Gravity changes and crustal deformation due to hydrology loading, *Geophy. Res. Abstr.*, **7**, 07166, 2005.

Boy, J. P. and J. Hinderer, Study of the seasonal gravity signal in superconducting gravimeter data, *J. Geodyn.*, **41**, 227–233, 2006.

Crossley, D., J. Hinderer, O. Casula, O. Francis, H. T. Hsu, Y. Imanishi, G. Jentzsch, J. Kääriäinen, J. Merriam, B. Meurers, J. Neumeyer, B. Richter, D. Sato, K. Shihuya, and T. van Dam, Network of Superconducting Gravimeters Benefits a Number of Disciplines, *EOS. Trans. Am. Geophys. Union*, **80**(11), 125–126, 1999.

Crossley, D., J. Hinderer, and J. P. Boy, Regional gravity variations on Europe from superconducting gravimeters, *J. Geodyn.*, **28**, 325–342, 2004.

Crossley, D., J. Hinderer, and J. P. Boy, Time variation of the European gravity field from superconducting gravimeters, *Geophys. J. Int.*, **161**, 257–264, doi:10.1111 /j.1365-246X.2005.02586.x, 2005.

Dehant, V., Tidal Parameters for an Inelastic Earth, *Phys. Earth Planet. Inter.*, **49**, 97–116, 1987.

Desai, S. D., Observing the pole tide with satellite altimetry, *J. Geophys. Res.*, **107**(C11), 3186, doi:10.1029/2001JC001224, 2002.

Döll, P., F. Kaspar, and B. Lehner, A global hydrological model for deriving water availability indicators: model tuning and validation, *J. Hydrol.*, **270**, 105–134, 2003.

Fan, Y. and H. van den Dool, The CPC global monthly soil moisture data set at 1/2 degree resolution for 1948-present, *J. Geophys. Res.*, **109**, D10102, DOI:1029/2003JD004345, 2004.

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

Flechtner, F., GFZ Level-2 Processing Standards Document for Level-2 Product Release 0003, Rev.1.1, Nov. 04, 2005, GRACE 327-743, JPL/Pasadena, 2005.

Förste, C., F. Flechtner, R. Schmidt, U. Meyer, R. Stubenvoll, F. Barthelmes, R. König, K. H. Neumayer, M. Rothacher, Ch. Reigber, R. Biancale, S. Bruinsma, J.-M. Lemoine, and J. C. Raimondo, A New High Resolution Global Gravity Field Model Derived From Combination GRACE and CHAMP Mission and Altimetry/Gravimetry Surface Gravity Data, Poster G004_EGU05-A-04561 presented at EGU General Assembly 2005, Vienna, Austria, 24–29, April 2005, 2005.

Francis, O. and P. Mazzega, Global charts of ocean tide loading effects, *J. Geophys. Res.*, **95**, 11411–11424, 1990.

Goodkind, J. M., The Superconducting gravimeter, *Rev. Sci. Inst.*, **70/11**, 4131–4152, 1999.

Harnisch, G. and M. Harnisch, Seasonal variations of hydrological influences on gravity measurements at Wettzell, *Bull. D'Inf. Marees Terr.*, **137**, 10849–10861, 2002.

Hinderer, J. and H. Legros, Elasto-gravitational deformation, relative gravity changes and Earth dynamics, *Geophys. J. Int.*, **97**, 481–495, 1989.

Hinderer, J., O. Andersen, F. Lemoine, D. Crossley, and J. P. Boy, Seasonal changes in the European gravity field from GRACE: A comparison with superconducting gravimeters and hydrology model predictions, *J. Geodyn.*, **41**, 59–68, 2006.

Huang, J., H. M. Van den Dool, and K. P. Georgakakos, Analysis of model-calculated soil moisture over the United States (1931-1993) and applications to long-range temperature forecasts, *J. Climate*, **9**, 1350–1362, 1996.

Jekeli, C., *Alternative methods to smooth the Earth's gravity field*, p. 48, Department of Geodetic Science and Surveying, Ohio State University, Columbus, Ohio, 1981.

Kroner, C., Hydrological effects on gravity data of the Geodynamic Observatory Moxa, *J. Geodyn. Soc. Jpn.*, **47**(1), 353–358, 2001.

Kroner, C. and T. Jahr, Hydrological experiments around the superconducting gravimeter at Moxa observatory, *J. Geodyn.*, 2005 (in press).

Lefevre, F., FES2004 package for Jason and ENVISAT Geophysical Data Records, personal communication, 2005.

Lefevre, F., F. H. Lyard, C. Le Provost, and E. J. O. Schrama, FES99: a global tide finite element solution assimilating tide gauge and altimetric information, *J. Atmos. Oceanic Technol.*, **19**, 1345–1356, 2002.

Le Provost, C., F. Lyard, F. Lefevre, and L. Roblou, FES 2002—A new version of the FES tidal solution series, Abstract Volume Jason-1 Science Working Team Meeting, Biarritz, France, 2002.

Mautz, R., Solving Nonlinear Adjustment Problems by Global Optimization, *Boll. Geodes. Sci. Affini*, **61**(2), 2002.

Mautz, R. and S. Petrovic, Erkennung von physikalisch vorhandenen Periodizitäten in Zeitreihen, *ZfV Z. Geodäs. Geoinform. Landmanage.*, **130**(3), 156–165, 2005.

Meurers, B., M. Van Camp, T. Petermans, K. Verbeeck, and K. Vanneste, Investigation of local atmospheric and hydrological gravity signals in Superconducting Gravimeter time series, *Geophys. Res. Abstr.*, **7**, 07463, 2005.

Merriam, J. B., Atmospheric pressure and gravity, *Geophys. J. Int.*, **109**, 488–500, 1992.

Milly, P. C. D. and A. B. Shmakin, Global modeling of land water and energy balances. Part I: The Land Dynamics (LaD) Model, *J. Hydrometeorol.*, **3**(3), 283–299, 2002.

Neumeyer, J., P. Schwintzer, F. Barthelmes, O. Dierks, Y. Imanishi, C. Kroner, B. Meurers, H. P. Sun, and H. Virtanen, Comparison of Superconducting Gravimeter and CHAMP Satellite derived Temporal Gravity Variations, in *Earth Observations with CHAMP Results from Three Years in Orbit*, edited by Ch. Reigber, H. Lühr, P. Schwintzer, and J. Wickert, 31–36, 2004a.

Neumeyer, J., J. Hagedoorn, J. Leitloff, and T. Schmidt, Gravity reduction with three-dimensional atmospheric pressure data for precise ground gravity measurements, *J. Geodyn.*, **38**, 437–450, 2004b.

Neumeyer, J., F. Barthelmes, O. Dierks, F. Flechtner, M. Harnisch, G. Harnisch, J. Hinderer, Y. Imanishi, C. Kroner, B. Meurers, S. Petrovic, Ch. Reigber, R. Schmidt, H. P. Sun, and H. Virtanen, Combination of temporal gravity variations resulting from superconducting gravimeter (SG) recordings, GRACE satellite observations and hydrology models, *J. Geod.*, **79**, 573–585, 2006.

Petrovic, S., R. Schmidt, J. Wünsch, F. Barthelmes, A. Güntner, and M. Rothacher, Towards a characterization of temporal gravity field variations in GRACE observations and global hydrology models, *Proceedings of the 1st International Symposium of the International Gravity Field Service (IGFS) "GRAVITY FIELD OF THE EARTH", Harita Dergisi (Journal of Mapping, Istanbul), Special Issue*, **18**, 199–204, 2007.

Pick, M., J. Picha, and V. Vyskocil, *Theory of the Earth's Gravity Field*, Publishing House of the Czechoslovak Academy of Sciences, Prague, 1973.

Preisendorfer, R. W., Principal component analysis in meteorology and oceanography, edited by C. D. Mobley, Elsevier Science Publishers, Amsterdam, 1988.

Reigber, Ch., R. Schmidt, F. Flechtner, R. König, U. Meyer, K. H. Neumayer, P. Schwintzer, and S. Y. Zhu, An Earth Gravity Field Model Complete to Degree and Order 150 from GRACE: EIGEN-GRACE02S, *J. Geodyn.*, **39**, 1–10, 2005.

Sato, T., Y. Fukuda, Y. Aoyama, H. McQueen, K. Shibuya, Y. Tamura, K. Asari, and M. Ooe, On the observed annual gravity variation and the effect of sea surface height variations, *Phys. Earth Planet. Inter.*, **123**, 45–63, 2001.

Sato, T., J. P. Boy, Y. Tamura, K. Matsumoto, K. Asari, H. P. Plag, and O. Francis, Gravity tide and seasonal gravity variation at Ny-Alesund, Svalbard in Arctic, *J. Geodyn.*, **41**, 234–241, 2006.

Schmidt, R., F. Flechtner, Ul. Meyer, Ch. Reigber, F. Barthelmes, Ch. Foerste, R. Stubenvoll, R. König, K. H. Neumayer, and S. Y. Zhu, Static and Time-Variable Gravity from GRACE Mission Data, in *Observation of the Earth System from Space*, edited by J. Flury, R. Rummel, C. Reigber, M. Rothacher, G. Boedecker, and U. Schreiber, 115–129 and 293–296, Observation of the Earth System from Space, Springer Berlin Heidelberg New York, 2005.

Schmidt, R., P. Schwintzer, F. Flechtner, Ch. Reigber, A. Güntner, P. Döll, G. Ramillien, A. Cazenave, S. Petrovic, H. Jochmann, and J. Wünsch, GRACE Observations of Changes in Continental Water Storage, *Global and Planetary Change*, **48/4**, 259–273, 2006.

Sun, H.-P., *Static deformation and gravity changes at the Earth's surface due to the atmospheric pressure*, Observatoire Royal des Belgique, Serie Geophysique Hors-Serie, Bruxelles, 1995.

Tapley, B. D. and Ch. Reigber, The GRACE mission: status and future plans, *EOS Trans. AGU*, **82**(47), Fall Meet. Suppl., G41 C-02, 2001.

Thomas, M., J. Suendermann, and E. Maier-Greiner, Consideration of ocean tides in an OGCM and impacts on subseasonal to decadal polar motion excitation, *Geophys. Res. Lett.*, **12**, 2457, 2001.

Torge, W., *Gravimetry*, de Gruyter, Berlin, New York, 1989.

Vanicek, P. and E. J. Krakiwsky, *Geodesy: The Concepts*, North-Holland Publishing Company Amsterdam, New York, Oxford, 1982.

Virtanen, H., Hydrological studies at the gravity station Metshovi, Finland, *J. Geodetic. Soc. Jpn.*, **47**(1), 328–333, 2001.

Wahr, J., M. Molenaar, and F. Bryan, Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, **103**(12), 30205–30229, 1998.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna, Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, **31**(11), L11501, doi: 10.1029/2004GL019779, 2004.

Wenzel, H. G., The nanogal software: data processing package Eterna 3.3, *Bull. Inf. Marees Terrestres*, **124**, 9425–9439, 1996.

Wilks, D. S., *Statistical methods in the atmospheric sciences: an introduction*, Academic Press, San Diego, 1995.

Zürn, W. and H. Wilhelm, Tides of the Earth, in *Landolt-Börnstein*, 259–299, Springer Verlag Berlin Heidelberg New York Tokyo, Vol. 2, 1984.

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