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Seasonal effects of non-tidal oceanic mass shifts in observations with superconducting gravimeters

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Abstract

In order to achieve a consistent combination of terrestrial and satellite-derived (GRACE) gravity field variations reductions of systematic perturbations must be applied to both data sets. At the same time evidence needs to be provided that these reductions are both necessary and sufficient. Based on the OMCT and the ECCO model the gravity effect of non-tidal oceanic mass shifts is computed for various sites equipped with a superconducting gravimeter (SG) and esp. the long-periodic contributions are studied. With these oceanic models the dynamic ocean response to atmospheric pressure loading is automatically computed, and thus goes beyond the more simplistic concepts of an inverted barometer, or alternately a rigid ocean, which is a clear advantage.

The findings so far are ambiguous: For instance the systematic seasonal change of about 10 nm/s^2 in gravity for mid-European stations is presently not found in the observed gravity variations. Generally, the order of magnitude of the total effect of 22 to 27 nm/s^2 is surprisingly large for inland stations. In some data sections the reduction leads to the removal of some of the larger residuals. The results obtained for the South-African station Sutherland differ. Here the modelled seasonal variation caused by the non-tidal oceanic mass redistribution and gravity residuals generally correlate, and thus by the reduction an improvement of the signal-to-noise ratio in the gravity observations is achieved.

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An explanation for the different results might be found in the global hydrological models. Such a model is needed in order to remove the effect of large-scale variations in continental water storage in the gravity observations. This reduction plays a greater role for European stations than for the South African site. A critical impact of the land-sea-mask used in the oceanic models and the subsequent insufficient resolution of the North and Baltic Sea on the computations at the mid-European sites could not be confirmed.

From a comparison between the OMCT and the ECCO model substantial discrepancies in some regions of the earth emerge, while both predict variations at inland stations in Europe, South Africa, and Asia of similar magnitude. We currently hesitate to recommend including this reduction in the routine processing of SG data because the seasonal order of magnitude for inland stations is unexpectedly large and partly significant deviations between the modelled oceanic effects exist. If the order of magnitude proves to be correct universally, this reduction has to be applied.

Key words: superconducting gravimetry, ocean models, GRACE validation, long-periodic gravity variations

1. Introduction

Recently, long-term gravity changes in terrestrial observations have again moved into focus, as several year-long high-quality data sets of superconducting gravimeters (SG) worldwide have become available. Further interest is added with respect to a validation of temporal gravity field variations derived from satellite data, e. g. from the GRACE mission, by ground-based SG observations and a combination of both data sets (Hinderer et al., 2006; Neumeyer et al., 2008; Crossley et al., 2009; Weise et al., 2009). The study of long-periodic geodynamic phenomena as well as the investigation of mass shifts in the Earth's system, i. e. related to hydrology, which is a topic of increased interest, require an adequate understanding of all additional signals occurring in the same spectral range and sufficiently accurate methods for their removal. Thus, a number of investigations of the last years were aimed to improve the reduction of

effects induced by atmospheric mass shifts (Neumeyer et al., 2004, 2006; Abe et al., 2008) and the analysis of hydrological signals (Kroner et al., 2004; Hinderer et al., 2006; Naujoks et al., 2008) to name only a few. Further studies dealt specifically with seasonal gravity signals (Boy & Hinderer, 2006; Sato et al., 2006), long-periodic oceanic tides (Boy et al., 2006) or the gravity effect of the oceanic pole tide (Chen et al., 2008).

Following the agenda to improve the understanding of signal contributions in the spectral range of several weeks and longer and to improve the signal-to-noise ratio, also the effect of non-tidal mass shifts in the oceans should be considered. As shown by Fratepietro et al. (2006) and Boy & Lyard (2008) due to storm surges a significant gravity effect of some 10 nm/s^2 can occur at inland stations affecting the short-periodic spectral range. Hence, the question arises whether there might be also non-negligible long-periodic effects. Additionally, this is of interest as the effect of non-tidal oceanic mass shifts is routinely taken into account in the processing of the GRACE observations. Thus, for a rigorous combination of satellite and terrestrial data, this reduction should likewise be considered in the processing of the latter. One additional benefit would be that the response of the oceans upon changes in atmospheric pressure would be inherently included, and assumptions on an inverted-barometer response would become redundant.

In the present study two models are considered: the 'Ocean Model for Circulation and Tides' (OMCT, Dobslaw and Thomas, 2007) and the model for 'Estimating the Circulation and Climate of the Ocean' (ECCO, provided by JPL). Before the gravity effect at selected stations is computed from the models, time series of ocean bottom pressure extracted from the models are compared at various locations worldwide. Europe is of particular interest because here a regional network of superconducting gravimeters exists. The region is therefore most suitable for the validation of GRACE observations and studies of spatial and temporal gravity variations caused by e. g. hydrological mass transport. The study ends with a first comparison between modelled gravity changes and gravity residuals for the example of the SG stations Moxa (Germany) and Sutherland (South Africa).

2. Models for non-tidal oceanic mass shifts

In the following some details on the ocean models used in this study are summarized based on information given in Dobslaw and Thomas (2007) and at www.ecco-group.org.

OMCT. In this model the nonlinear balance equations for momentum, the continuity equation, and conservation equations for heat and salinity are solved. Hydrostatic and the Boussinesq approximations are employed in the modelling of the currents. The model forcing comes from 6 h wind stresses, atmospheric surface pressure, 2 m-air temperature and freshwater fluxes due to precipitation, and evaporation in which model data from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used. Runoff represented by an additional hydrological model is also taken into account. The model consists of 13 layers and has a resolution of 1.875° in latitude and longitude. The OMCT is a global model with a thermodynamic ice model included. For the present study ocean bottom pressure data with a temporal resolution of 6 h are available.

ECCO. The ECCO model is based on the MIT Ocean General Circulation Model (MITgcm, e. g. Marshall et al., 1997; Marotzke et al., 1999). It is dedicated to the study of seasonal to interannual changes in ocean circulation from assimilating observations with a global ocean circulation model with emphasis on the tropical Pacific Ocean. The model is forced with 12 h wind stress and daily diabatic air-sea fluxes taken from the National Center for Environmental Predictions (NCEP) reanalysis products. The model contains 46 layers of which 15 are equidistantly spaced in the upper 150 m. The model covers the area between 78°S and 78°N with a 1° latitude and longitude resolution except for a region within 20° around the equator. There the latitudinal resolution is gradually increasing to 0.3° . The temporal resolution for ocean bottom pressure is 12 h.

Due to the grid of the global models the European shelf areas are insufficiently resolved in both ocean models.

In Figure 1 time series of ocean bottom pressure for the years 2001 to 2006 extracted from the models are shown for five arbitrary locations worldwide. Black dots mark sites at which presently a superconducting gravimeter is operating. Compared with the ECCO model the OMCT-derived variations mostly contain clearly more and stronger fluctuations, which can only be partly explained by the different temporal resolution of the data sets. Apart from the two locations in the western Pacific a generally good agreement is found between both amplitudes and phases at all sites as far as seasonal changes are concerned. The discrepancies occurring in the western Pacific are probably related to the complex bathymetry conditions and coastal structure in that area. With regard to the expected gravity effect induced by these long-periodic variations we note that ocean bottom pressure time series contain a pronounced seasonal change. In the north-Atlantic it is garland-like with a maximum in January. Noting the strength of these variations traces of them might be expected in the SG observations.

Figure 1

3. Estimate of gravity effect induced by non-tidal oceanic mass shifts

The gravity effect caused by non-tidal mass shifts in the oceans consists of two components: the attraction effect of the water masses and the deformation effect due to the combined load of the water and air columns on the earth's elastic crust. The effect was computed with a modified version of the program *load97.for* for ocean loading by Francis (Francis & Dehant, 1987; Francis & Mazzega, 1990) which is distributed with the ETERNA 3.4 software package (Wenzel, 1996). For the loading computations an earth structure according to PREM (Dziewonski & Anderson, 1981) was assumed. The same Green's function was used in all loading computations (cf. section 4). The ocean bottom pressure data can be directly used with the program instead of changes in water column heights by utilizing the equation for hydrostatic pressure.

In Figure 2 the results for five globally distributed SG stations are given. In Table 1 the coordinates, elevation, approximate distance to the nearest coast and nearest center of model cell are listed. None of the stations is an immediate coastal station, but both,

Sutherland and Canberra station are close enough to the ocean to experience larger loading effects, which is well known from studies regarding ocean tidal loading (Sato et al., 2002; Neumeier et al., 2006). Taking into account the cell size of the models, the distances between station location and model ocean are similar to the real distance from the station to the nearest oceanic mass.

Table 1

Figure 2

The peak-to-peak amplitude of the ocean-based effect amounts to 22 to 27 nm/s^2 in the case of the OMCT and to 10 to 12 nm/s^2 in the case of the ECCO model which is in a similar order of magnitude as the gravity effect of ocean tidal loading. The seasonal part in the OMCT-based estimate has only a slightly higher amplitude than the one obtained from the ECCO model. These results suggest that the seasonal contributions of non-tidal mass redistribution with respect to long-periodic signals, for instance related to polar motion (amplitude: several 10 nm/s^2) or changes in continental water storage (peak-to-peak amplitude: about 40 nm/s^2 for mid-Europe, 13 nm/s^2 for Sutherland), are not negligible. The order of magnitude of the long-periodic effects obtained for Bad Homburg, Moxa, and Wuhan comes as a surprise, since these stations are several 100 km away from the oceans with shelf areas treated as land in the ocean models. The seasonal gravity changes obtained for Bad Homburg and Moxa based on the two ocean models agree well with each other. The characteristics of the seasonal variations are also found in the ocean bottom pressure time series for the north Atlantic shown in Figure 1. A good agreement between the modelled gravity effects is likewise obtained for Canberra. For Sutherland and Wuhan a phase shift of some months exists in the seasonal variations. The respective long-periodic amplitude is again similar.

4. Comparison with observations

As a next step the modelled non-tidal oceanic loading effect is compared with the gravity residuals from the stations Moxa and Sutherland. These observatories are se-

lected as they are located in two different regions of the earth and are characterized by a high data quality. At both stations local hydrological effects which might also introduce seasonal variations into gravity can be removed with sufficient accuracy. Because of the higher temporal resolution and separate files for the oceanic and the atmospheric contribution (cf. section 2) only the OMCT-derived gravity change is considered in the comparison. The atmospheric part covers also the land surface, so that the deformation effect caused by the atmosphere can be computed from one consistent data set.

The gravity data are reduced for all known long-periodic signals. The attraction effect of the atmosphere is removed by applying a three-dimensional (3D) atmospheric reduction up to a distance of 5° from the SG station (Neumeyer et al., 2004, 2006; Abe et al., 2008) using 3D (surface + upper level) model data from ECMWF (Integrated Forecast System (IFS) – Daily Analysis and Error Estimates, 6 h time interval). The attraction effect of the atmosphere above the rest of the earth's surface is computed according to Merriam (1992) based on the surface pressure data used in the OMCT computations and a model atmosphere. The SG data are detided using parameters determined for the stations from tidal analyses with the ETERNA 3.4 software package (Wenzel, 1996) except for the long-periodic tides SA and SSA. For these tidal constituents model parameters based on the Wahr-Dehant-Zschau model (Wahr, 1981; Dehant, 1987) are used. The effect of ocean tidal loading is reduced using the parameters obtained from the 'Ocean Loading Provider' by M. S. Bos and H.-G. Scherneck (www.oso.chalmers.se/~loading/index.html) for the ocean model FES2004 (Lyard et al., 2006). The polar motion signal and the effect of variations in length-of-day are eliminated with an amplitude factor for the long-periodic tides and a phase of 0° (Wahr, 1985). The gravity effect of the pole tide in the oceans is removed according to Chen et al. (2008). The uncertainties in global hydrological models notwithstanding the influence of changes in continental water storage is eliminated using the WaterGAP Global Hydrological Model (WGHM, Döll et al., 2003). In the case of Sutherland the local long-term hydrological influence is reduced in the gravity observations with a coefficient of $8.18 \text{ nm/s}^2/\text{m}$ and water level observations in the vicinity of the SG site as proxy for soil moisture changes. Considering the complex hydrological situation and stronger hydrological influence compared to Sutherland, a reduction from

a local hydrological–gravimetric model is applied to the Moxa data (Naujoks et al., 2008),(Weise et al., 2009). The drift in both gravity data sets is eliminated assuming a linear trend using repeated absolute gravity measurements at the sites as an additional constraint.

The resulting gravity residuals for Moxa and Sutherland together with the OMCT–derived gravity effect and the residuals reduced for the influence are shown in Figures 3 and 4.

Figure 3

Figure 4

No real agreement is found between the gravity residuals from Moxa observatory and the seasonal variations in the OMCT–based gravity effect. In contrast, clear correlations exist on shorter time scales such as one month or below, e. g. around December 03, March 05, or May 06, but also periods with no agreement at all, e. g. during November–December 05. At times when observed and simulated gravity changes correspond to each other, the application of the reduction significantly improves the signal–to–noise ratio of the gravity residuals in these time windows. Altogether improvements and degradations balance each other leading to almost identical rms values for the unreduced and the reduced gravity residuals. These findings in the short–periodic range as well as the missing agreement in the seasonal spectral range might occur for several reasons. One explanation could be that the gravity residuals still contain another significant influence which is larger than the effect caused by non–tidal oceanic mass shifts. Changes in the European continental water storage are a likely candidate. The WGHM in its present version has a lateral resolution of 0.5° and a monthly time step. This might not be sufficient to adequately remove regional–scale hydrological effects in the SG data from European stations. A possible critical impact of the land–sea–mask of the oceanic models and the resulting insufficient resolution of the North and Baltic Sea could not be confirmed. The OMCT and the ECCO model have with 1.875° and 1° a different spatial resolution. The incorporation of a high resolution model (BSHcmod, $5' \times 3'$, resp. $50'' \times 30''$) for the North and Baltic Sea from

the BSH (Bundesamt für Seeschifffahrt und Hydrographie, Dick et al., 2001) does not change substantially the general order of magnitude of the seasonal variations or their features.

A slightly different situation exists at Sutherland. Here a rudimentary agreement between the gravity residuals and the changes modelled with the OMCT is found. From the point of view of the gravity observations the effect of non-tidal ocean loading appears to be even underestimated. When the reduction is applied the rms-value decreases by 9%. Currently, one explanation might be thought of why the non-tidal ocean loading reduction appears to work for a South African station but not for a mid-European one. This could be due to the significantly smaller variations in the large-scale continental water storage, which produce a gravity effect of only about one fifth of the effect found for mid-Europe. For Sutherland the conclusion would be that the reduction for non-tidal oceanic mass shifts ought to be applied.

5. Conclusions

In the endeavour to improve signal-to-noise ratios in the long-period spectral range of high-precision SG records, but likewise to ensure data treatment consistent with the processing of time-dependent satellite observations, the influence of non-tidal mass shifts in the oceans needs to be considered. Gravity effects estimated on the basis of the OMCT and the ECCO model emerge in the order of 12 to 27 nm/s^2 peak-to-peak. A seasonal change of roughly 10 nm/s^2 for SG stations worldwide even at distances of several 100 km from the coast is found. The agreement between the effects derived from the two ocean models is good in Europe. Larger discrepancies exist mainly at stations bordering the western Pacific.

At the Moxa station in mid-Europe a limited improvement in the gravity residuals results from the reduction. The modelled seasonal gravity variations are not seen in the observed gravity data. Similar results are obtained for other mid-European SG stations. In the case of the South African station Sutherland, however, we find a correlation between gravity residuals and the seasonal terms. One possible explanation might be that large-scale changes in continental water storage have not sufficiently been taken care

of in case of the mid-European station. This would explain why the reduction works for the Sutherland time series but apparently not for mid-European ones as shown for the example of Moxa. The local hydrological effects at the SG stations investigated are sufficiently well understood to exclude a significant remaining influence.

In order to obtain more clarity regarding the gravity effect of non-tidal oceanic mass shifts for the European region and the possible necessity of its removal the influence of changes in the European continental water storage will be recomputed based on more advanced hydrological models. These models will become available soon (Menzel, pers. comm., 2008), one with an improved orographic resolution and later on a second one which will incorporate an extended hydrological database.

The investigation needs also to be extended to other SG stations worldwide. If the order of magnitude of the seasonal component in the gravity effect of non-tidal oceanic mass shifts is confirmed, this effect has to be considered basically in all studies related to phenomena in gravity acting at periods of weeks and longer, in particular when terrestrial and satellite-derived data sets of temporal gravity variations are to be combined.

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Captions

Table 1. Details on the stations considered regarding the effect of non-tidal oceanic mass shifts.

Figure 1. Relative variations in ocean bottom pressure for five locations worldwide extracted from the OMCT and the ECCO model for the period 2001–2006. Black dots mark current superconducting gravimeter stations. Denote the different scaling of the pressure axis.

Figure 2. Gravity effect computed for five globally distributed SG stations for OMCT (–) and ECCO (–) model for the years 2001 to 2006.

Figure 3. Gravity residuals for Moxa observatory, OMCT-derived gravity effect, and residuals reduced for the influence, years 2003–2006.

Figure 4. Gravity residuals for Sutherland observatory, OMCT-derived gravity effect, and residuals reduced for the influence, years 2002–2006.

Table 1:

station	latitude	longitude	elevation	coastal	center near. cell [km]	
	[°N]	[°E]	[m]	distance [km]	OMCT	ECCO
Bad Homburg (Germany)	50.2285	8.6113	190	400	430	380
Canberra Australia)	-35.3206	149.0077	724	100	250	140
Moxa (Germany)	50.6447	11.6156	455	450	430	470
Sutherland (South Africa)	-32.3814	20.8109	1791	200	360	280
Wuhan (China)	30.5159	114.4898	89	650	700	720

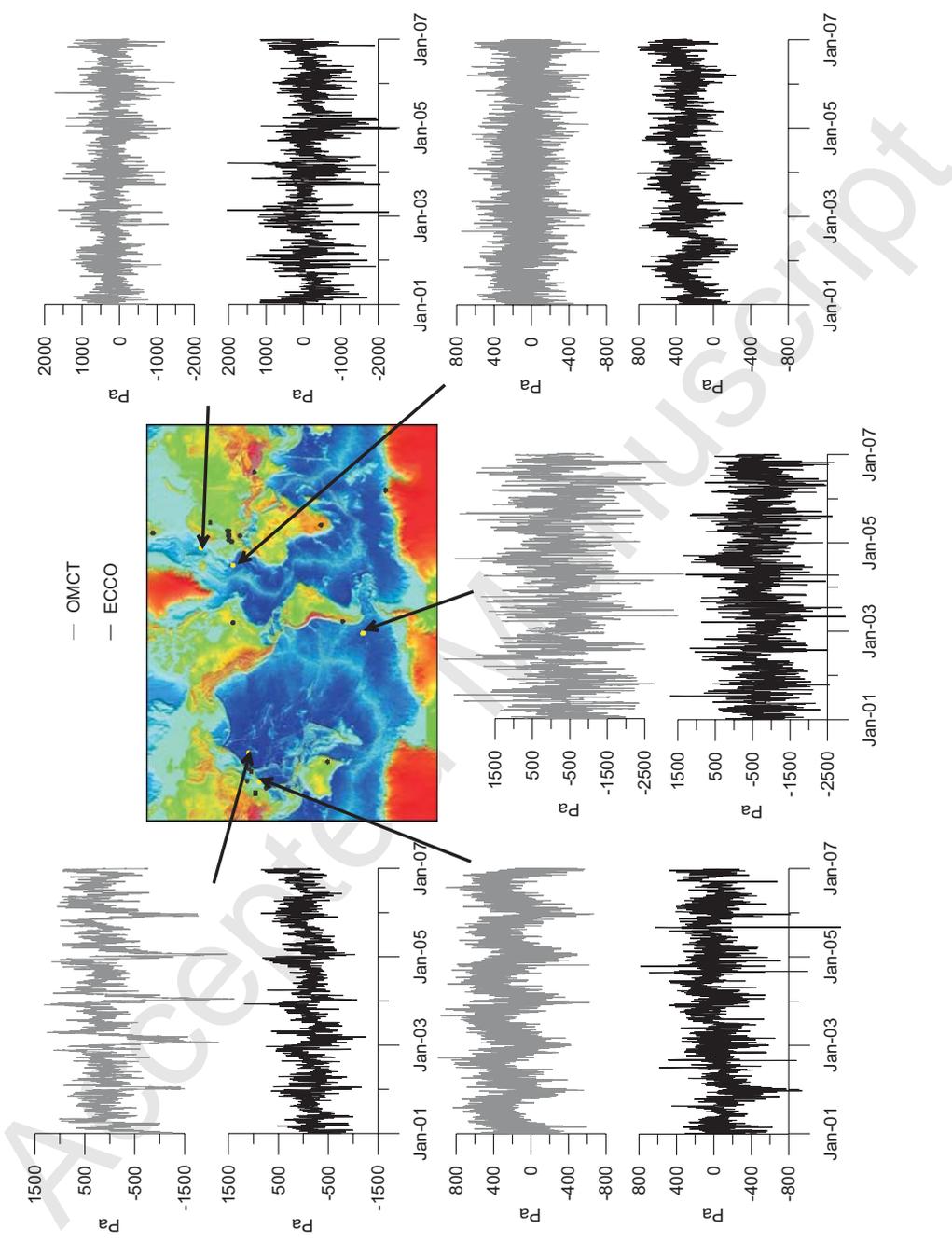


Figure 1:

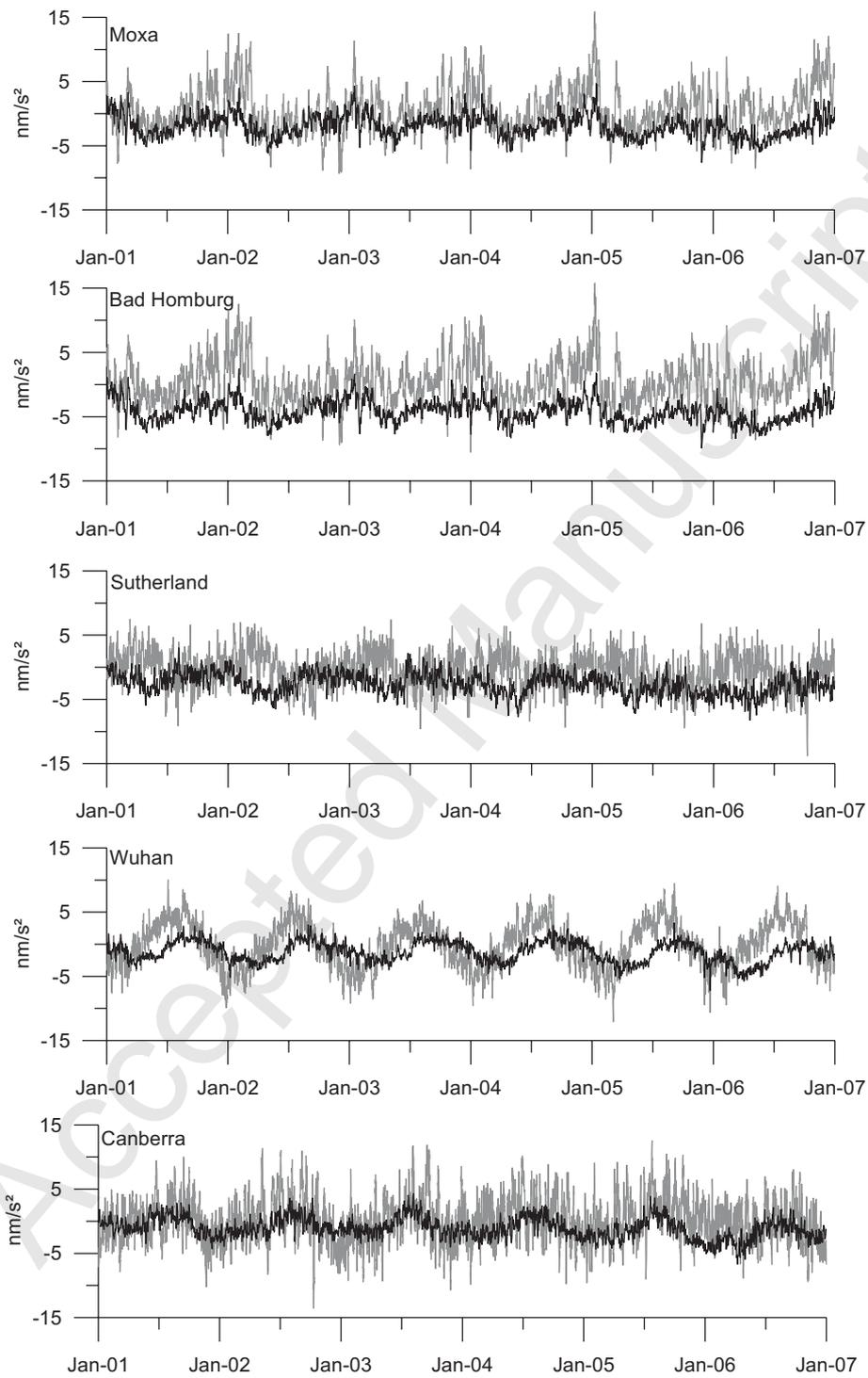


Figure 2:

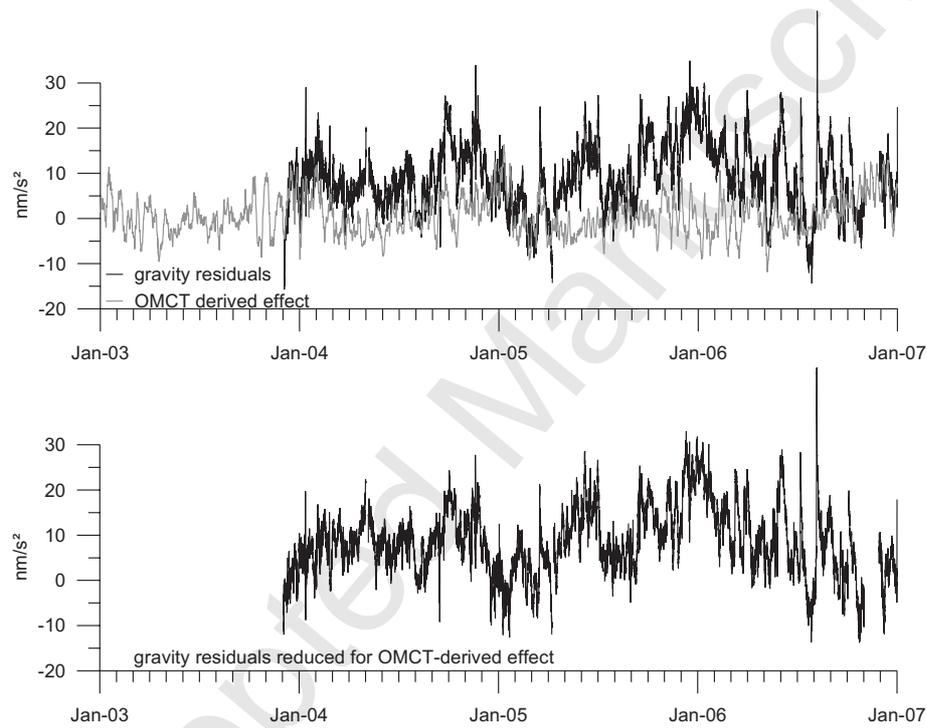


Figure 3:

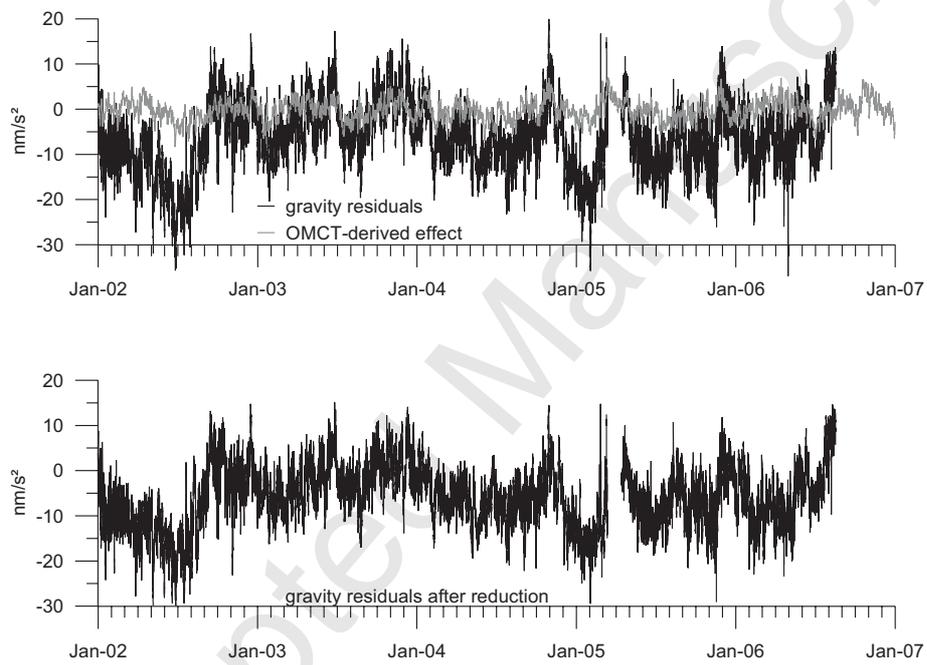


Figure 4: