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ORIGINAL PAPER

COMPARISON OF VERTICAL DEFORMATIONS OF THE EARTH'S SURFACE OBTAINED USING GRACE-BASED GGMS AND GNSS DATA – A CASE STUDY OF SOUTH-EASTERN POLAND

Walyeldeen GODAH, Malgorzata SZELACHOWSKA*, Jagat Dwipendra RAY and Jan KRYNSKI

Institute of Geodesy and Cartography, Centre of Geodesy and Geodynamics, 27 Modzelewskiego St., 02–679 Warsaw, Poland

**Corresponding author's e-mail:* malgorzata.szelachowska@igik.edu.pl

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ABSTRACT

The development of knowledge on geodynamic processes is one of the most important issues in the Earth's science. Over decades, geodetic techniques have been applied to study the geodynamics. The Global Navigation Satellite Systems (GNSS) have been reliably used for monitoring geodynamic processes. The satellite gravimetric missions such as GRACE (Gravity Recovery And Climate Experiment) and GRACE Follow-On (GRACE-FO) missions have provided numerous valuable information concerning temporal mass variations within the Earth system which can subsequently be converted to surface deformations of the Earth. The main aim of this study is to compare vertical deformations of the Earth's surface over the area of South-Eastern Poland obtained from GNSS data with the corresponding ones determined from GRACE data.

The GNSS data for the period between 2008 and 2013 from 25 permanent GNSS stations operating in South-Eastern Poland and the latest release of GRACE-based Global Geopotential Models (GGMs) were used. GNSS data and GRACE-based GGMs were processed with the GAMIT/GLOBK and the IGiK–TVGMF (Institute of Geodesy and Cartography – Temporal Variations of Gravity/Mass Functionals) packages, respectively. The results obtained indicate that monthly vertical deformations of the Earth's surface determined using GNSS data are generally in a good agreement with the corresponding ones obtained from GRACE satellite mission data. Coefficients of correlation between these vertical deformations range from 0.60 to 0.90 and standard deviations of their differences are in the range of 2.6 – 5.7 mm.

1. INTRODUCTION

The Earth's surface is deformed in the time domain ranging from sub-daily to decadal and even longer periods. This deformation occurs in the space domain ranging from local to global scales. The main reasons for this deformation can be ascribed to the tidal force, tectonics, glacial isostatic adjustment and mass redistribution within the Earth system (e.g. masses of atmosphere, cryosphere, and hydrosphere). The development of knowledge concerning the Earth's surface deformation is one of the most important issues in the Earth's science.

Over decades, geodetic techniques such as the Global Navigation Satellite Systems (GNSS) have played an essential role for the determination of the Earth's surface deformation. From the beginning of this millennium, the dedicated gravity satellite missions, in particular the Gravity Recovery And Climate Experiment (GRACE; Tapley et al., 2004) operated between March 2002 and October 2017, and GRACE Follow-On (GRACE-FO) launched on 22 May 2018, have provided valuable information concerning temporal mass variations within the Earth system. On the basis of GRACE satellite mission and GNSS data, many research concerning the Earth's surface deformations induced by mass loading changes have been conducted on a global scale, e.g. Kusche and Schrama (2005); Tregoning et al. (2009); Rietbroek et al. (2014), on a continental scale, e.g. Bevis et al. (2005) in South America, and van Dam et al. (2007) in Europe, as well as on a local/regional scale, e.g. Davis et al. (2004) in the Amazon basin, Nahmani et al. (2012) in the West Africa, Birhanu and Bendick (2015) in the East Africa, Steckler et al. (2010) in Bangladesh, Zhang et al. (2016) in China, Pan et al. (2016) in Tibet, Bevis et al. (2012) in Greenland, and Tan et al. (2016) in North America. Except van Dam et al. (2007) that indicated poor correlation between the annual vertical crustal deformation from GRACE and 36 GPS (Global Positioning System) stations over Europe, all those studies revealed a good agreement between vertical deformations of the Earth's surface obtained from GRACE and from GNSS data.

For the area of Poland, Rajner and Liwosz (2011) indicated a good agreement between deformations due to the continental water storage and height changes obtained from GPS data of four permanent Polish GNSS stations. Rajner and Liwosz (2017) analyzed

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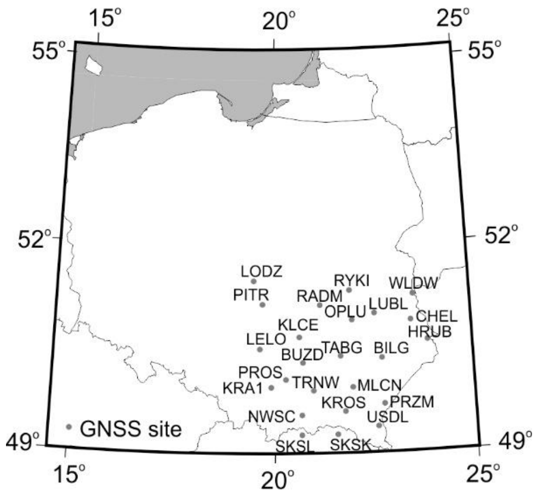

Fig. 1 The location of GNSS stations investigated

seasonal position variations determined from GPS, GRACE and hydrological data at eight permanent Polish GNSS stations. Bogusz and Figurski (2014) estimated the annual signal in the time series of coordinates of the ASG-EUPOS (Active Geodetic Network of the European Position Determination System)[1] stations for five years of observations (GPS weeks 1465–1729). They recommended further investigation concerning the use of GRACE satellite mission data to improve the reliability of vertical deformations determined from GPS solutions.

In the last decade, extreme land hydrology events like flooding in 2010 and increased precipitation in 2011 were observed in the area of South-Eastern Poland (Kuczynska-Siehien et al., 2019). The main aim of this study is to compare vertical deformations of the Earth's surface over the area of South-Eastern Poland obtained from GNSS data with the corresponding ones determined from GRACE data within the period of those extreme hydrologic events. The data used and the methods implemented for the determination of vertical deformations of the Earth's surface are described in Section 2. The results obtained are presented and discussed in Section 3. Finally, in Section 4, conclusions and recommendations concerning vertical deformations of the Earth's surface determined using GNSS and GRACE satellite mission data for the area and the period investigated are drawn.

2. DATA AND METHOD USED

In this study, vertical deformations of the Earth's surface for the period 2008–2013 were determined at 25 GNSS stations of the ASG-EUPOS network located in South-East of Poland (cf. Fig. 1) using GNSS and GRACE satellite mission data.

The quality of GNSS data from 25 stations aforementioned were checked using TEQC (Translation, Editing, and Quality Checking) software developed by UNAVCO (Estey and Meertens, 1999). Then, they were processed using the GAMIT/GLOBK software version 10.7 (Herring et al., 2015, 2018). The signal delay caused by first-order ionospheric refraction was eliminated using linear combination of L1 and L2. The delay caused by second- and third-order ionospheric refraction of the carrier wave was also removed using daily IONosphere map EXchange format (IONEX) files, which represent the ionosphere in the form of global maps of the vertical total electron content (VTEC) and are provided by the Centre for Orbit Determination in Europe (CODE, Schaer et al., 1998; Petrie et al., 2010). The tropospheric delay for each station was estimated for every 2h from GNSS data acquired at ASG-EUPOS stations investigated using the piecewise linear function. The Vienna Mapping Function (VMF1) with a priori hydrostatic delay estimates based on the global pressure and temperature (GPT2) model (Lagler et al., 2013) were used to estimate the tropospheric delay (Kouba, 2008). Deformation induced by atmospheric loading was removed by applying the atmospheric loading model (ATML, Tregoning and van Dam, 2005) at the observation level. These ATML models were provided by the Massachusetts Institute of Technology (MIT). Deformation arising from oceanic tidal loading was removed using the Finite Element Solutions 2004 (FES2004) tidal model (Lyard et al., 2006).

The daily loosely constrained solutions obtained from GAMIT were combined with global solutions provided by the MIT using GLOBK. One of the main advantages of using these global solutions can be ascribed to the fact that global solutions provide ready access to more frame defining sites and hence give more robust estimation than regional solutions (Legrand et al., 2010). Within the course of this step of processing, the reference frame was defined using GLORG that imposes generalized constraints on frame defining sites while estimating translation and rotation. Finally, time series of daily vertical deformation were estimated in the International Terrestrial Reference Frame 2014 (ITRF2014, Altamimi et al., 2016). The main processing steps

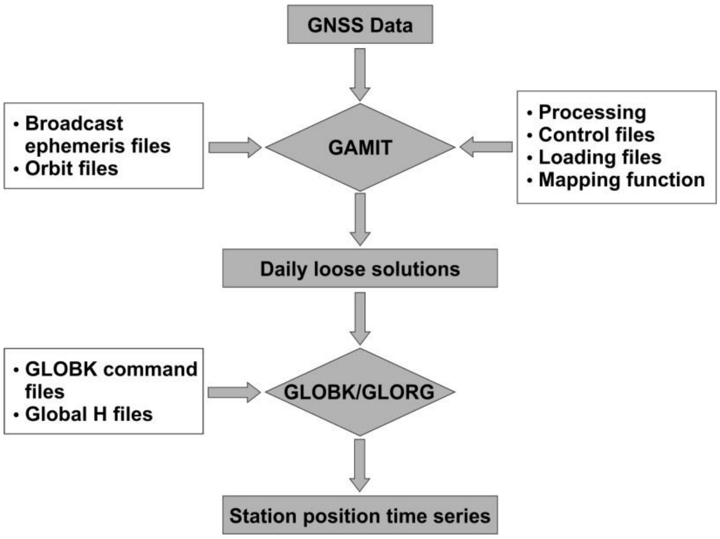

Fig. 2 General scheme of processing GNSS data to obtain daily vertical deformations

implemented to obtain daily vertical deformations from GNSS data were illustrated in Figure 2. The daily repeatability of vertical deformations of the Earth's surface obtained from GNSS data are within the range of 3 mm to 4 mm. Daily vertical deformation values that exceed the daily repeatability within the same month were considered as outliers. These outliers were detected using GAMIT/GLOBK MATLAB TOOL (Herring, 2003) and subsequently removed. Monthly vertical deformations were obtained by averaging all daily vertical deformations of each month.

The release 6 (RL06) of monthly GRACE-based GGMs developed by the official GRACE Science Data System (SDS) computing centres, i.e. the GFZ (GeoForschungsZentrum Potsdam; Dahle et al., 2019), CSR (Centre for Space Research at the University of Texas, Austin; Bettadpur, 2018) and JPL (Jet Propulsion Laboratory; McCullough and Wiese, 2018) centres, were used in this study. The low-degree harmonic coefficients, i.e. degree-1 and degree-2, of these GGMs were replaced by the corresponding ones obtained from the solution described in Sun et al. (2016) and from Satellite Laser Ranging (SLR) observations (Cheng and Ries, 2017), respectively. The decorrelation filter, in particular, the DDK3 filter (cf. Kusche et al., 2009) that indicates a good performance over the area investigated (Godah et al., 2017), was applied to reduce the noise included in RL06 GRACE-based GGMs. Moreover, taking into consideration the spatial resolution of monthly solutions obtained from GRACE satellite mission, i.e. $3^o \times 3^o$ at the equator, these GGMs were truncated at d/o 60.

In order to select the suitable models among the monthly GGMs developed by GRACE SDS centres, a preparatory investigation was conducted. Temporal variations of the equivalent water thickness ΔEWT were determined at the location of GNSS stations investigated (see Fig. 1) using monthly RL06 GRACE-based GGMs from the CSR, GFZ and JPL computing centres as follows (cf. Wahr et al., 1998; Godah, 2019):

$$\Delta EWT = \frac{a \times \rho_{ave}}{3} \sum_{n=0}^{N_{\max}} \left(\frac{2n+1}{1-k_n} \right) \sum_{m=0}^{n} P_{nm} \left(\sin\varphi \right) \left(\Delta C_{nm} \cos m\lambda + \Delta S_{nm} \sin m\lambda \right) \tag{1}$$

with

$C_{nm} = C_{nm}^{W} - C_{nm}^{U}$ *and* $S_{nm} = S_{nm}^{W} - S_{nm}^{U}$,

where

φ, λ	are spherical geocentric coordinates of the computation point,
a	is the Earth's equatorial radius,
ρ_{ave}	is the Earth's average density,
k	represents load Love numbers based on the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) obtained from (Wang et al., 2012),
C_{nm}^{U}, S_{nm}^{U}	denote spherical harmonic coefficients of the normal gravity field,
C_{nm}^{W}, S_{nm}^{W}	are the fully normalized Stokes coefficients from GRACE-based GGMs,
ΔC_{nm}, ΔS_{nm}	are differences between C_{nm} and S_{nm} obtained from monthly RL06 GRACE-based GGMs and the corresponding ones obtained from a suitable reference model,
P_{nm}	are the fully normalized Legendre functions of degree n and order m, and
$N_{\max}$	is the maximum degree applied.

The ΔEWT determined from monthly RL06 GRACE-based GGMs were evaluated using the corresponding ones obtained from the WaterGAP (Water – Global Assessment and Prognosis) Global Hydrological Model (WGHM; Döll et al., 2014) to identify which of the GRACE SDS computing centres provide the most suitable monthly RL06 GRACE-based GGMs.

Vertical deformations of the Earth's surface were determined at the locations of GNSS stations investigated (see Fig. 1) using the selected monthly RL06 GRACE-based GGMs as follows (cf. Wahr et al., 1998; Zhang et al., 2017; Godah, 2019):

$$\Delta h = \frac{3a\rho_w}{\rho_{avg}} \sum_{n=0}^{N_{max}} \sum_{m=0}^{n} P_{nm}(\sin\varphi) \frac{h_n}{2n+1} \left(\Delta C_{nm}^{\sigma} \cos m\lambda + \Delta S_{nm}^{\sigma} \sin m\lambda \right) \tag{2}$$

with surface density coefficients ΔC_{nm}^{σ} and ΔS_{nm}^{σ} defined as

$$\begin{Bmatrix} \Delta C_{nm}^{\sigma} \\ \Delta S_{nm}^{\sigma} \end{Bmatrix} = \frac{\rho_{avg}}{3\rho_w} \frac{2n+1}{1+k_n} \begin{Bmatrix} \Delta C_{nm} \\ \Delta S_{nm} \end{Bmatrix},$$

where h_n are load Love numbers of degree n and ρ_w is the water density.

The ΔEWT and Δh were determined from RL06 GRACE-based GGMs using the IGiK–TVGMF (Institute of Geodesy and Cartography –Temporal Variations of Gravity/Mass Functionals) package (Godah, 2019). The WGS84 (World Geodetic System 1984) and the EGM2008 (Earth Gravitational Model 2008; Pavlis et al., 2012) truncated at d/o 60 were utilized as a reference system and reference model, respectively.

3. RESULTS

Temporal variations of the equivalent water thickness ΔEWT at the location of GNSS stations illustrated in Figure 1 were obtained from the WGHM and independently determined using RL06 GRACE-based GGMs developed by the official GRACE SDS computing centres, i.e. the CSR, GFZ and JPL centres for the period of 2008–2013. The correlations between them as well as standard deviations of their differences are depicted in Figures 3 and 4, respectively. The results presented in Figures 3 and 4 indicate that the three GRACE SDS computing centres perform quite similarly over the area investigated. In terms of correlation coefficients RL06 GRACE-based GGMs developed by the JPL computing centre perform slightly better, i.e. their correlation coefficients are higher by 0.01 to 0.05, at 18 GNSS stations (i.e. 72 % of GNSS stations investigated) than the corresponding GGMs developed by the CSR and GFZ computing centres. At 20 GNSS stations (i.e. 80 % of GNSS stations investigated), standard deviations of differences between ΔEWT obtained from the WGHM and from JPL RL06 GRACE-based GGMs are lower by 0.1 mm to 3.5 mm than the respective ones obtained with the use of RL06 GRACE-based GGMs developed by the CSR and GFZ centres. Thus, monthly RL06 GRACE-based GGMs developed by the JPL computing centre were chosen for the determination of vertical deformations of the Earth's surface. It should be noted that the spatial resolution of GRACE data is 3°×3° at the equator, while the spatial resolution of WGHM data is 0.5°×0.5°. Thus, strength of ΔEWT signal obtained from GRACE data and from WGHM can be different.

Vertical deformations of the Earth's surface Δh for the period 2008–2013 were determined on the basis of JPL RL06 GRACE-based GGMs and GNSS data from permanent GNSS stations of the ASG-EUPOS network (Fig. 1) using the method described in Section 2. Figure 5 shows time series of vertical deformations of the Earth's surface at the GNSS stations investigated obtained from GNSS data along with time series of Δh determined from JPL RL06 GRACE-based GGMs. It shows that due to technical issues such as changing the GNSS antenna, gaps occurred in the time series of vertical deformations of the Earth's surface obtained from GNSS data at TRNW and SKSL sites. Coefficients of correlation between these time series are illustrated in Figure 6. Standard deviations of differences between Δh obtained from GNSS data and the corresponding ones determined from JPL RL06 GRACE-based GGMs at the GNSS stations investigated are shown in Figure 7. Except the GNSS station SKSK, the results presented in Figure 5 reveal a distinctive seasonal pattern. This pattern indicates minimum values of Δh obtained within the winter–spring seasons and maximum values of Δh observed within the summer–fall seasons. For the area investigated, i.e. territory of Poland, this pattern could be ascribed to the change of mass loading induced by seasonal water mass variations of maximum values in March and minimum values in July–September (Krynski et al., 2014). Figure 5 also indicates that Δh obtained from GNSS data fit well to the corresponding ones determined from JPL RL06 GRACE-based GGMs. The results presented in Figure 6 reveal that coefficients of correlation between the corresponding Δh obtained from GNSS data and JPL RL06 GRACE-based GGMs range from 0.6 to 0.9 except stations NWSC and PRZM. Figure 7 illustrates that for all GNSS stations investigated except stations NWSC, PRZM and TRNW, standard deviations of differences between Δh obtained from GNSS data and JPL RL06 GRACE-based GGMs are at the level of 3±1 mm which corresponds to the accuracy of vertical component of coordinates determined using GNSS data. Relatively large standard deviation values, i.e. from 4.9 to 5.7 mm, observed at NWSC, PRZM and TRNW stations might be attributed to the local Δh signal that is detected by GNSS data as well as site dependent errors in GNSS estimates or/and the change of the antenna position (e.g. station TRNW in November 2011). The possible local Δh signal in GNSS

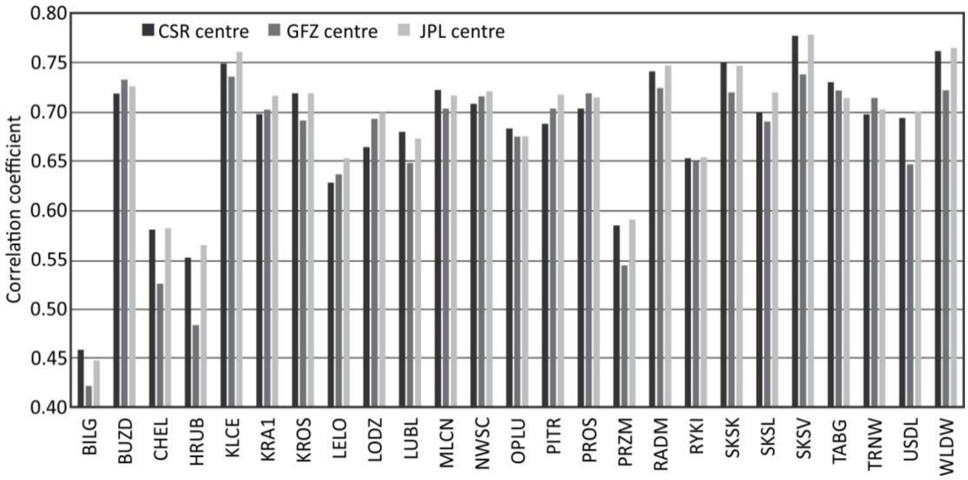

Fig. 3 Coefficients of correlation between ΔEWT obtained from the WGHM and the corresponding ones determined from RL06 GRACE-based GGMs developed by the CSR, GFZ and JPL computing centres.

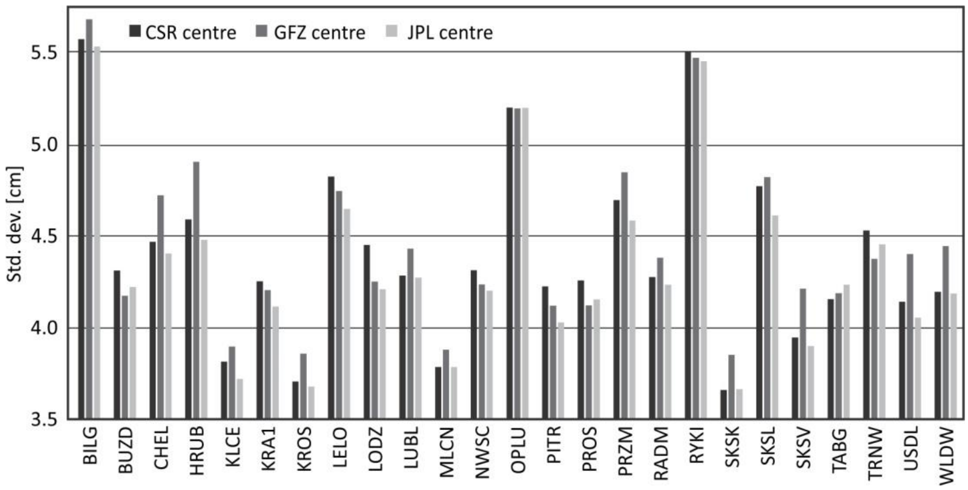

Fig. 4 Standard deviations of differences between ΔEWT obtained from the WGHM and the corresponding ones determined from RL06 GRACE-based GGMs developed by the CSR, GFZ and JPL computing centres.

data may be ascribed to the local variation of hydrological conditions that are not sensed by GRACE satellite mission. The investigated area of South-Eastern Poland was affected by extreme events like flooding in 2010 and increased precipitation in 2011 (Kuczynska-Siehien et al., 2019). The stations with lower correlations and higher standard deviations (NWSC – no GNSS data in 2010, PRZM and TRNW) might have been affected by the extreme events mentioned above relatively more than the other stations in the area investigated. The local Δh signal induces discrepancy in both phase and amplitude (low correlation and high standard deviation) between Δh obtained from GNSS data and the corresponding ones determined from JPL RL06 GRACE-based GGMs in the case of the stations NWSC and PRZM. The high correlation and larger standard deviation obtained for the station TRNW reveal that the local Δh signal induces discrepancy only in the amplitude between Δh obtained from GNSS data and the corresponding ones determined from JPL RL06 GRACE-based GGM.

4. CONCLUSIONS AND RECOMMENDATIONS

This paper discusses the vertical deformation of the Earth's surface obtained from GNSS and GRACE satellite mission data. GNSS data from 25 GNSS stations located in South-Eastern Poland as well as the RL06 GRACE-based GGMs developed by the official GRACE Science Data System (SDS), i.e. the CSR, GFZ and JPL, computing centres and the WGHM were utilized.

Firstly, a comparison between temporal variations of equivalent water thickness ΔEWT obtained from the WGHM and the corresponding ones determined from RL06 GRACE-based GGMs developed by GRACE SDS centres was conducted to select the most appropriate monthly GGMs datasets for this research. In terms of coefficients of correlation between ΔEWT obtained from the WGHM and GRACE-based GGMs developed by the GRACE SDS computing centres as well as standard deviations of their differences, JPL RL06 GRACE-based GGMs are slightly better than the RL06 GRACE-based GGMs

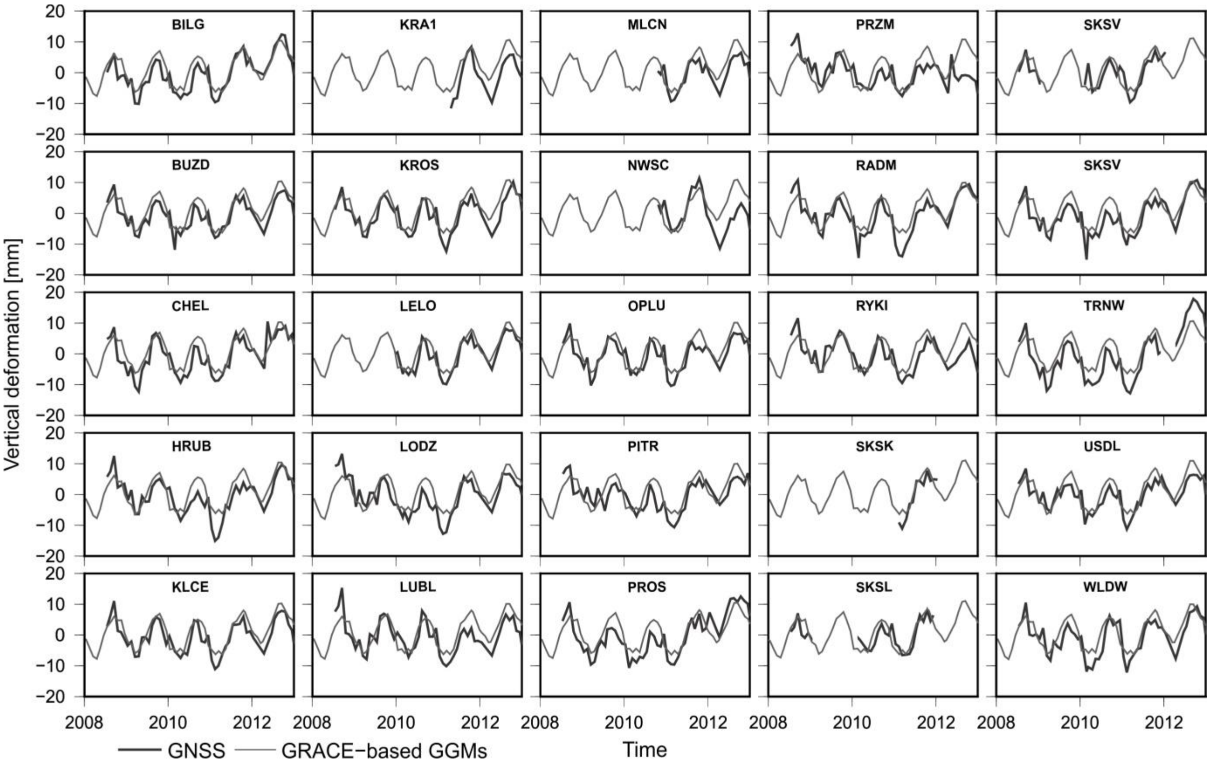

Fig. 5 Time series of monthly vertical deformations obtained from GNSS data and JPL RL06 GRACE-based GGMs for the period of 2008–2013.

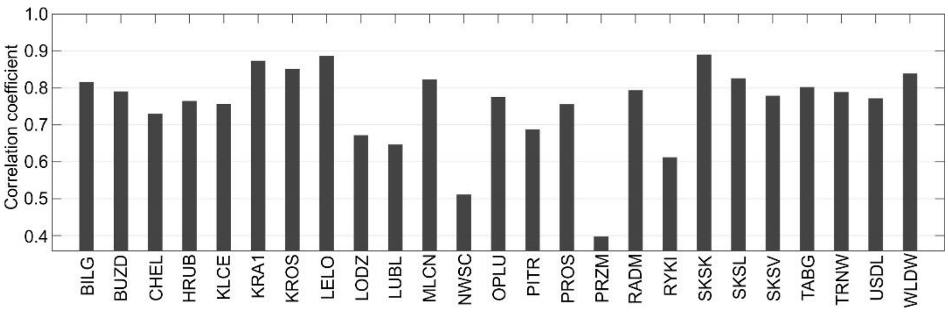

Fig. 6 Coefficients of correlation between monthly vertical deformations obtained from GNSS data and the corresponding ones obtained from JPL RL06 GRACE-based GGMs for the period of 2008–2013.

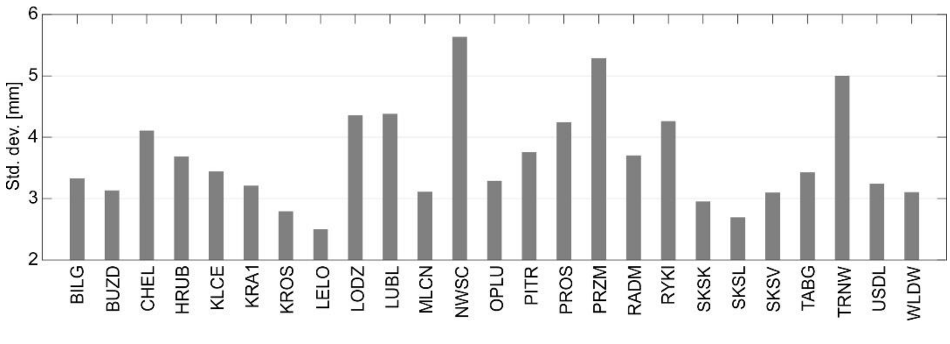

Fig. 7 Standard deviations of differences between monthly vertical deformations obtained from GNSS data and the corresponding ones obtained from JPL RL06 GRACE-based GGMs for the period of 2008–2013.

developed by other GRACE SDS centres. Thus, JPL RL06 GRACE-based GGMs were chosen for the determination of vertical deformation of the Earth's surface.

Secondly, monthly vertical deformations of the Earth's surface Δh obtained from GNSS data at the aforementioned 25 GNSS stations compared with the corresponding ones determined from JPL RL06 GRACE-based GGMs indicate mutual correlation. Coefficients of correlation between Δh obtained from GNSS data and the corresponding ones determined using JPL RL06 GRACE-based GGMs for all GNSS stations, except NWSC and PRZM stations, range from 0.60 to 0.90. Standard deviations of differences between Δh obtained from GNSS data and the corresponding ones from JPL RL06 GRACE-based GGMs range from 2.6 mm to 5.7 mm. They may reflect the local temporal mass variation signal that can be sensed by GNSS observations but not by GRACE satellite mission measurements or site dependent errors in the vertical position determined from GNSS data.

Overall, the results obtained show that monthly vertical deformations of the Earth's surface for long periods, e.g. 5 years, and short periods, e.g. several months, determined using GNSS data are merely in a good agreement with the corresponding ones obtained from GRACE satellite mission data. However, further investigations concerning vertical deformations of the Earth's surface obtained using GNSS data for a longer period, i.e. more than 5 years, as well as GNSS data from the remaining ASG-EUPOS stations are recommended to increase the reliability of results and to better understand geodynamic processes over the area of Poland.

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