

On the selection of GRACE-based GGMs and a filtering method for estimating mass variations in the Earth system over Poland

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Abstract: Since the launch of the GRACE (Gravity Recovery And Climate Experiment) satellite mission in 2002, significant progress in the knowledge regarding the temporal variations of the Earth's gravity field has been achieved. The main objectives of this contribution are to define a suitable filter to reduce the noise contained in the latest release, i.e. RL05, of GRACE-based GGMs as well as to select the most suitable GRACE-based GGM time series for estimating mass variations in the Earth system over Poland. The performance of the Gaussian filter with different radii and the de-correlation filters (DDK1–DDK5) applied to reduce the noise contained in those GGMs was examined. First, they were investigated globally. Then, they were examined over the area of Poland, in particular, over two basins, i.e. the Vistula river basin and the Odra river basin. Moreover, both the internal and external accuracy of RL05 GRACE-based GGMs were assessed. Error degree variances of geoid heights were calculated on the basis of these models. Equivalent water thickness variations obtained from GRACE-based GGMs were compared with the corresponding ones obtained from the hydrology model. The obtained results were analysed and discussed. Finally the filtering method and the GGM time series most suitable for estimating mass variations in the Earth system over Poland were selected.

Keywords: GRACE, GGM, filter, equivalent water thickness

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1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March 2002 by the US National Aeronautics and Space Administration (NASA) and the German Aerospace Centre (DLR). The primary goal of GRACE is to accurately map temporal variations of the Earth's gravity field at ~30 day intervals (e.g. Tapley et al., 2004). The mission is expected to be in operation until 2018 (e.g. Tapley et al., 2015). Research on the usefulness of GRACE data to study temporal mass variations in the Earth system has already been conducted by numerous teams worldwide

(e.g. Tapley et al., 2004; Chambers, 2006; Swenson and Wahr, 2007; Luthcke et al., 2013; Krynski et al., 2014; Wu and Helfin, 2015). For the area of Poland and surrounding areas the temporal variations of the Earth's gravity field, in terms of geoid height as well as mass variations, using Release 4 (RL04) GRACE-based Global Geopotential Models (GGMs) were investigated by Krynski et al. (2014). The authors showed that the amplitudes of geoid height variations for the area of Central Europe reach up to 7 mm. They also investigated the suitability of RL04 GRACE-based GGMs datasets and the filtering method applied to these GGMs. They concluded that the DDK1 filter and GGMs developed

by the JPL (Jet Propulsion Laboratory) centre were suitable for estimating mass variations in the Earth system over Central Europe. Birylo and Nastula (2012a) focused on filters applied to reduce the noise contained in RL04 GRACE-based GGMs. Their work indicated the superiority of the Anisotropic Non-symmetric filter (cf. Klees et al., 2008) for reducing the noise contained in those GGMs. Further, Birylo and Nastula (2012b) investigated the use of RL04 GRACE-based GGMs for predicting river flooding in Poland. Recently, Birylo et al. (2015) continued the investigation on GRACE-based GGMs. They studied the combination of these GGMs as well as combined GRACE and GOCE (Gravity field and steady-state Ocean Circulation Explorer; ESA, 1999) GGMs with metrological models for modelling flood risks over Poland.

During the GRACE mission, several groups of solutions for GRACE-based GGMs were developed: Release 1, Release 2, Release 3, Release 4, and the latest Release 5 (RL05). The solutions provided by computational centres were consequently improving, leading to better and better results (Dahle et al., 2014). The GGMs developed on the basis of GRACE data are strongly affected by noise due to the mission characteristics, in particular, the orbit configu-

ration (Tapley et al., 2004). This noise appears as meridional stripes in the final gravity field functionals determined from GRACE-based GGMs. Application of a suitable filter may substantially minimize that noise (the meridional stripes) contained in GRACE data (Ditmar et al., 2012). On the other hand, the applied filter should leave as much as possible of the gravity signal that allows reliable analysis of temporal variations of the gravity field functional to be conducted. The Gaussian filter has frequently been used as a standard due to its easy implementation and intuitive interpretation (Wahr et al., 1998). However, more recent works tend to apply probabilistic de-correlation methods in the post-processing of GRACE solutions, usually in conjunction with additional smoothing. The idea behind the de-correlation is to identify and remove error correlation in the sets of spherical harmonic coefficients using an a priori synthetic model of the observation geometry (Kusche et al., 2009). The main objectives of this contribution are to define a suitable filter to reduce the noise contained in the latest release, i.e. RL05, GRACE-based GGMs as well as to select the most suitable GRACE-based GGM time series for estimating mass variations in the Earth system over Poland.

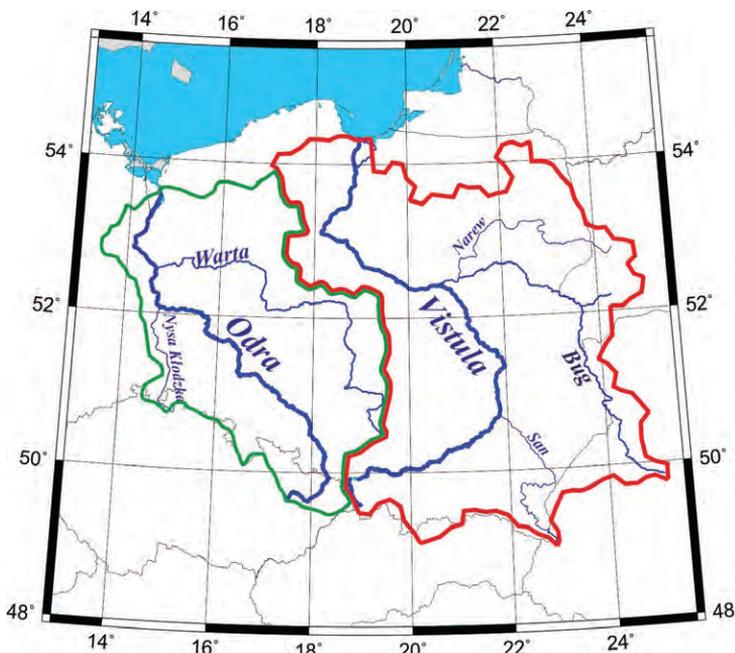


Fig. 1. The Vistula river basin (red polygon) and the Odra river basin (green polygon) in the study area

2. Study area and data used

2.1 Study area

The area of Poland was chosen as the main study area. In this area two main river basins are distinguished: the Vistula river basin, and the Odra river basin (Fig. 1). The Vistula river basin covers an area of ~194 424 km² while the area covered by the Odra river basin is about 118 861 km².

2.2 Data used

The GGMs computed on the basis of GRACE data from 30 day time intervals are made available by several computational centres, i.e. the GFZ (Geo-ForschungsZentrum), the CSR (Centre for Space Research) and the JPL as well as by some other

scientific teams, e.g. the ITG (Institut für Geodäsie und Geoinformation of Bonn University), the DMT-1 (Delft University of Technology – Release 1), the AIUB (Astronomical Institute of Bern University), the CNES/GRGS (Centre National d’Etudes Spatiales/The Space Geodesy Research Group), the ULux (University of Luxembourg) and the Tongji (Tongji University). Several releases of GRACE-based GGMs were elaborated. The CSR, GFZ, and JPL were identified in the mission proposal as the GRACE Science Data System. They were considered as the official continuously releases monthly GRACE-based GGMs (cf. Bettadpur, 2012; Dahle et al., 2014; Watkins and Yuan, 2014). Moreover, the CSR, GFZ and JPL GRACE-based monthly GGMs cover a longer period compared to other scientific teams. Thus, in this study, the focus will be on the latest, i.e. RL05, GRACE-based GGMs

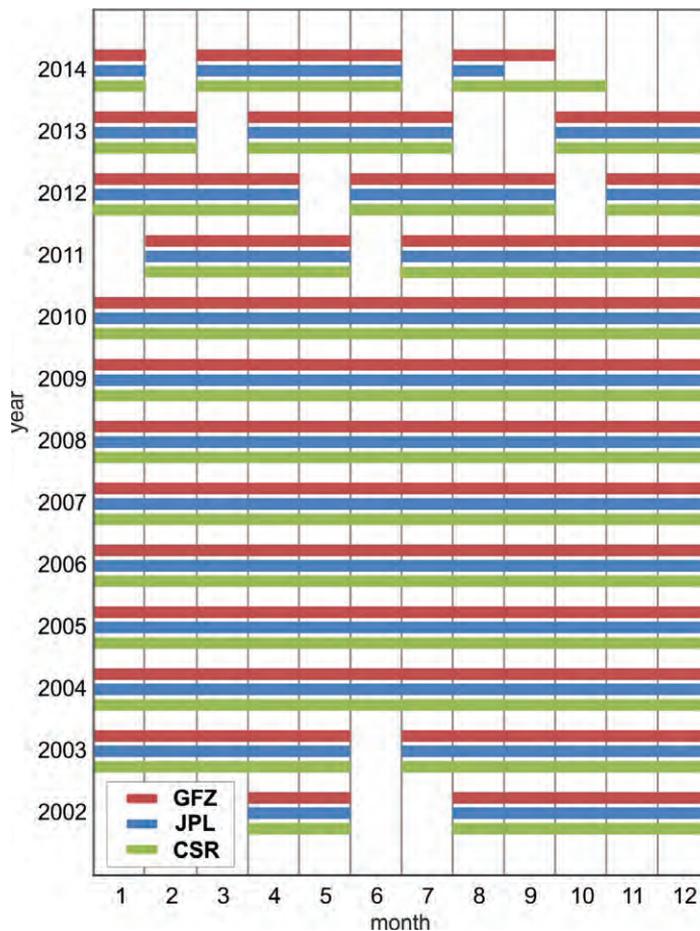


Fig. 2. Availability of RL05 GRACE-based GGMs from the CSR, GFZ, and JPL centres

from the CSR, GFZ, and JPL centres. They are released on the ICGEM (International Centre for Global Earth Models) website <http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html>. The availability of these GGMs is shown in Figure 2. Most of the gaps in the GGM time series are common for the computational centres considered. The spatial resolutions of RL05 GRACE-based GGMs developed by the GFZ and the CSR centres are up to d/o 90 and d/o 96, respectively. The spatial resolutions of RL05 GRACE-based GGMs developed by the JPL centre are not uniform. They vary from d/o 60 to d/o 90.

The WaterGAP (Water Global Assessment and Prognosis) Global Hydrological Model (WGHM) developed by the research team from the University of Kassel and the University of Frankfurt, Germany was used for the evaluation of GRACE-based GGMs. This model is based on global hydrological and metrological datasets as well as a $0.5^\circ \times 0.5^\circ$ spatial resolution of monthly runoff and river discharge (see Döll et al., 2003). The WGHM used in this study was obtained, in the form of monthly $1^\circ \times 1^\circ$ grids, from the DFG (Deutsche Forschungsgemeinschaft) priority programme – *Mass Transport and Mass Distribution in the Earth System*.

3. Methodology

In the first part of this study, the effect of using different filtering methods on RL05 GRACE-based GGMs was examined. Gaussian filters with different radii as well as the de-correlation filters (i.e. DDK filters) were applied (cf. Wahr et al., 1998; Kusche, 2007; Kusche et al., 2009). The equivalent water thickness (EWT) values were computed at monthly intervals using RL05 GRACE-based GGMs as follows (Wahr et al., 1998):

$$EWT^{(GRACE)} = \frac{R \times \rho_{av}}{3} \sum_{n=0}^{N_{max}} \left(\frac{2n+1}{1+k_n} \right) \sum_{m=0}^n \bar{Y}_m(\varphi, \lambda) \quad (1)$$

with

$$\bar{Y}_{nm}(\varphi, \lambda) = (C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) \bar{P}_{nm}(\sin\varphi) \quad (2)$$

where φ, λ are the latitude and the longitude, respectively, of the computation point P , N_{max} is the applied maximum degree of the GRACE-based GGM, R is the Earth's mean radius, ρ_{av} is the average density of the Earth, k_n are load Love numbers, C_{nm}, S_{nm} are

dimensionless coefficients of degree n and order m , $\bar{P}_{nm}(\sin\varphi)$ are fully normalized associated Legendre functions.

The temporal variations of the equivalent water thickness $\Delta EWT^{(GRACE)}$ from RL05 GRACE-based GGMs were computed as follows:

$$\Delta EWT_i^{(GRACE)} = EWT_i^{(GRACE)} - EWT_{mean}^{(GRACE)} \quad (3)$$

where $EWT_i^{(GRACE)}$ represents the equivalent water thickness obtained from RL05 GRACE-based GGMs, i denotes the month, $EWT_{mean}^{(GRACE)}$ is the mean value obtained from the time series of $EWT_i^{(GRACE)}$.

In order to select the most suitable RL05 GRACE-based GGM time series for estimating mass variations in the Earth system over Poland, both the internal accuracy and the external accuracy of RL05 GRACE-based GGMs were investigated. The internal accuracy of these GGMs was evaluated using the error degree variances for geoid heights ε_N calculated as follows (Pavlis, 1988):

$$\varepsilon_N^2 = \left(\frac{GM}{\gamma a} \right)^2 \left(\frac{a^2}{R^2} \right)^{n+1} \sum_{m=0}^n \left(\varepsilon_{C_{nm}}^2 + \varepsilon_{S_{nm}}^2 \right) \quad (4)$$

where $\varepsilon_{C_{nm}}, \varepsilon_{S_{nm}}$ are errors of spherical harmonic coefficients of RL05 GRACE-based GGMs, and a is the semimajor axis of the reference ellipsoid.

The external accuracy of these GGMs was examined using independent datasets. For this purpose, the temporal variations of the equivalent water thickness were computed from the WGHM as follows:

$$\Delta EWT_i^{(WGHM)} = EWT_i^{(WGHM)} - EWT_{mean}^{(WGHM)} \quad (5)$$

where $EWT_i^{(WGHM)}$ represents the equivalent water thickness obtained from the WGHM monthly grids, $EWT_{mean}^{(WGHM)}$ is the mean value obtained from time series of $EWT_i^{(WGHM)}$. These $\Delta EWT_i^{(WGHM)}$ were compared with the corresponding $\Delta EWT_i^{(GRACE)}$ obtained from RL05 GRACE-based GGMs. The differences $d\Delta EWT_i$ between those equivalent water thickness variations are obtained as follows:

$$d\Delta EWT_i = \Delta EWT_i^{(WGHM)} - \Delta EWT_i^{(GRACE)} \quad (6)$$

4. Results and analysis

First, the performance of Gaussian filters of different radii and de-correlation filters (DDK1–DDK5) in a global scale was investigated. The results were

basically obtained with the use of Eq. (1) and Matlab codes developed by the DFG. Figure 3 illustrates the equivalent water thickness variations between March 2005, and September 2005 obtained from RL05 GRACE-based GGMs computed by the JPL centre. It shows that among all filters investigated, the DDK1 filter and the Gaussian filter with a radius of 700 km substantially reduce the noise contained in RL05 GRACE-based GGMs. The amplitudes of equivalent water thickness variations ranged from -48 cm to 25 cm and from -66 cm to 31 cm after applying the Gaussian filter with a radius of 700 km and the DDK1 filter, respectively. This indicates that the Gaussian filter removed 24 cm more of equivalent water thickness variations signal than the DDK1 filter. Therefore, it can be concluded that the DDK1 filter is more suitable than other

filters applied to reduce the noise contained in RL05 GRACE-based GGMs.

Then, the performance of using Gaussian filters of different radii and de-correlation filters (DDK1–DDK5) was investigated in a local/regional scale, in particular, over the Vistula river basin and the Odra river basin. Most of the results were obtained using the ICGEM calculation services (cf. <http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html>). Figure 4 illustrates time series of equivalent water thickness variations $\Delta EWT^{(GRACE)}$ for those river basins. It shows that the differences between CSR, GFZ, and JPL RL05 GRACE-based GGMs are merely negligible when applying DDK1 and DDK2 filters. The results presented in Figure 4 also indicate clear pattern of seasonal water mass variations, with the maximum values in March and minimum

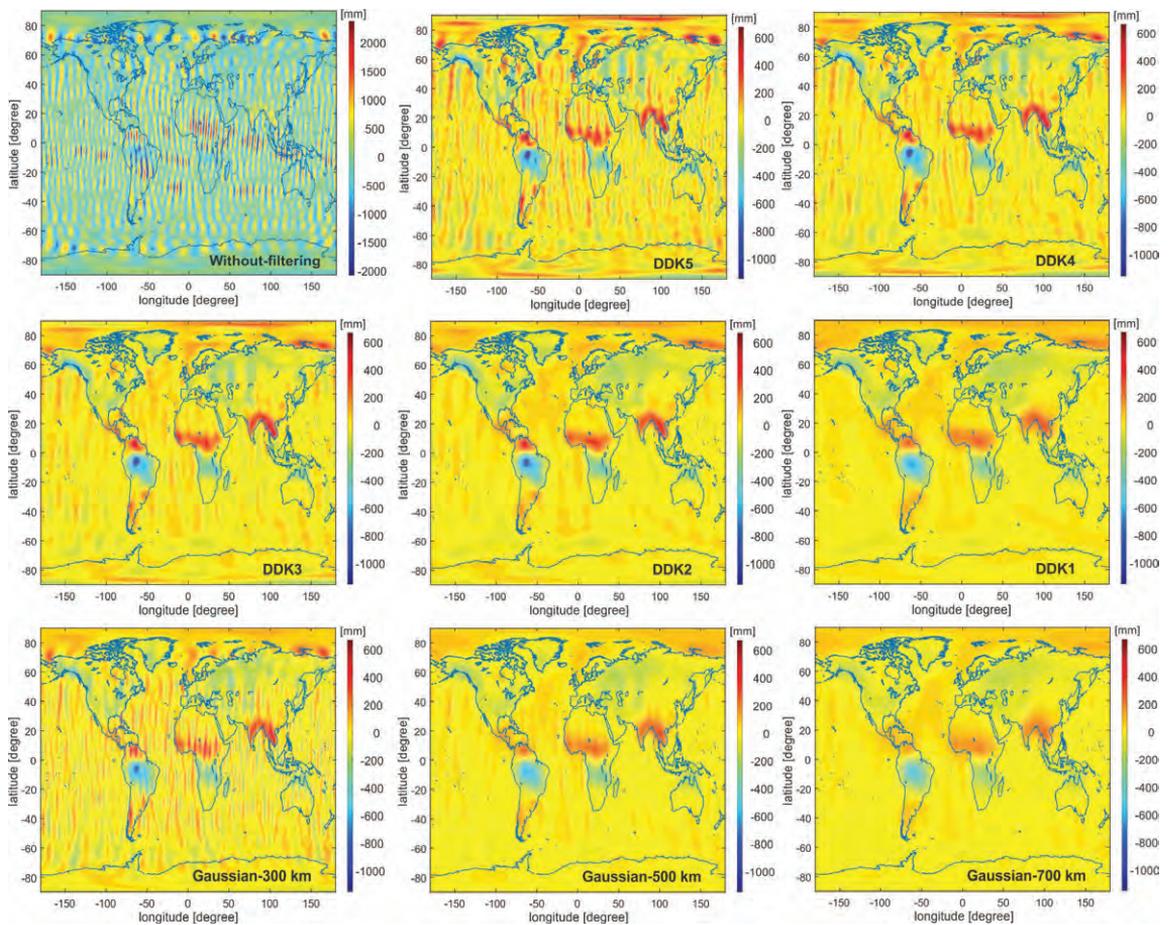


Fig. 3. The equivalent water thickness variations between March 2005 and September 2005 obtained from RL05 GRACE-based GGMs computed by the JPL centre

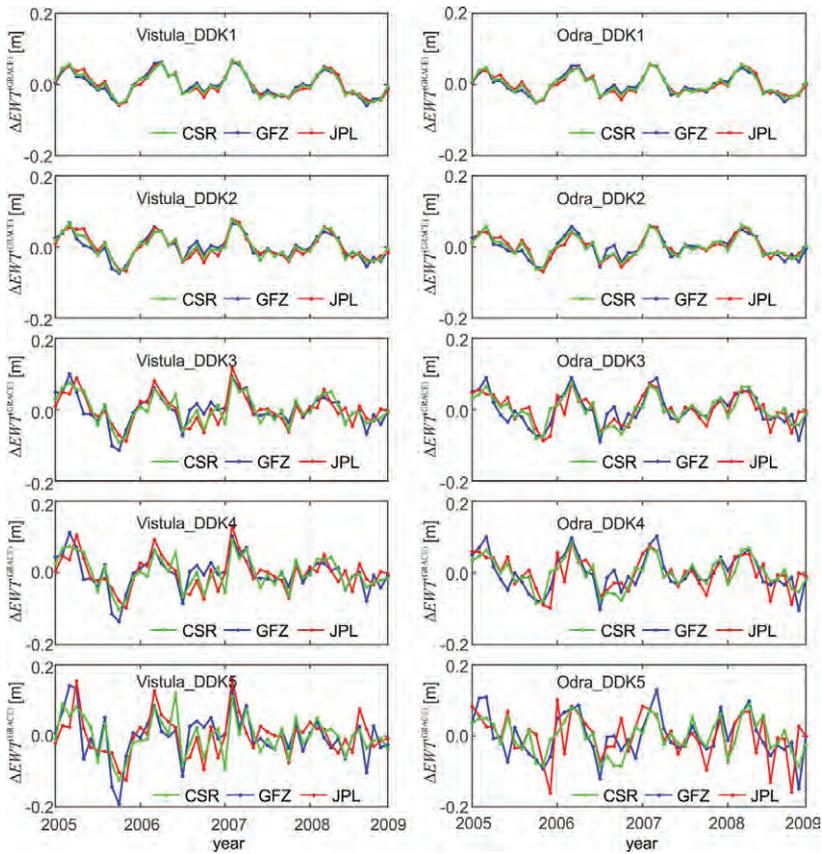


Fig. 4a. Time series of $\Delta EWT^{(GRACE)}$ for the Vistula river basin (left panels) and the Odra river basin (right panels) using DDK1, DDK2, DDK3, DDK4, and DDK5 filters

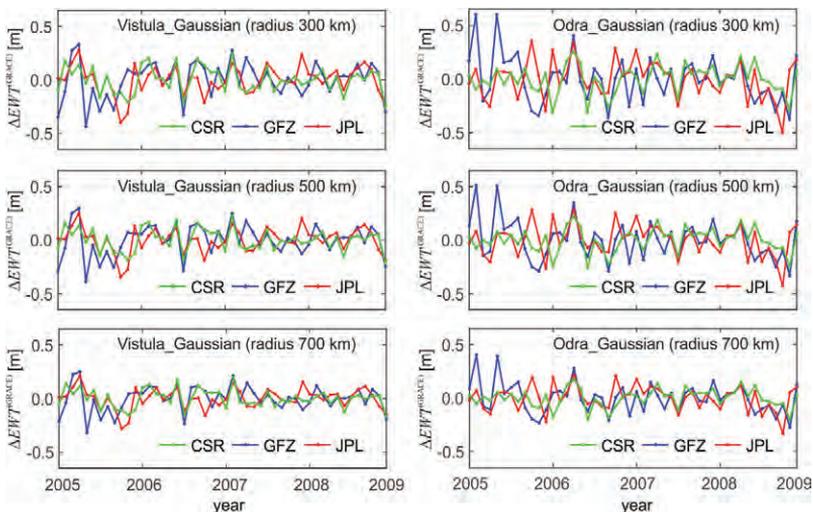


Fig. 4b. Time series of $\Delta EWT^{(GRACE)}$ for the Vistula river basin (left panels) and the Odra river basin (right panels) using Gaussian filters with radii of 300 km, 500 km, and 700 km

values in July–September. This pattern of seasonal water mass variations may reveal that the increases/decreases in water masses over the area investigated are due to the melting of snow that was accumulated in the winter season, and water evaporation during dry months in the summer season. On the other hand, when applying DDK3, DDK4, DDK5 filters and Gaussian filters for all radii investigated, differences between $\Delta EWT^{(GRACE)}$ obtained from CSR, GFZ, and JPL RL05 GRACE-based GGMs became visible. Furthermore, the pattern of seasonal water mass variations of $\Delta EWT^{(GRACE)}$ cannot be clearly observed when applying the latter filters. This may indicate that the noise remaining, after applying the DDK3, DDK4, DDK5 filters and Gaussian filters for all radii investigated, dominates the $\Delta EWT^{(GRACE)}$ signal. These results were obtained for the Vistula river basin and the Odra river basin, separately. They show that RL05 GRACE-based GGMs allow the estimation of mass variations in the Earth system for each of these basins independently. The results obtained may also reveal that the DDK1 and DDK2 filters are recommended to reduce the noise contained in RL05 GRACE-based GGMs, when estimating mass variations in the Earth system over Poland. This consequence agreed with the one presented in Krynski et al. (2014), which revealed that the DDK1 filter reduced the noise contained in release 4 GRACE-based GGMs sufficiently. Thus, the DDK1 filter was chosen as the best filter to perform further analysis in this contribution.

The errors of the spherical harmonic coefficients of RL05 GRACE-based GGMs developed by the

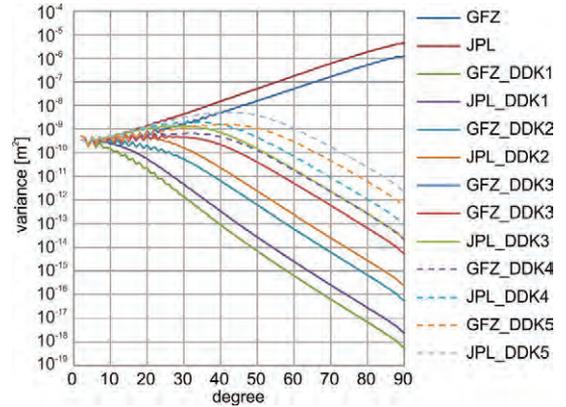


Fig. 5. The error degree variances for geoid heights from RL05 GRACE-based GGMs

CSR centre are not available, thus the internal accuracy of RL05 GRACE-based GGMs developed only by GFZ and JPL centres was examined. With the use of Eq. (4), the error degree variances for geoid heights were calculated for RL05 GRACE-based GGMs for the period from January 2008 to December 2009. Figure 5 shows the mean values of error degree variances for geoid heights for that period. The results presented in Figure 5 revealed that RL05 GRACE-based GGMs developed by the GFZ centre are more accurate than the ones developed by the JPL centre. This may be due to the essential improvement in developing GRACE-based GGMs from RL04 to RL05 by the GFZ centre (see Dahle et al., 2014).

The $\Delta EWT^{(GRACE)}$ obtained from RL05 GRACE-based GGMs filtered with the use of the DDK1 filter were compared with the corresponding $\Delta EWT^{(WGHM)}$

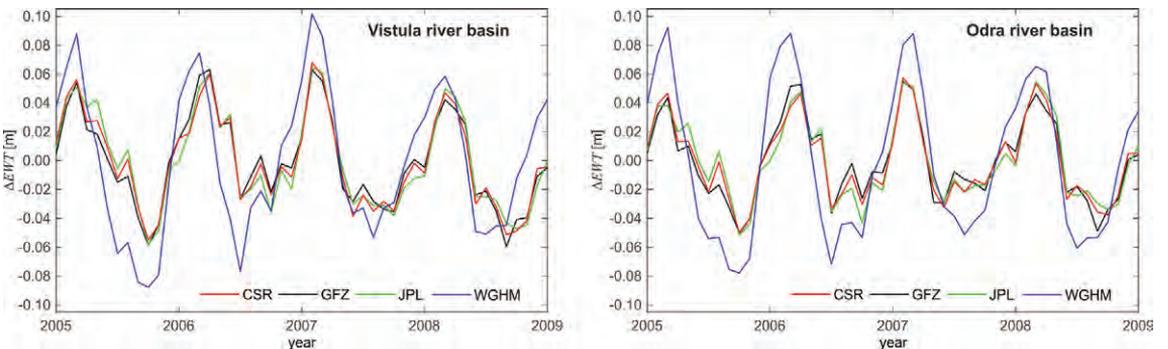


Fig. 6. Time series of equivalent water thickness variations $\Delta EWT^{(WGHM)}$ and $\Delta EWT^{(GRACE)}$ for the Vistula river basin and the Odra river basin

obtained from the WGHM monthly grid over the Vistula river basin and Odra river basin. Figure 6 illustrates time series of equivalent water thickness variations $\Delta EWT^{(GRACE)}$ and $\Delta EWT^{(WGHM)}$ for the Vistula river basin and the Odra river basin.

The results presented in Figure 6 show the pattern of seasonal water mass variations with maximum values of ΔEWT in the spring months, while minimum values of those ΔEWT are usually observed in July–September. This may justify the interoperation of the results concerning the increase/decrease in water masses over the investigated area (cf. Figure 4). Overall, the results presented in both Figures 4 and 6 may reveal that RL05 GRACE-based GGMs can be used sufficiently to estimate the temporal mass variations in the Earth system, e.g. equivalent water thickness variations, over Poland, in particular, over both the Vistula river basin and Odra river basin, independently.

The differences between $\Delta EWT^{(WGHM)}$ and $\Delta EWT^{(GRACE)}$ were computed using Eq. (6). Their statistics are given in Table 1. They indicate that RL05 GRACE-based GGMs provided by the GFZ centre are superior with respect to the other time series investigated, i.e. RL05 GRACE-based GGMs provided by the CSR and the JPL centres, in terms of standard deviation of the differences and the range of the differences. This result also agrees with the one presented in Figure 5. Thus, it can be concluded that for estimating mass variations in the Earth system over the area of Poland, RL05 GRACE-based GGMs developed by the GFZ centre are more recommended than the corresponding GGMs developed by CSR and JPL centres.

Table 1. Statistics of the differences between the corresponding equivalent water thickness variations $\Delta EWT^{(WGHM)}$ and $\Delta EWT^{(GRACE)}$ for the Vistula river basin and the Odra river basin [m]

Statistics	Vistula river basin			Odra river basin		
	GFZ	JPL	CSR	GFZ	JPL	CSR
Min	-0.067	-0.073	-0.070	-0.059	-0.063	-0.056
Max	0.047	0.048	0.046	0.053	0.065	0.059
Std	0.030	0.033	0.031	0.030	0.032	0.030
Max-Min	0.114	0.121	0.117	0.112	0.128	0.115

5. Conclusions

In this contribution, the applied filters to reduce the noise contained in the latest release of GRACE-based GGMs as well as the most suitable GRACE-based GGM time series for estimating mass variations in the Earth system over Poland were investigated.

In a global scale, both the DDK1 filter and the Gaussian filter with a radius of 700 km substantially reduce the noise in GRACE-based GGMs. Moreover, the results obtained show that the DDK1 filter recovers ~25% more of equivalent water thickness variations signal than the Gaussian filter with a radius of 700 km. This may indicate that the DDK1 filter is more suitable to reduce the noise contained in RL05 GRACE-based GGMs than other filters investigated.

In a local scale, in particular, over the area of Poland, the obtained results revealed that DDK1 and DDK2 filters seem more suitable than the Gaussian filter with a radius of 300 km, 500 km and 700 km as well as DDK3, DDK4, and DDK5 filters, to reduce the noise included in RL05 GRACE-based GGMs over the investigated area. This result agrees with that of a previous investigation concerning the selection of the best filtering method to reduce the noise contained in RL04 GRACE-based GGMs (cf. Krynski et al., 2014).

The comparison between error degree variances for geoid heights for RL05 GRACE-based GGMs from GFZ and JPL centres suggests that the GGMs developed by the GFZ centre are more accurate than the corresponding ones developed by the JPL centre. Moreover, over the area of Poland, the comparison between equivalent water thickness variations obtained from RL05 GRACE-based GGMs and the corresponding ones obtained from the WGHM revealed the superiority of RL05 GRACE-based GGMs developed by the GFZ centre to estimate temporal mass variations in the Earth system over Poland, over other GGM time series investigated.

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Wybór globalnych modeli geopotencjału opracowanych na podstawie danych z misji GRACE oraz metody filtracji, do wyznaczania zmian rozkładu mas w systemie Ziemia na obszarze Polski

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Streszczenie: Satelitarna misja GRACE (Gravity Recovery And Climate Experiment zapoczątkowana w 2002 roku znacząco przyczyniła się do rozwoju wiedzy o zmianach w czasie pola siły ciężkości Ziemi. Głównym celem niniejszego opracowania jest zdefiniowanie odpowiedniego filtra do redukcji szumu zawartego w ostatniej wersji, tj. wersji 5. globalnych modeli geopotencjału opracowanych na podstawie danych z misji GRACE, jak również wybór najbardziej odpowiedniego szeregu czasowego globalnych modeli geopotencjału wyznaczonych na podstawie danych z misji GRACE, do określenia zmian rozkładu mas w systemie Ziemia dla obszaru Polski. W szczególności badano wpływ filtrów Gaussa o różnych promieniach oraz filtrów dekorelacyjnych (DDK1–DDK5) na redukcję szumu zawartego w globalnych modelach geopotencjału. Na początku wpływ użycia filtra był badany w ujęciu globalnym. Następnie wpływ ten został zbadany dla obszaru Polski – oddzielnie dla dorzeczy Wisły i Odry. Ponadto, została oszacowana zarówno wewnętrzna, jak i zewnętrzna dokładność wersji 5. globalnych modeli geopotencjału opracowanych na podstawie danych z misji GRACE. Obliczono wariancje błędów wysokości geoidy dla poszczególnych stopni badanych modeli. Zmiany ekwiwalentnej warstwy wody wyznaczone z globalnych modeli geopotencjału opracowanych na podstawie danych z misji GRACE zostały porównane z odpowiednimi zmianami otrzymanymi z modelu hydrologicznego. Wyniki poddano analizie i dyskusji. Ostatecznie wybrano metodę filtracji oraz szereg czasowy globalnych modeli geopotencjału najbardziej odpowiednie do oszacowania zmian rozkładu mas w systemie Ziemia dla obszaru Polski.

Słowa kluczowe: GRACE, globalny model geopotencjału, ekwiwalentna warstwa wody