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Time variations of the gravity field over Europe obtained from GRACE data

Grazyna Kloch-Glowka, Jan Krynski, Malgorzata Szelachowska

Institute of Geodesy and Cartography, Warsaw, Poland

e-mail: gkloch@gmail.com, krynski@igik.edu.pl, malgorzata.szelachowska@igik.edu.pl

Abstract. Time variations of the gravity field derived from time series of geopotential model developed from GRACE data can be interpreted in terms of geoid heights, and mass time variations with unprecedented temporal resolution. Following the results of authors previous research presented at 2^{nd} General Assembly of the IGFS, 20-22 September 2010, Fairbanks, Alaska, the series of monthly solutions of geopotential models developed from GRACE data in JPL, filtered with the use of DKK1 filter, and GLDAS hydrological model were used in the analyses. Variations of hydrology as well as variations of geoid heights for the period August 2002 – June 2010 at the continental part of Europe and selected 14 subareas were estimated with spatial resolution of $0.5^\circ \times 0.5^\circ$. Variations in mass distribution obtained from geopotential models were compared with the respective results obtained from hydrological data. Models of geoid height changes (parameters of trend and seasonal variations) were determined for the area of Europe and for 14 subareas. To verify models of geoid height changes, over the period July 2010 - October 2010 values of geoid height changes calculated using GRACE data were compared with values based on the models developed.

Keywords: geoid height variations, GRACE mission, geopotential models

1 Introduction

The beginning of the satellite mission GRACE in 2002 was a milestone in modelling the Earth gravity field. The GRACE consisted of two low-orbiting spacecrafts linked by a microwave ranging system. Observations from the ranging system, together with GPS tracking data and accelerometer data from GRACE, are used to generate global geopotential models. The models developed are of spatial resolution of a few hundred kilometres, temporal resolution of one month or even higher and unprecedented earlier accuracy. Differences between two solutions reflect time variations of gravity. They are related to physical processes in the Earth crust like postglacial land uplift, vertical movement of the Earth crust, and seasonal land hydrosphere cycles.

On the basis of GRACE data, a whole series of static gravity models was produced, e.g. GGM02 (Tapley *et al.*, 2005), EIGEN-GL04C (Förste *et al.*, 2008). Also geopotential models, typically with temporal resolution of one month, are computed independently in several computational centres, initially in CSR, JPL, GFZ, CNES/GRGS, and later also in AIUB, with the use of different softwares (e.g. Ilk *et al.*, 2005; Luthcke *et al.*, 2006; Bettadpur, 2007; Biancale *et al.*, 2007; Lemoine *et al.*. 2007; Flechtner, 2007; Watkins and Yuan, 2007; Flechtner *et al.*, 2010; Liu *et al.*, 2010); they thus provide different solutions for the same periods of time (WWW-1, WWW-2).

"Pure" GRACE solutions, delivered to scientific community by particular computational centres, contain contaminated information about the Earth gravity field, which results from the sensor error characteristics, the mission geometry, limitations in analysis strategies and background models. Therefore, the solutions require filtering to sense gravity variations (Horwath i Dietrich, 2006). A number of averaging filters have already been proposed. The simplest are isotropic Gaussian filters, the more sophisticated are anisotropic filters (e.g. Wahr *et al.*, 1998; Chen *et al.*, 2006a; Sasgen *et al.*, 2006; Swenson and Wahr, 2006; Kusche, 2007; Wouters and Schrama, 2007; Davis *et al.*, 2008; Klees *et al.*, 2008). Each of those filters has advantages as well as disadvantages. Isotropic Gaussian filters are independent of any sort of a priori information or error model, the optimal filters rely on the principle that external knowledge of the problem (for example solution errors) can be used to guide the filter in deciding what is noise and what is signal. Some of them work better than others with a given type of noise. The results obtained using GRACE data are also successfully used to infer the changes in surface mass and gravity field variations (e.g. Tapley *et al.*, 2004; Andersen and Hinderer, 2005; Chambers, 2006; Chen *et al.*, 2006b, Ramillien *et al.*, 2006; Schmidt *et al.*, 2006) as well as changes in geoids heights.

The major objective of this study is to estimate time variations of the gravity field over Europe using GRACE data in terms of both, variations of mass distribution and geoid heights, to evaluate the relationship between the signal from GRACE data and from hydrological models as well as to model time variations of geoid being a reference surface for a vertical system.

2 Data used and filtering method applied

The following issues were taken into account when determining suitability of geopotential models provided by CNES/GRGS, CSR, GFZ, and JPL for investigating the temporal changes of the Earth gravity field: accuracy of solutions, spatial resolution (maximum degree and order), time coverage, and stability of the solution in terms of the number of observation days used for generating the models. The mean geoid degree variances for models from all centres are the same but the mean error degree variances for particular centres differ, especially for the lowest degrees. Models Release 4 from the JPL centre exhibit the smallest error variance. Moreover, the even and odd coefficients following one after another are evaluated with similar accuracy. Those models were chosen for further analysis (Szelachowska *et al.*, 2010).

The functionals of the Earth gravity field, for example the geoid height or equivalent water height, can be evaluated on the basis of the GRACE level 2 data, which has a form of spherical harmonic coefficients. The equivalent water heights for Europe were calculated for the period August 2007 - July 2009 using different filters to JPL solutions: Gauss filters that are universal in terms of data used – Gauss filter with filter length $y = 400$ km, and Gauss filter with $y = 600$ km, as well as DKK1, DKK2, DKK3 filters that seem more suitable to GRACE data (Kusche *et al.*, 2009). The latter filters are freely available. They are based on a simplified (order-convolution) approach of the de-correlation and smoothing method (Kusche, 2007). The analysis of numerical experiments confirms the necessity of filtering the level 2 data from GRACE mission because of large noise. The results obtained using DKK2 and DKK3 filters and the Gauss filter with 400 km filter length are still contaminated with noise in the form of distinguished parallel stripes. Both, DKK1 filter and Gauss filter with y = 600 km reduce the stripes sufficiently but in case of the Gauss filter with y = 600 km also the signal becomes very strongly reduced. Therefore data filtered with DKK1 filter was used in further analysis (Szelachowska *et al.*, 2010).

The most reliable way of verifying results is comparing them with the results obtained independently using another computational method and, what is even more valuable, with another type of data. In the case of GRACE models, the comparison can be carried out using hydrological models. The following issues were taken into account when analysing suitability of global hydrological models for comparing them with GRACE-derived geopotential models: temporal resolution, spatial resolution, time coverage, and Earth coverage. From considered freely available hydrological models CPC, GLDAS, LadWorld, Reanalysis-I, CDAS-1, and ECMWF, the GLDAS models were chosen for further analysis (Szelachowska *et al.*, 2010).

3 Geoid height variations vs. mass variations represented by equivalent water height

Geoid height variations ΔN can be expressed in terms of variations of residual spherical harmonic coefficients ΔC_{lm}, ΔS_{lm} of the geopotential

$$\Delta N(\vartheta,\lambda) = R \sum_{l=L_{min}}^{L_{max}} \sum_{m=0}^{l} (\Delta C_{lm} \cos m\lambda + \Delta S_{lm} \sin m\lambda) P_{lm}(\cos\vartheta) \tag{1}$$

Eq. (1) is used to compare different geopotential models and to investigate temporal variations of the Earth gravity field with the use of GRACE data. Similarly, variations of surface mass density $\Delta\sigma$ can be expressed as a function of residual spherical harmonic coefficients $\Delta\overline{C}_{lm}, \Delta\overline{S}_{lm}$

$$\Delta\sigma(\vartheta, \lambda) = R\rho_w \sum_{l=L_{min}}^{L_{max}} \sum_{m=0}^{l} (\Delta\overline{C}_{lm} \cos m\lambda + \Delta\overline{S}_{lm} \sin m\lambda) P_{lm}(\cos\vartheta) \tag{2}$$

providing that they concern a thin water layer on the Earth surface. In this case ρ_w is water density of 1000 kg/m^3. The parameter $\Delta\sigma/\rho_w$ represents variations of equivalent water layer height and is frequently used in the analysis of monthly solutions from GRACE. The relation between residual spherical harmonic coefficients of surface density and geopotential is as follows

$$\begin{Bmatrix} \Delta\overline{C}_{lm} \\ \Delta\overline{S}_{lm} \end{Bmatrix} = \frac{\rho_{\text{ave}}(2l+1)}{3\rho_w(1+k_l)} \begin{Bmatrix} \Delta C_{lm} \\ \Delta S_{lm} \end{Bmatrix} \tag{3}$$

where ρ_{ave} is an average Earth density of 5517 kg/m^3, and k_l are load Love numbers (Wahr *et al.*, 1998). Coefficient $1 + k_l$ in Eq. (3) besides mass potential considers solid Earth loading deformation potential.

4 Analysis of series of temporal variations of Earth gravity field in terms of temporal variations of mass distribution

Time series of equivalent water height variations was analysed for the area of Europe as well as for its 14 chosen subareas. Those subareas, corresponding to geographical regions, together with the number of points, i.e. nodes of 0.5° × 0.5° grid, used to determine the average representative for particular regions are shown in Figure 1.

The results of analysis indicate occurrence of a strong seasonal signal not only for the whole area of Europe but also for its 9 subareas (2 and 7-14) (Fig. 2) (Kloch-Glowka *et al.*, 2011). For subareas 1 and 3-6 a determination coefficient of linear model fitted into a variable, from which seasonal signal was removed, exhibited relatively large value. The results obtained enable to divide area of Europe onto regions of domination of seasonal signal and regions where dominates the trend (Fig. 3).

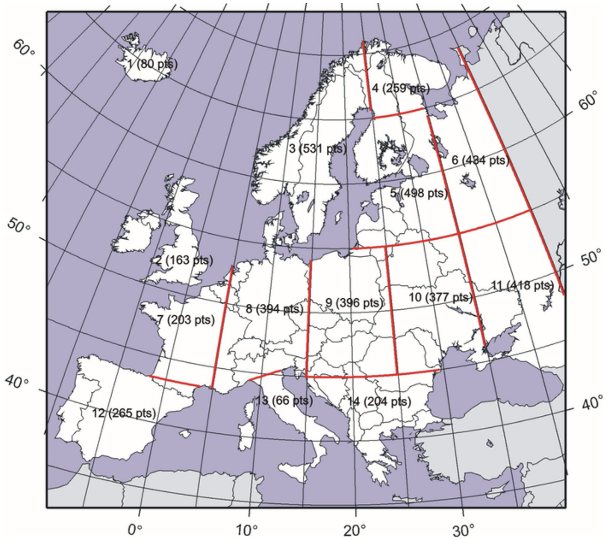

Figure 1. *Division of Europe onto 14 subareas and the number of points used to determine the average representative for each region (in brackets)*

5 Comparison of GRACE-derived temporal variations of mass distribution with hydrological models

Equivalent water height variations obtained using GRACE models were compared with corresponding equivalent water height variations calculated using hydrological GLDAS data. The value of the signal (variations of equivalent water height) obtained from the hydrological models GLDAS for Europe and for all subareas (except 1 and 2) is larger than the respective one obtained from GRACE data. It is probably mainly due to filtering method applied to process GRACE data. Both period of seasonal component and months of occurrence of minimum and maximum of the signal are similar for the two time series investigated. The correlation coefficient of the GRACE and GLDAS results is for Europe at the level of 0.82 Time series of equivalent water height variations calculated using GRACE and GLDAS models for the area of Europe and two subareas: one of the highest (0.84 - subarea 9) and one of the lowest (0.20 - subarea 1) correlation are shown in Figure 4 (Kloch-Glowka *et al.*, 2011).

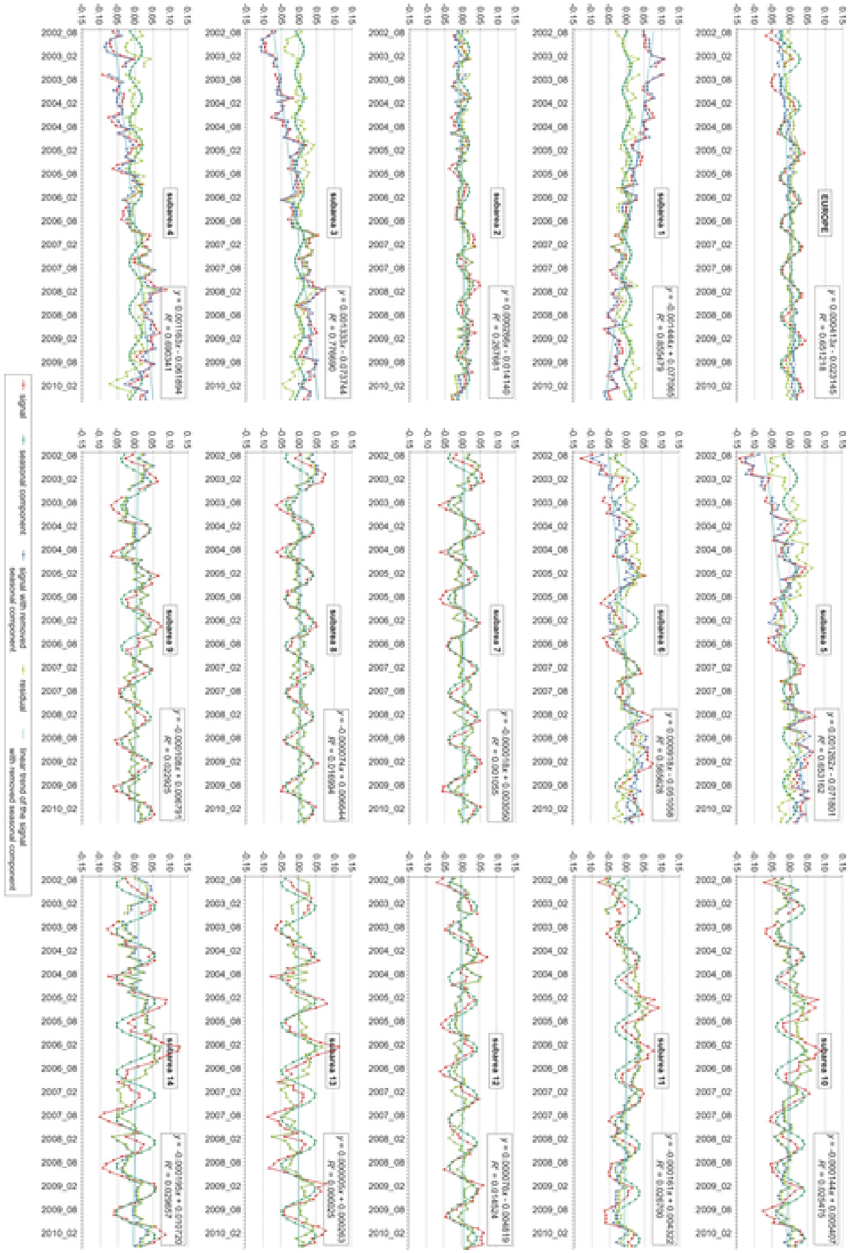

Figure 2. *Temporal variations of mass distribution, their seasonal component, variations corrected for seasonal effect, linear trend and the residual*

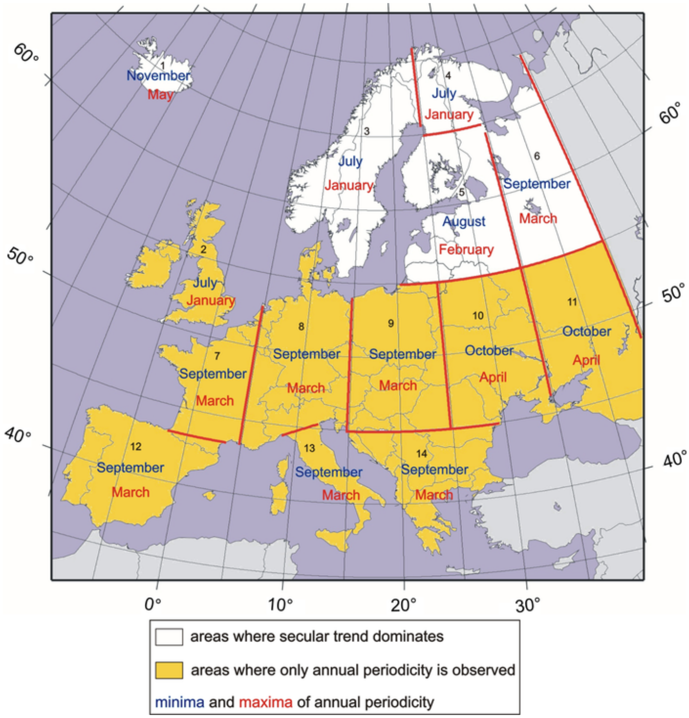

Figure 3. *Trend and annual periodicity of equivalent water height variations (indicated months where minima and maxima occur)*

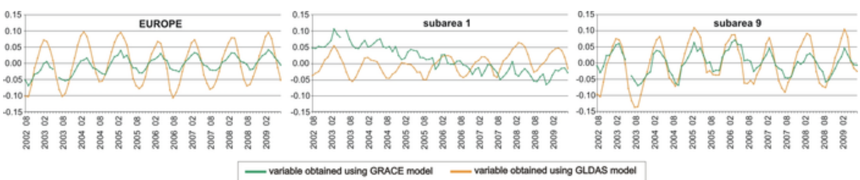

Figure 4. *Equivalent water heights variation obtained using GRACE and GLDAS models*

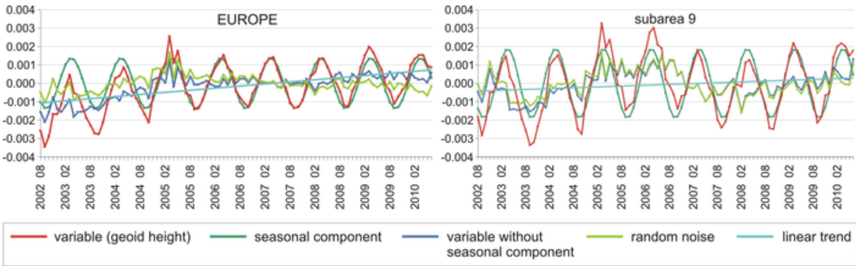

Figure 5. *Geoid height variations*

6 Geoid height variations from GRACE data

Time series of geoid height variations was analysed in the same way as time series of equivalent water height variations. Practically in all areas investigated the annual signal is observed (Kloch-Glowka *et al.*, 2011). Figure 5 shows the results for Europe and for the subarea 9 that covers the area of Poland.

Variations of geoid height were predicted for consecutive months using exponential adjustment. The results obtained were compared with geoid height variations determined from GRACE data. Correlation coefficients of predicted geoid heights and their values obtained using GRACE models vary from 0.28 in subarea 3 through 0.92 at subarea 9 up to 0.99 in subareas 4, 11, and 12. Variations of geoid heights derived from GRACE data, smoothed series, residual series and predicted geoid height variations for the period July 2010 - June 2011 are given in Figure 6.

7 Modelling of geoid height variations

Analysis of geoid height variations in Europe and all 14 subareas shows that the investigated signal consists of two major components: annual oscillation and trend. In some subareas, however, it is sufficient to model the signal with linear trend only. Therefore modelling of geoid height variations was performed on both, regional (whole Europe) and local (14 subareas) scales. A number of models with linear, logarithmic and 2nd order polynomial trend

Figure 6. *Variations of geoid heights derived from GRACE data, smoothed series, residual series and predicted geoid height variations for the period July 2010 - June 2011*

Figure 7. *Optimum model against the observed variation of geoid height[m]*

were investigated. The performance of the models did not differ substantially. For each subarea, however, the optimum model was specified (Fig. 7). The fit of the model is substantially better in the subareas of a distinct domination of seasonal component in geoid height variations. In case of all models investigated for Europe and 14 subareas the average residual equals to 0 mm. It proves that models consisting of seasonal component and trend sufficiently approximate geoid height variations. It also indicates that the residuals obtained can be interpreted as random "measurement errors" of GRACE data.

8 Prediction of geoid height variations

Models developed for Europe and its 14 subareas on the basis of GRACE data from the period August 2002 - June 2010 were used to predict geoid height variations for next four months, i.e. July - October 2010. The predicted values were then compared with the respective ones obtained from GRACE data. Prediction quality was estimated using correlation coefficient. Correlation coefficients for 14 subareas investigated are shown in Figure 8. For Europe the correlation coefficient equals to 0.93. Except of subarea 3, where the negative correlation coefficient indicates inverse correlation between the predicted and GRACE-derived values, very good correlation is observed; for 9 subareas it exceeds 0.9.

9 Conclusions

GRACE-derived geopotential models carry a unique information for geodynamics, valuable for water management and for developing hydrological models. Time variations in mass distribution determined with the use of GRACE data are comparable with the respective ones obtained from GLDAS hydrological models. Equivalent water height variations determined on regional scale may substantially differ from the respective ones determined on local scale. The results obtained for Europe indicate both, seasonal component as well as relatively strong linear trend. Analysis performed on local scale indicates that Europe can be divided onto the regions with dominating seasonal component and the regions where the trend dominates in the signal.

Geoid height variations determined from GRACE data for Europe as well as its 14 subareas besides a linear trend contain a strong annual component. Models consisting of those components fit very well to the observed data. The estimated seasonal changes of geoid heights in Poland are within the range of ± 2 mm. Within the period of August 2002 - June 2010, the averaged geoid heights vary, however, in the subarea 9 containing Poland by up to 7 mm. Thus, actual geoid height changes exceeding 1 cm can be expected in Poland. The concept of static geoid as a reference surface in precise heighting, with the use of contemporary global positioning techniques becomes outdated. There is a growing need for kinematic models of gravimetric geoid. The results obtained show the

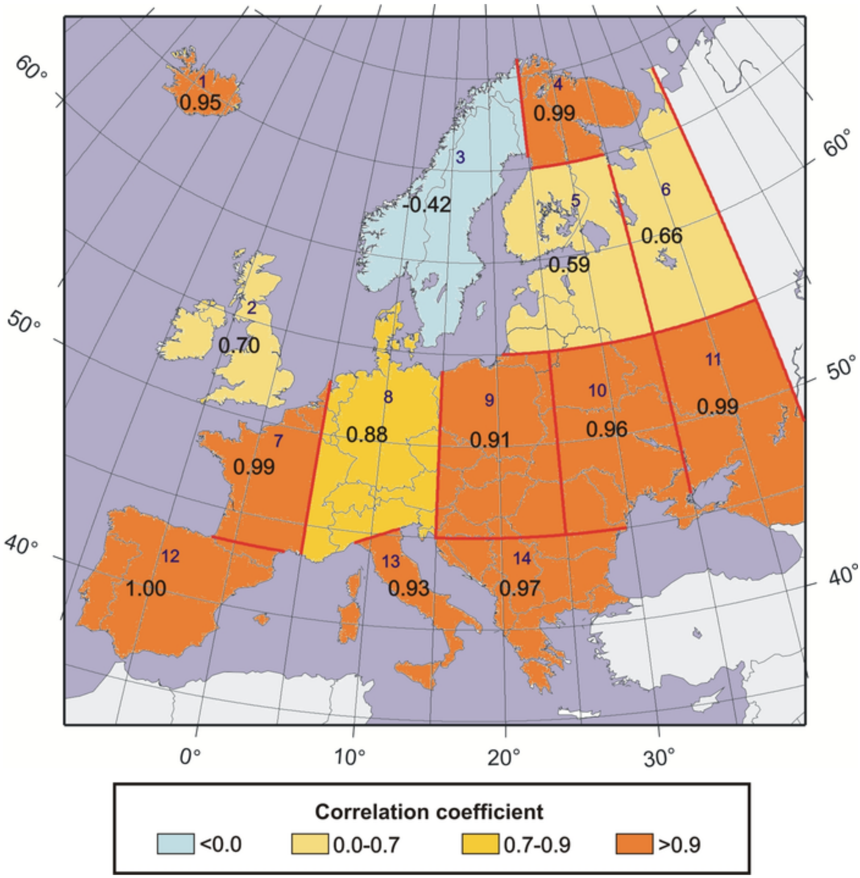

Figure 8. *Correlation of geoid height variations from GRACE data with the predicted one for the period July - October 2010*

necessity of urgent launch of GRACE-type mission that could ensure continuation of monitoring gravity field variations with high spatial and temporal resolution.

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WWW-1 ( ) `http://icgem.gfz-potsdam.de/ICGEM/`.

WWW-2 ( ) `http://www.csr.utexas.edu/research/ggfc/dataresources.html`.