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Testing Correlation between Vertical Crustal Movements and Geoid Uplift for North Eastern Polish Border Areas

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Abstract. Long time span of observations from GNSS permanent stations can be used in the development of models of vertical crustal movements. The absolute vertical crustal movement related to the ellipsoid consists of the observed movement with relation to the mean sea level, the eustatic movement and the geoid uplift. The geoid uplift can be determined from GRACE satellite mission observations. The calculated parameters can be compared with the theoretical ones.

The aim of this study is to check the correlation between vertical crustal movements and a geoid height variations determined from satellite data. GNSS data, levelling data and satellite observations for north eastern Polish border areas were used as a case study. Temporal variations of geoid were calculated based on the geopotential models from GRACE satellite observations. The obtained results give an overview of a possibility of the proposed method usage.

Keywords: geoid changes, vertical crustal movements, GRACE.
Conference topic: Technologies of Geodesy and Cadastre.

Introduction

The availability of large amounts of various data allows us to create models of physical phenomena, and to search or verify their mutual dependence. These data can be obtained from ground-based measurements (levelling, GNSS, tide gauges observations) or space observations (satellite missions, e.g. GRACE).

The GRACE (Gravity Recovery and Climate Experiment) satellite mission was launched on 17 March 2002 to map the global gravity field of the Earth. Combined observations from all components (Tapley *et al.* 2004) are used to generate global geopotential models. These models are computed independently with one-month typical temporal resolution in several computational centres. They provide different solutions for the same periods of time calculated with the use of a variety of software.

GRACE data are used to study physical phenomena including geopotential differences (Lyszkowicz *et al*. 2015; Kuczynska-Siehien *et al.* 2016), hydrological changes (Birylo *et al.* 2016) and geoid height variations (Krynski *et al.* 2011).

The aim of this study is to check the correlation between vertical crustal movements and a geoid uplift determined from GRACE data. Moreover, results allow for a preliminary verification of the assumptions concerning these values published by Sjöberg (1982). In addition, the impact of a tide model and a seasonal component on the determined geoid changes over time were evaluated.

Data

According to (Sjöberg 1982) geoid changes over time does not exceed 0.1 of vertical movements of the Earth's crust. This assumption was verified on the model of geoid changes over time developed for the selected area. In our study, we used GFZ GRACE Level-2 Product Release 05 data in a form of spherical harmonic coefficients truncated at d/o 60. The geoid heights were calculated for the period from April 2002 to March 2016 for the area ($52^o<\phi<55^o$ and $19^o<\lambda<25^o$) on 325 (0.25' x 0.25') grid nodes. However, these data need filtering because of large noise. We tested different DDK (1-8) filters (Kusche *et al.* 2009).

Obtained models were compared with models of vertical movements of the Earth's crust developed on the basis of previous results (Kowalczyk 2005; Kowalczyk 2015). These movements were determined from levelling data (Kowalczyk 2008), and the GNSS data using mathematical and network solutions (Kowalczyk, A., Kowalczyk, K. 2014).

To check the compatibility of the geoid changes from GRACE and specified in the work (Sjöberg 1989) extrapolation method and approximate fit were used.

Temporal variations of geoid heights

As a result of the conducted calculations, 27 data sets containing a total of 148200 values were obtained. These data are grouped according to the used tide model and the applied filter.

The seasonal components were calculated for all 27 sets. They differ slightly between the used filters. However, there was no effect of the used tide model on the geoid height seasonality (Fig. 1).

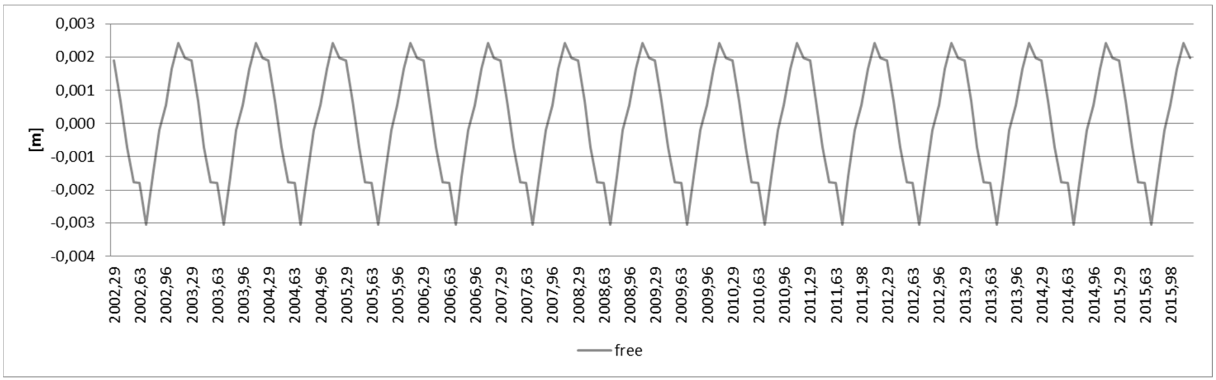

Fig. 1. Seasonal component of the geoid height variations (DDK3 filter and tide-free model)

For each of the 27 cases, the relationships between the signal (geoid height) and the seasonal component were investigated. Similarly, there was no effect of the used tide model on the results (Fig. 2).

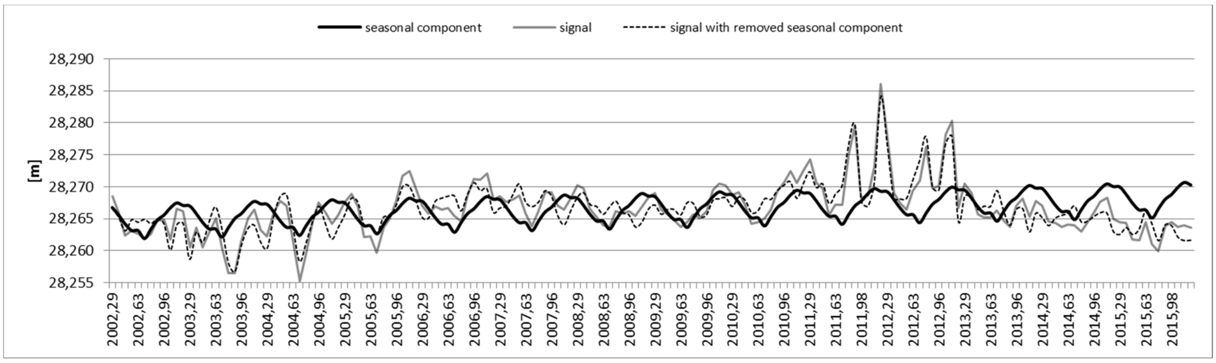

Fig. 2. Geoid height variation and seasonal component (DDK3 filter, tide-free model)

For each of the cases, the amplitudes of the adjacent values of geoid height were calculated. There was also no effect of the used tide model on the obtained differences (Fig. 3). The maximum amplitude was approximately 17 mm (without filtering – GSM2 model) at epoch 2003.29, in other cases does not exceed 14 mm at the epoch 2013.21 (Fig. 4). This amount differs slightly depending on the filter.

Fig. 3. Geoid height variations for various tide models (DDK3 filter)

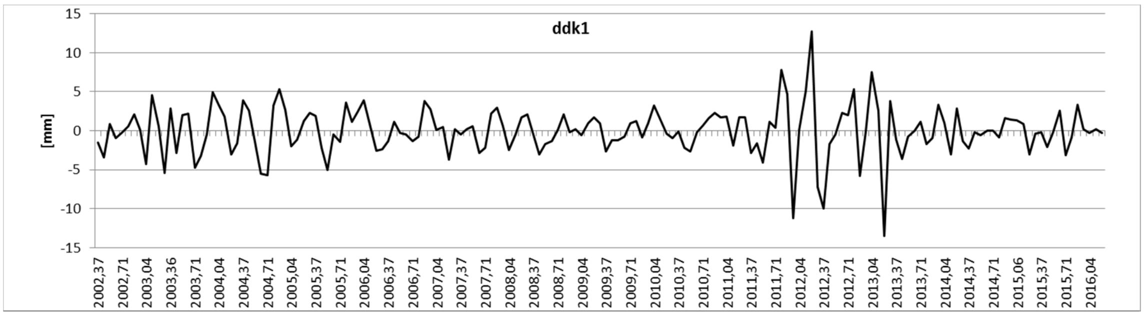

Fig. 4. Amplitude of the adjacent values of geoid height (DDK1 filter, tide-free model)

Figure 5 shows the differences in amplitude in comparison to the values obtained using DDK1 filter. Maximum differences were obtained for GSM2 and DDK8. The effect of the applied filter on the received height differences is shown on the figure.

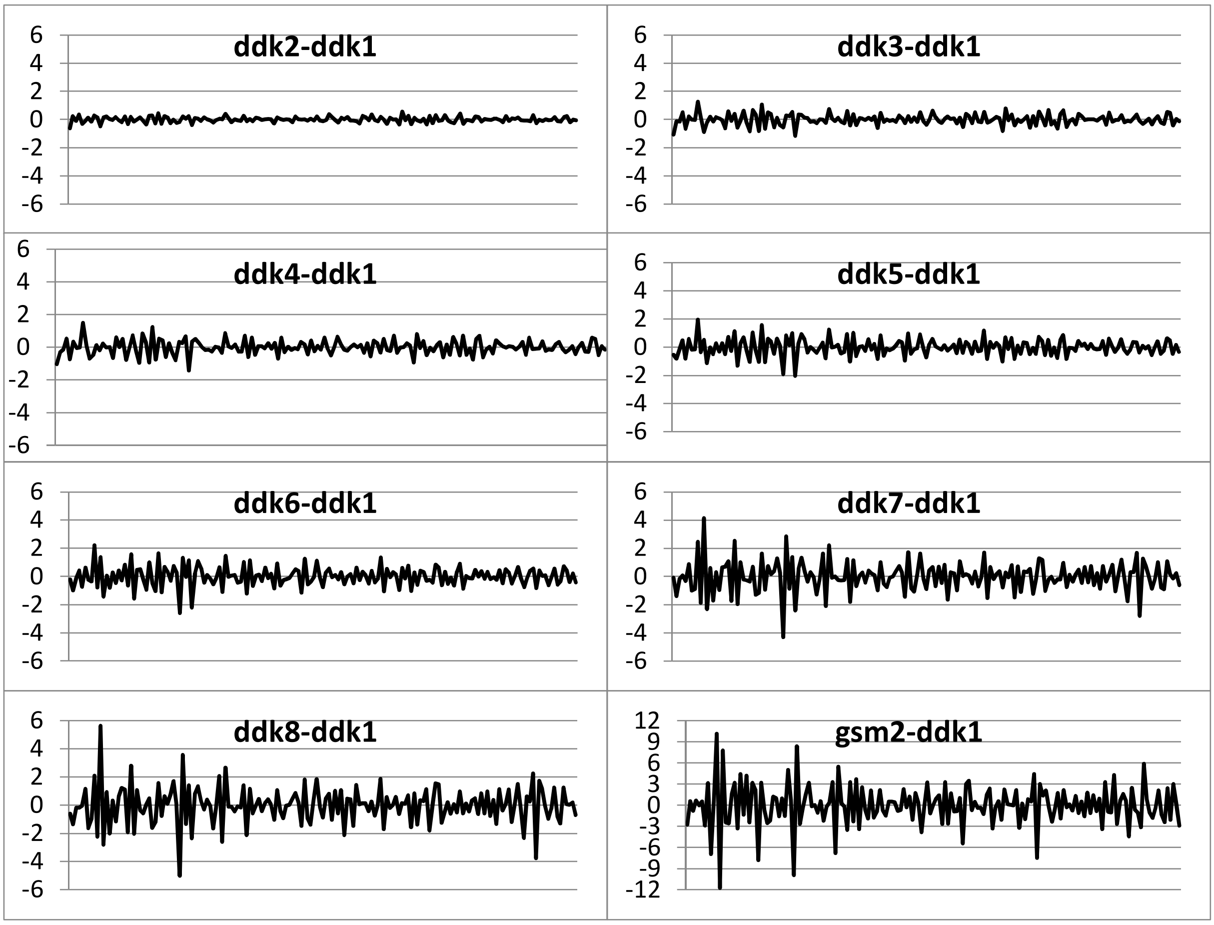

Fig. 5. Amplitude differences from DDK1 filter [mm] (tide-free model)

In order to develop models of geoid changes over time, the velocity was calculated for each data set using a linear trend. Table 1 shows the results obtained for the raw signal and the signal with removed seasonal component. For all filters these values are very similar. Obtained differences are at the level of 0.01mm/y. The computed linear trend was not influenced by the used tide model, neither the seasonal component.

For each from 27 data sets, the model of geoid change over time was developed (Fig. 6). The obtained values are slightly different for the used various filters. This differences are at the level of a few hundredths of a mm/y and are clearly seen for GSM2.

Moreover, the fit of a linear trend for each time series was evaluated. Fig. 7 presents the distribution of the matching coefficient R^2 to the raw signal. In most cases, it ranges from 0.04 to 0.08. As shown in Table 1, for the signal with removed seasonal component it is at the level of 0.21 to 0.27.

Table 1. Velocity and linear trend of geoid changes over time

Filtr	Signal (free)		Signal with removed seasonal component (free)		Signal with removed seasonal component (mean_tide)		Signal with removed seasonal component (zero)	
	V [mm]	R2	V [mm]	R2	V [mm]	R2	V [mm]	R2
DDK1	0.21	0.04	0.22	0.21	0.22	0.21	0.22	0.21
DDK2	0.22	0.05	0.23	0.21	0.23	0.21	0.23	0.21
DDK3	0.25	0.06	0.26	0.27	0.26	0.27	0.26	0.27
DDK4	0.25	0.06	0.26	0.26	0.26	0.26	0.26	0.26
DDK5	0.24	0.05	0.25	0.24	0.25	0.24	0.25	0.24
DDK6	0.23	0.05	0.24	0.23	0.24	0.23	0.24	0.23
DDK7	0.23	0.05	0.24	0.22	0.24	0.22	0.24	0.22
DDK8	0.23	0.05	0.24	0.23	0.24	0.23	0.24	0.23
GSM2	0.34	0.09	0.34	0.40	0.34	0.40	0.34	0.40

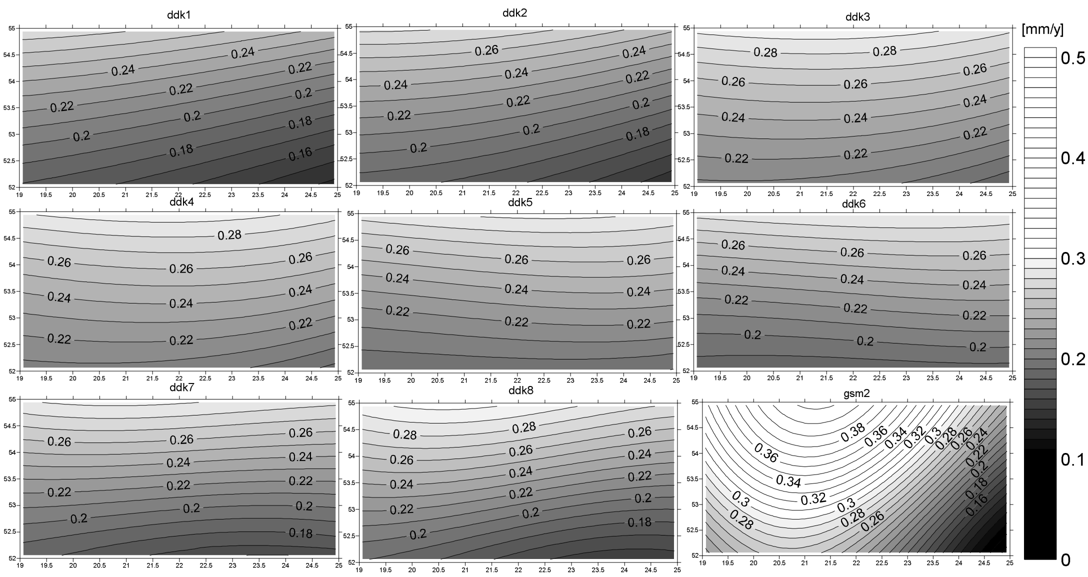

Fig. 6. Models of geoid change over time (tide-free model)

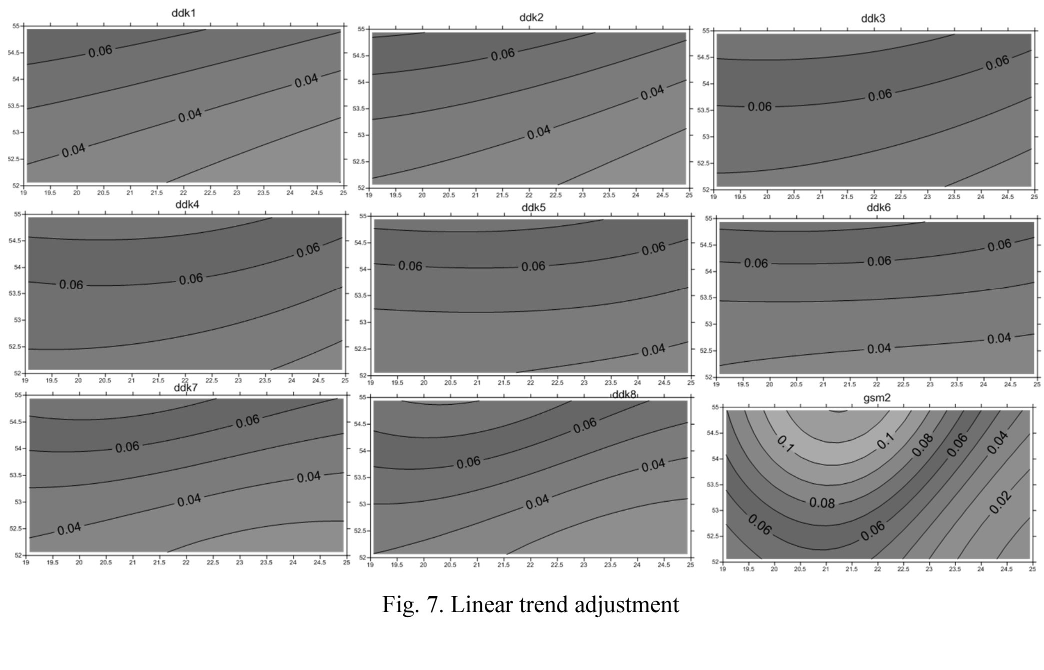

Fig. 7. Linear trend adjustment

Comparison of geoid height variations and vertical movements of the Earth's crust

As was shown at (Kowalczyk *et al.* 2014a), the ellipsoidal height changes in relation to the mean sea level and the geoid undulation is defined by the equation:

$$\partial h_e = \partial h + \partial N \,, \tag{1}$$

where: ∂h_e – change of ellipsoidal height; ∂h – change of height in relation to mean sea level; ∂N – change of geoid and mean sea level (eustatic movement).

The total vertical crustal movements can be calculated based on the equation:

$$v_a = v_o + v_e + v_g \tag{2}$$

where: v_a – total vertical crustal movements (absolute) related to the ellipsoid; v_o – observed vertical movement with relation to the mean sea level; v_e – eustatic movement; v_g – movement caused by the geoid uplift.

The known values of Eq. 2 components can be mutually verified. They are also partly correlated. It is assumed that the value of geoid changes over time equals 0.1 of the observed vertical movement of the Earth's crust (Sjöberg 1982) obtained e.g. from levelling data, tide gauges data or GNSS.

Fig. 8 and Fig. 9 show the course of the Earth's crust vertical movements isolines in the study area. These movements are related to the mean Baltic Sea level changes observed at a tide gauge in Wladyslawowo. Vertical movements of the Earth's crust obtained from levelling data and from GNSS data are similar to each other. They range from –2.0 mm/y to 3.2 mm/y. Comparing Figures 8, 9 and 6 and the values in Table 1, we can confirm the assumption (Sjöberg 1982) that the geoid change over time does not exceed 0.1 of the observed vertical movement of the Earth's crust. However, the direction of the geoid change is opposite to the direction of the vertical movement.

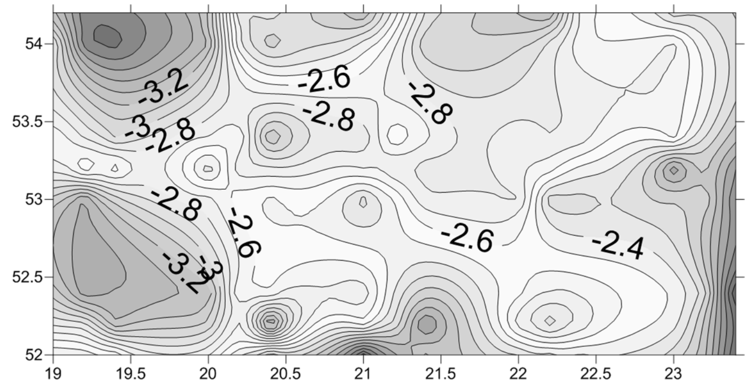

Fig. 8. Vertical movements of the Earth's crust from levelling data (Kowalczyk 2005)

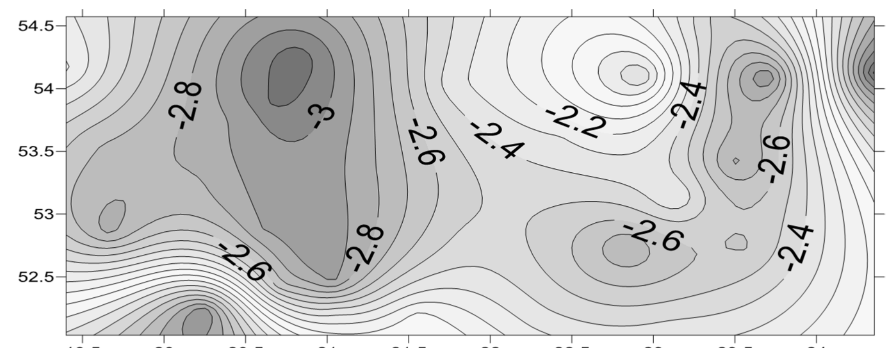

Fig. 9. Vertical movements of the Earth's crust from GNSS data (Kowalczyk *et al.* 2014b; Kowalczyk 2015)

An approximate comparison of the model of geoid changes over time obtained from GRACE data and the results of the extrapolation of values from (Sjöberg 1989) was made (Fig. 10). The results of visual analysis indicate a large convergence of these results.

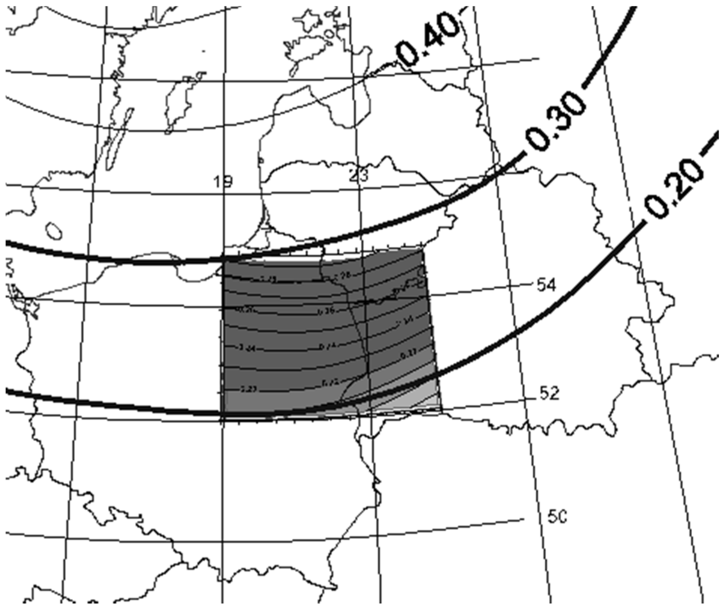

Fig. 10. Geoid changes over time obtained from GRACE and extrapolated from values of geoid changes given in (Sjöberg 1989)

Conclusions

The value of the seasonal coefficient does not depend on the adopted tide model. However, there is an insignificant impact of the applied filter on this value. There are also slight differences in the relationship between the raw signal and the seasonal component for each tide model at the level of thousandths of a millimeter. This is a negligible value.

Differences of geoid height for adjacent values are the same for various tide models. The used tide model does not affect both the determined differences and the determined trend of geoid changes over time.

The difference between the trend of the raw signal and the trend of the signal with removed seasonal component seasonality effect is at the level of 0.01 mm/y. Adjustment coefficients for signal without seasonal component is 10 times greater than for the raw signal.

Isolines of the vertical movements of the Earth's crust in the tested area, partly coincide with the geoid height changes. Values of the geoid changes do not exceed 0.1 of the crustal movements, but the direction of these changes is opposite to the vertical movements.

Obtained values of the geoid height changes over time are correlated with the data extrapolated on the basis of the work (Sjöberg 1989).

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