TESTING THE RELATIONSHIP BETWEEN VERTICAL CRUSTAL MOVEMENT AND GEOID UPLIFT FOR THE SUDETES AREA

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Abstract: The aim of this study was to examine the relationship between vertical movements of the Earth's crust and variation in geoid height. Data from the Gravity Recovery and Climate Experiment (GRACE), precise levelling, tidal gauge observations and Global Navigation Satellite Systems (GNSS) stations for the Sudetes area were used. The GRACE data provided the possibility of the analysis of geopotential changes. The geoid heights were calculated for the period from April 2002 to March 2016, using data from GeoForschungsZentrum (GFZ) GRACE Level-2 Product Release 05 in the form of spherical harmonic coefficients, truncated at degree and order (d/o) 60. Different filters were used. The calculated geoid change over time has the approximate value of 0.16 mm/y. This value was compared to the expected change in geoid height, determined on the basis of the Earth's crustal movements.

Key words: Regional variation in geoid height, vertical crustal movements, GRACE, geodynamics.

INTRODUCTION

The availability of geodetic, gravimetric, magnetic, seismic and tectonic data allows the creation of models of physical phenomena and the determination or verification of relationships between them. For example, it is feasible to investigate the possible correlation between movements of the Earth's crust and the variation in geoid height over time (Mäkinen *et al.*, 1985; Mäkinen *et al.*, 2005; Steffen, 2008).

Global Navigation Satellite Systems (GNSS) measurements, tidal gauge observations and levelling data can be used to study the uplift (Ekman and Mäkinen, 1996; Kowalczyk, 2005; Lidberg *et al.*, 2007; Kowalczyk and Rapinski, 2017). Temporal variation in gravity and geoid height can be detected using absolute and relative gravimetry (Ekman and Mäkinen, 1996; Makinen *et al.*, 2005; Müller *et al.*, 2006) or the Gravity Recovery and Climate Experiment (GRACE) satellite mission (Wahr and Velicogna, 2003; Steffen *et al.*, 2009; Kryński *et al.*, 2014). For example, studies of the relationship between changes in the Earth's crust, determined from geodetic and tidal gauge data, and its isostatic changes can be found in Root *et al.* (2015), and Lidberg *et al.* (2007). These works were carried out mainly in the Fennoscandia region.

Knowledge of temporal variation in geoid height is applicable to many aspects of geodynamic research. Currently, changes of the surface of the Earth's crust are determined using observations from GNSS stations. Geoid change over time is a component of the absolute vertical movement of the Earth's crust with reference to the ellipsoid (Sjöberg, 1982; Torge, 1989; Kowalczyk *et al.*, 2014). In order to determine relative ("observed"; Kakkuri, 1987) vertical movements, which can be obtained, for example, through the simultaneous use of levelling and GNSS data, the reduction of absolute movements by geoid variation is necessary. The value of variation in the geoid height also can be used to assess the validity of determined vertical movements of the Earth's crust. These movements should be about ten times larger than the geoid change (Sjöberg, 1982). An alternative result may indicate that these are local movements, or that they were determined erroneously. Furthermore, knowledge about geoid change over time is important for maintaining global and regional systems of kinematic height and updating heights for geodetic datums (Krzan *et al.*, 2016).

The distribution of mass in the Earth's crust and post-glacial rebound have the main impact on the temporal varia-

tion of the geoid (Ekman and Mäkinen, 1996; Agren and Svensson, 2007). Isostatic movements affect the reference level and therefore the coordinate systems, as well. They are caused by the accumulation or melting of ice on the land, the accumulation of sediment on the bottom of the ocean or the construction of large water reservoirs. Sjöberg (1989) indicated that the reason for the occurrence of this effect is the classical rebound phenomenon and it is confirmed by the models developed from repeated precise levelling and tidal gauge data.

The area of Poland is influenced by the ice sheet that covered Fennoscandia. As shown by Lidberg *et al*. (2007), the maximum uplift reaches about 1 cm/year, which is related to a corresponding change in the potential of the Earth's gravity field by about -2 μGal/y (Ekman and Mainen, 1996). Likewise, Jeffreys (1970, p. 429) pointed out that comparing movements of the Earth's crust and geoid changes, they have opposite signs. However, this change may have the opposite direction (+1 μGal/y), if it is referenced to a particular point in space. This is connected with glacial isostatic adjustment (Steffen *et al*., 2015).

Changes in geoid height can be detected using data from the GRACE satellite mission. The main goal of the GRACE mission is to provide information on global geopotential models (GGMs) in a time sequence. This permits, among other things, the estimation of the geopotential value at a given point (Kuczynska-Siehien *et al*., 2016) and the determination of changes in the Earth's gravity field over time. As shown in Kryński *et al*. (2014), the amplitude of geoid variation in Europe fluctuates by up to ~4 mm over 8 years, whereas in the Gulf of Bothnia it fluctuates by up to ~3 mm over 5 years (Müller *et al*., 2006).

The GGMs are computed independently with one-month typical temporal resolution at several computational centres: the Centre for Space Research (CSR), University of Texas, the Jet Propulsion Laboratory (JPL), the GeoForschungs-Zentrum (GFZ), the Centre National d'Etudes Spatiales/

Groupe de Recherche de Géodésie Spatiale (CNES/GRGS) at Toulouse, the Institute of Geodesy and Geoinformation (ITG), University of Bonn and the Astronomical Institute University of Bern (AIUB), among others. The information provided about the gravitational field of the Earth is influenced by many factors (Swenson and Wahr, 2006) and requires filtration. Individual centres provide different solutions for the same periods of time, calculated with the use of a variety of software (available at ICGEM, 2017; http://icgem.gfz-potsdam.de/ICGEM/).

The occurrence of vertical movements of the Earth's crust is caused by natural factors or human activity (Ekman and Mäkinen, 1996). In addition to natural factors, such as earthquakes, changes in groundwater levels (Bednarczyk *et al*., 2015) and volcanic eruptions, there are also isostatic rebound effects, especially on a regional scale. Isostatic movements affect the Earth's gravitational field and are reflected in uplift of the land (Ekman and Mäkinen, 1996; Agren and Svensson, 2007). According to (Sjöberg, 1982), changes in geoid height over time do not exceed 0.1 mm/y of the measured vertical movements of the Earth's crust.

Movements of the Earth's crust are well documented in the area of Poland (Fig. 1) (Wyrzykowski, 1986; Kowalczyk, 2005; Bogusz and Kontny, 2012; Rapinski and Kowalczyk, 2013; Walo *et al*., 2016) and in the Sudetes area (Oberc and Woźniak, 1978; Stemberk *et al*., 2010; Jamroz *et al*., 2014). As shown by Kowalczyk (2005) on the basis of levelling data and by Kowalczyk and Rapinski (2017) on the basis of data from the GNSS stations, they fluctuate in the area of Poland on average from -3 mm/y to -1.5 mm/y with reference to the mean sea level, determined at the tide gauge in Władysławowo for the Baltic Sea.

The aim of the article is to verify the hypothesis given by Sjöberg (1982) that change in the geoid over time is ten times lower than the vertical movements of the Earth's crust, with reference to sea level. The research was con-
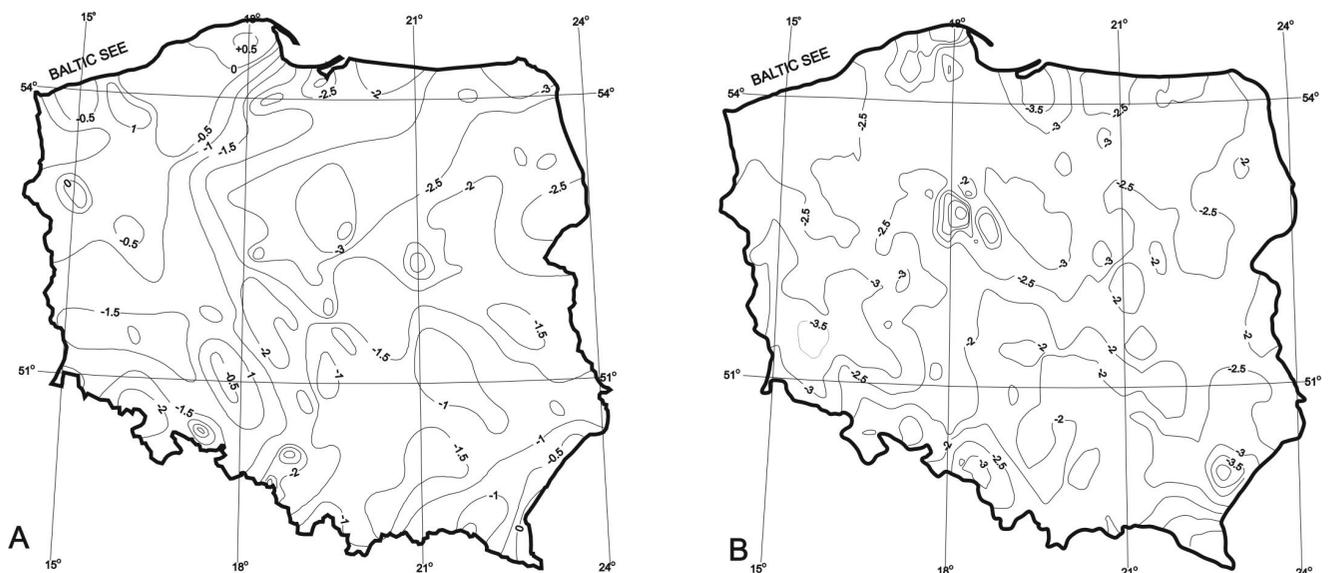
Fig. 1.   Vertical movements of the Earth's crust in Poland from levelling data with respect to the mean sea level of the Baltic Sea [mm]. **A.** According to Wyrzykowski (1986). **B.** According to Kowalczyk (2005, 2006c).

ducted in a relatively small area covering the southwestern part of Poland and the northern part of the Czech Republic. The variation in geoid height in this area is poorly documented. In addition, this area is in part mountainous and to some extent under development. Verification of the hypothesis can be used to assess the suitability of GNSS data for the study of vertical movements of the Earth's crust and will give information on the magnitude of variation in the geoid height. Additional objectives are to check the suitability of GRACE data for the determination of geoid changes in a relatively small area using a variety of filters and to evaluate the seasonality component in the time series investigated. Movements of the Earth's crust, determined on the basis of levelling observations, tide gauge observations and GNSS data were used for reference purposes. The movements of the Earth's crust were presented with reference to changes in mean sea level of the Baltic Sea, which corresponds to Sjöberg's assumptions (1982).

The article consists of two main parts. The first part describes the GRACE data and analyses of them in the study area. After removing the seasonal component from the GRACE time series, the variations in geoid height were determined. Amplitude changes of geoid height were analysed. The trend of geoid changes over time was determined, using a linear regression method. Finally, a model of geoid change over time was developed for nine different types of filter. The second part of the paper presents the magnitude of vertical movements of the Earth's crust in six variants in the study area. These variants differ in terms of the data used and the methods of developing them. At the end, a comparison of changes in geoid height over time and vertical movements was made.

DATA USED TO ANALYSE TEMPORAL VARIATION IN GEOID HEIGHT

The test area covers the southwestern part of Poland and the northern part of the Czech Republic ($49^O < \phi < 52^O$ and $14^O < \lambda < 19^O$) (Fig. 2). The geoid heights were obtained, using the International Centre for Global Earth Models (ICGEM) Calculation Service for the period from April 2002 to March 2016. The GFZ GRACE Level-2 Product Release 05 data (Dahle *et al*., 2012) in a form of spherical harmonic coefficients, truncated at degree and order (d/o) 60, were used. The GSM-2 model and DDK1, DDK2, DDK3, DDK4, DDK5, DDK6, DDK7, DDK8 filters (Kusche *et al*., 2009), based on the de-correlation and smoothing method (Kusche, 2007) were tested.

METHODS

Geoid Height Variation

The nine data sets (all based on GSM-2, including eight DDK-filtered time series) containing altogether 39,824 values of geoid height in 0.25° x 0.25° grid nodes were obtained for the study area. Owing to slight differences between the results obtained with the use of different DDK filters, the GSM-2 and the DDK3 filters were used for all graphical

representations. In the first step, the seasonality coefficients were calculated. The results show that there is a strong annual signal, with an amplitude close to 5 mm (Fig. 3). The variation in geoid height and the seasonal component were determined. The comparison of the a priori signal and the signal with the seasonal component removed is shown in Figures 4 and 5.

Geoid height variations between the adjacent-in-time geoid heights for the signal a priori are shown in Figure 6. The maximum amplitude for the filtered data was equivalent to approximately 18 mm, whereas the mean was 8 mm. For the geoid heights calculated on the basis of GSM-2 without any filters, the maximum amplitude was nearly 30 mm. The amplitude of variation in geoid height between the adjacent-in-time geoid heights for the signal with the seasonal component removed is shown in Figure 7. The maximum amplitude for DDK filters reaches 13 mm and for GSM-2 18 mm (Tab. 1). In order to determine the change of geoid height in the time span analysed, the differences between the geoid heights in the time series and the initial value (the geoid height in the epoch 2002.37) were calculated for the signal with the seasonal component removed (Fig. 8). The maximum change over a 14-year period was equivalent to 15 mm. The change did not usually exceed ±5 mm. The difference in the amplitude between GSM-2 and DDK3 data sets is shown in Figure 9.

Furthermore, in order to develop models of changes in geoid height over time, the linear trend *v* was calculated for each data set. The seasonal component was removed from each grid node in all time-series. The trend *v* and the coefficient of determination R^2 were calculated. The R^2 coefficient indicates a fit of a linear regression model to empirical data. It varies from 0 to 1, where values closer to 1 indicate greater agreement. The influence of the seasonal effect on the determined rates of geoid height change and on R^2 were calculated (Tab. 2). The determined linear trend for the a priori signal is similar for all DDK filters used and varies from 0.16 mm/y to 0.18mm/y. The differences do not exceed 0.02 mm/y (except for GSM-2). After removing the seasonal effect, these values did not change. However, the value of R^2 increased six times. Despite this, it is still at a low level, which means that the regression line does not fit the data well.

For the DDK3 and GSM-2 data sets, the models of geoid change over time were developed (Fig. 10). Interpolation using the minimum curvature method was used for modelling. Owing to the unsmoothed data, the GSM-2 model differs significantly from the DDK-filtered model.

Vertical crustal movements

Models of vertical movements of the Earth's crust in the Sudetes area were computed in six variants as "observed" movements. In variant *a*, vertical movements of the Earth's crust were determined at the nodal points of a precise levelling network (vA). It was developed on the basis of a double precise levelling, performed in the area between 1976 and 2003 with respect to level of the Baltic Sea. The double levelling network was referred to the tidal gauge in Władysławowo, where the changes in mean sea level were
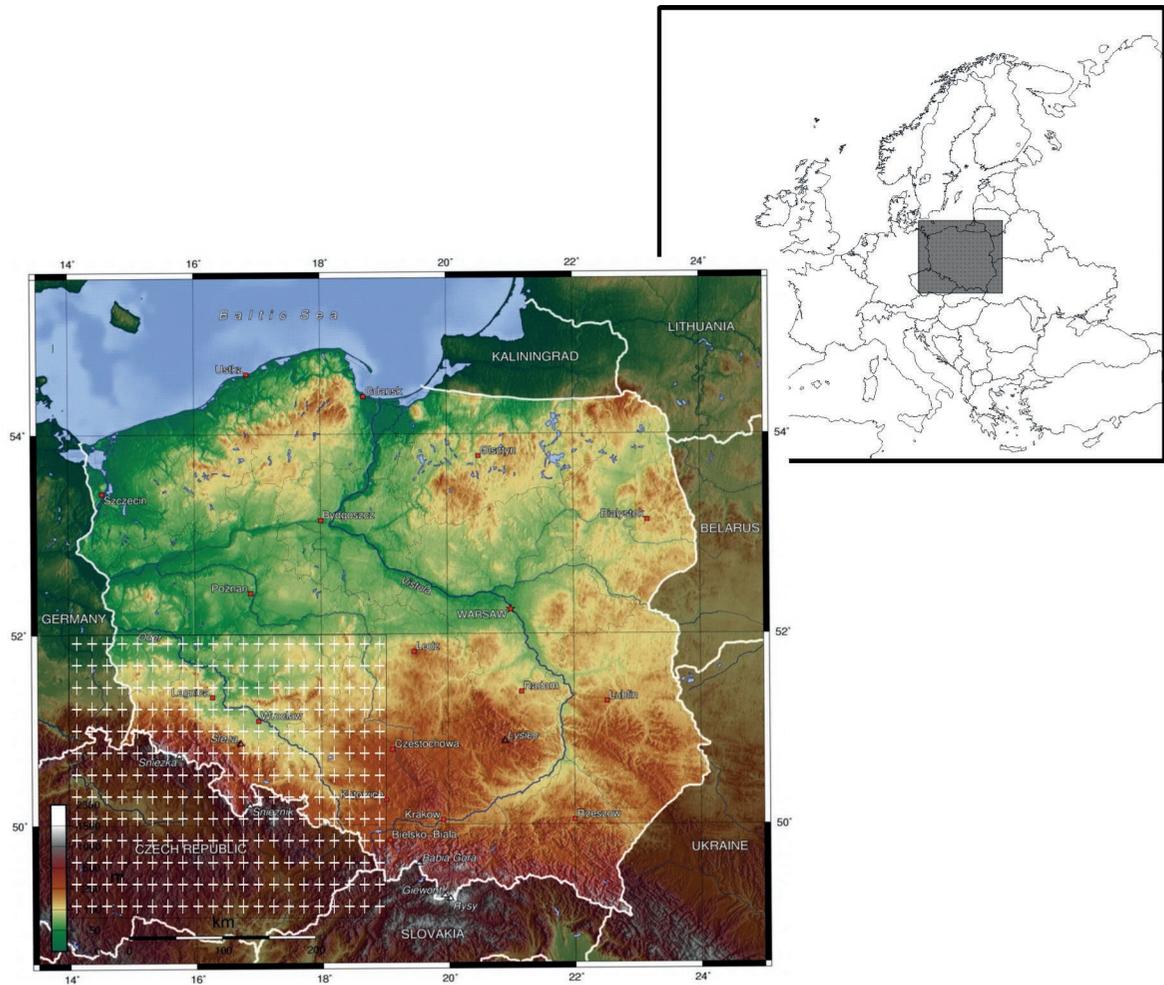
Fig. 2.   Location of the study area (*worldmap.pl*).

Table 1

The maximum amplitude of geoid height variation between the adjacent-in-time geoid heights
for the signal with the seasonal component removed and different DDK filters used.

Filter used	DDK1	DDK2	DDK3	DDK4	DDK5	DDK6	DDK7	DDK8	GSM-2
Maximum amplitude [mm]	10.39	10.51	10.79	10.94	11.54	11.96	13.01	13.33	17.51

Table 2

Linear trend of changes in geoid height and coefficient of determination.

Filter used	Signal a priori		Signal with the seasonal component removed	
	v [mm/y]	R^2	v [mm/y]	R^2
DDK1	0.16	0.03	0.15	0.23
DDK2	0.16	0.03	0.15	0.24
DDK3	0.18	0.04	0.17	0.24
DDK4	0.18	0.04	0.17	0.25
DDK5	0.18	0.04	0.17	0.25

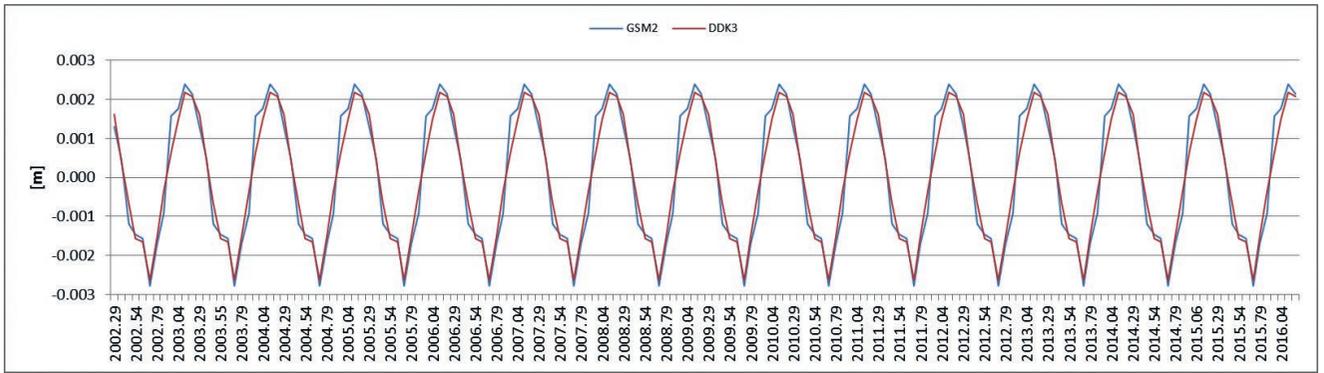| Filter used	Signal a priori		Signal with the seasonal component removed	
	v [mm/y]	R^2	v [mm/y]	R^2
DDK6	0.18	0.04	0.17	0.25
DDK7	0.18	0.04	0.17	0.24
DDK8	0.18	0.04	0.17	0.25
GSM-2	0.10	0.01	0.09	0.20

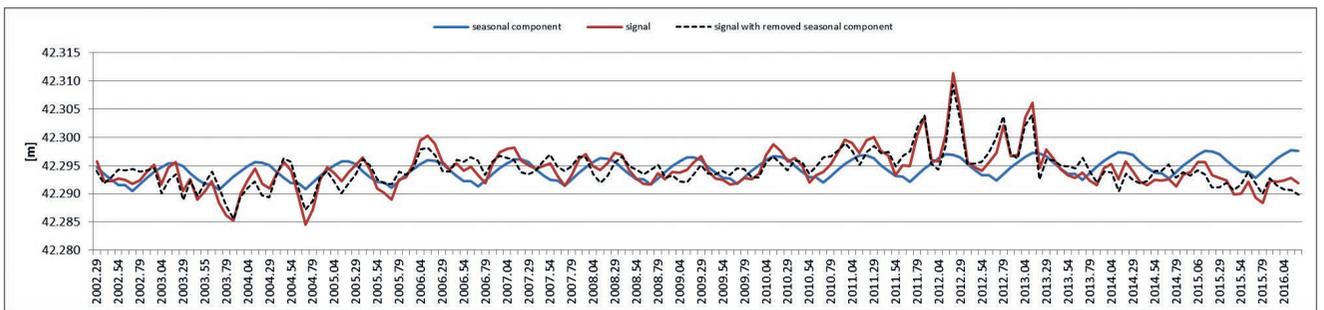**Fig. 3.** Seasonal variation in geoid height (the centre point of the area).

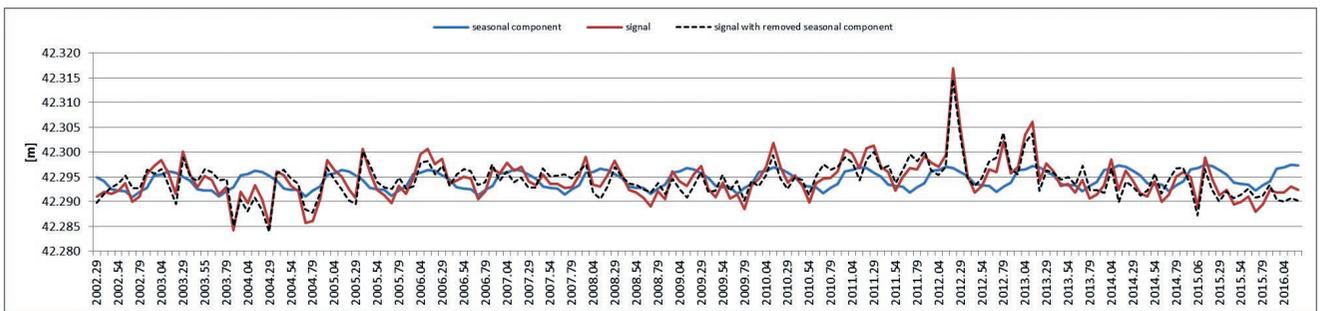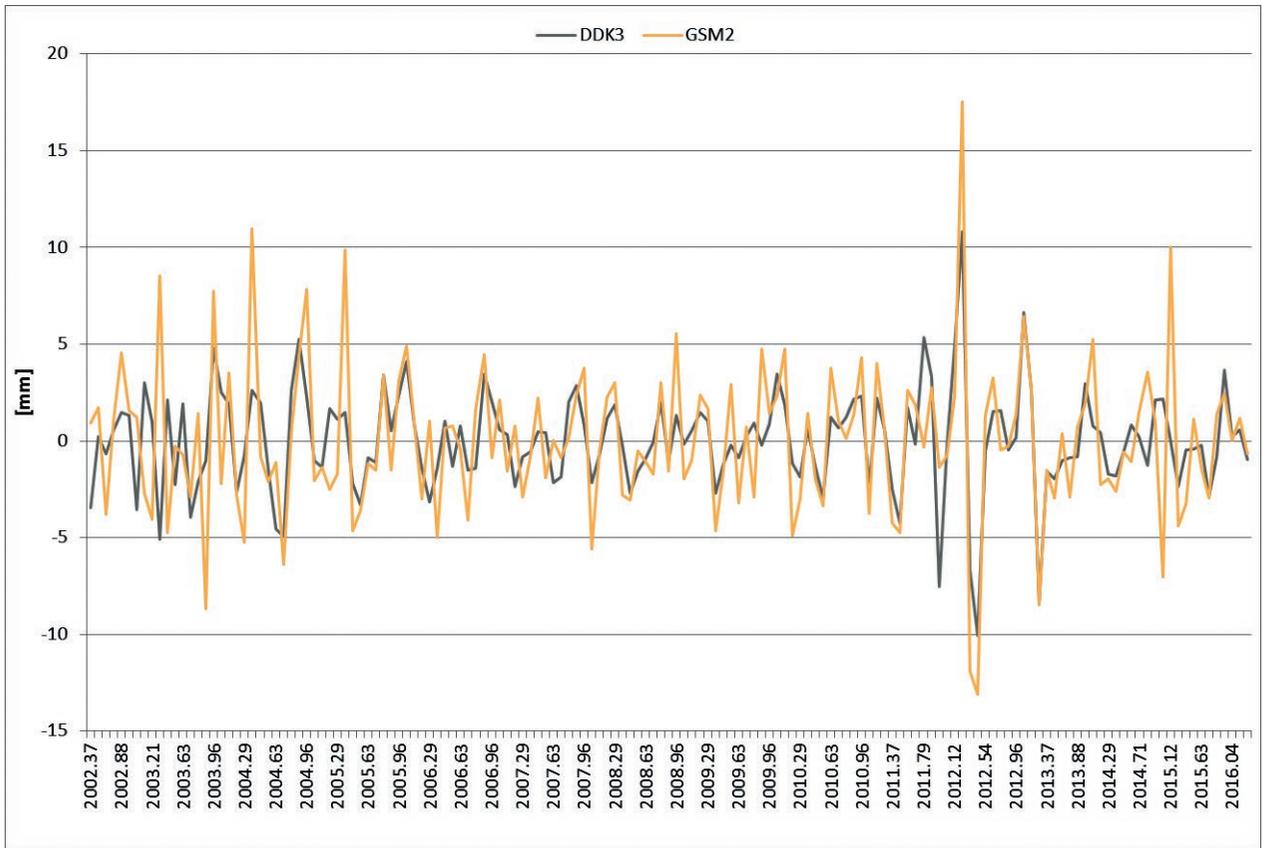**Fig. 4.** Variation in geoid height for DDK3 (the centre point of the area).

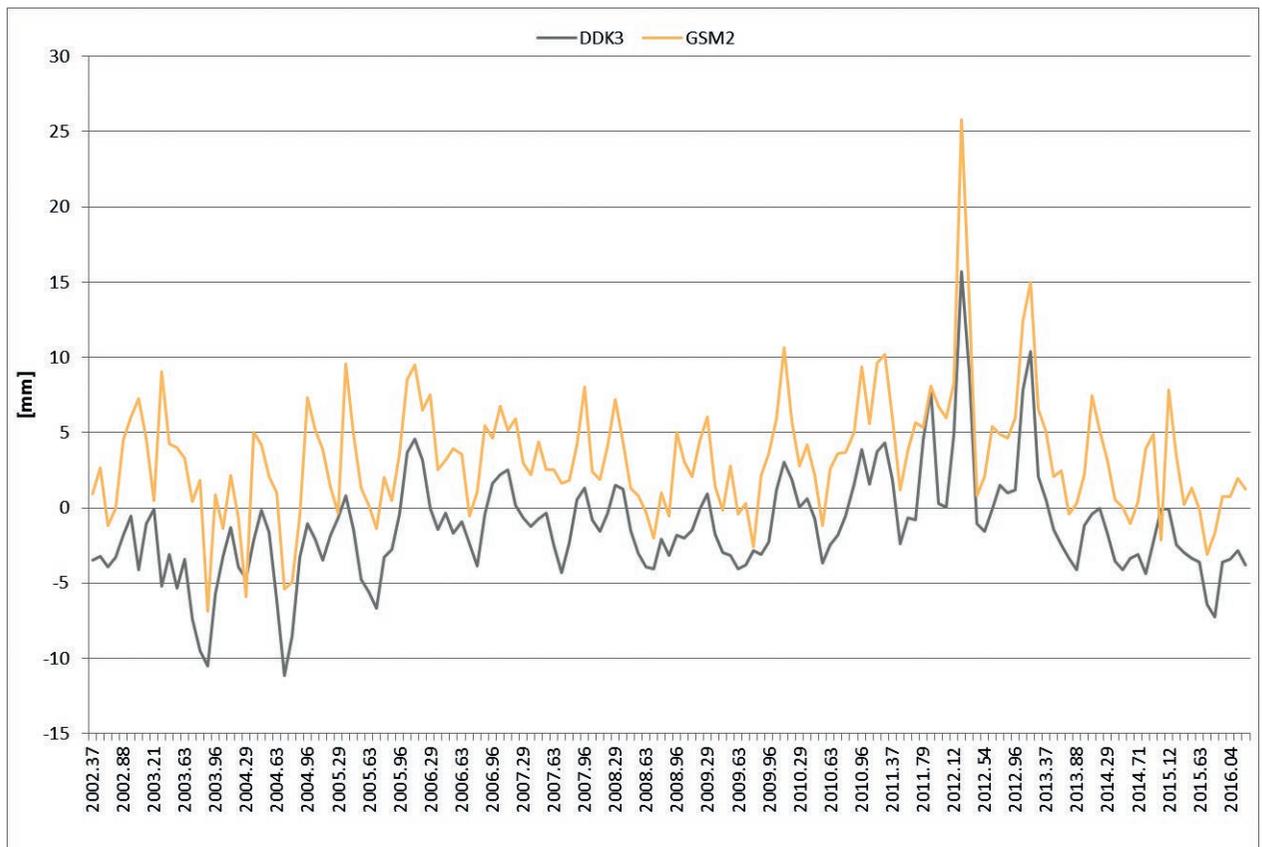**Fig. 5.** Variation in geoid height for GSM-2 (the centre point of the area).

determined (Kowalczyk, 2005). Variant *b* is the combination of variants *a* and *d* (vertical crustal movements at the grid nodes vG, combined with vertical crustal movements at the nodal points of a double precise levelling network vA). Variant *c* is the combination of variants *a* and *e* (vertical crustal movements at the nodal points of a double precise levelling network vA, combined with vertical crustal movements at the GNSS stations vS). In variant *d* vertical movements of the Earth's crust (vG) were obtained at 20' x 20' grid nodes on the basis of the adjusted velocities at the double levelling benchmarks, using the least squares collocation method (Kowalczyk, 2006a). All of the variants of the vertical movements of the Earth's crust present similar di-

rection and velocity for the Sudetes area. However, the most reliable is variant *d*.

In 2017, the height changes of the Earth's crust in Poland were determined on the basis of data obtained from the Active Geodetic Network – European Position Determination System (ASG-EUPOS) stations for the period 2008–2013 (Kowalczyk and Rapinski, 2017). Height differences between adjacent stations were used for calculations. The network of unadjusted vertical movements was created before it was adjusted with reference to the tide gauge at Władysławowo. In variant *e*, vertical crustal movements were determined at the GNSS permanent stations (vS). In this variant, a fragment of the adjustment for the Sude-

Fig. 6.   Variation in geoid height between the adjacent-in-time geoid heights for the signal with the seasonal component (the centre point of the area).

Fig. 7.   Variation in geoid height between the adjacent-in-time geoid heights for the signal with the seasonal component removed (the centre point of the area).
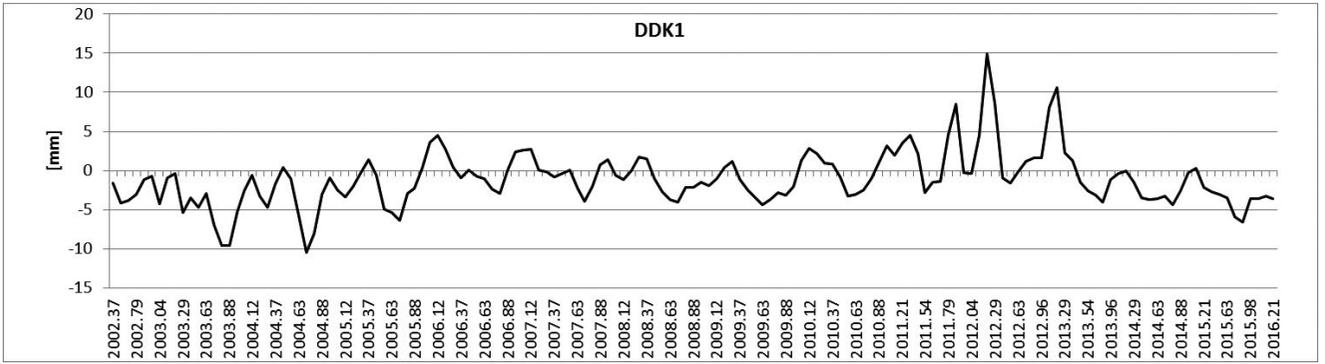
Fig. 8. Change in geoid height compared to the initial value (the centre point of the area).
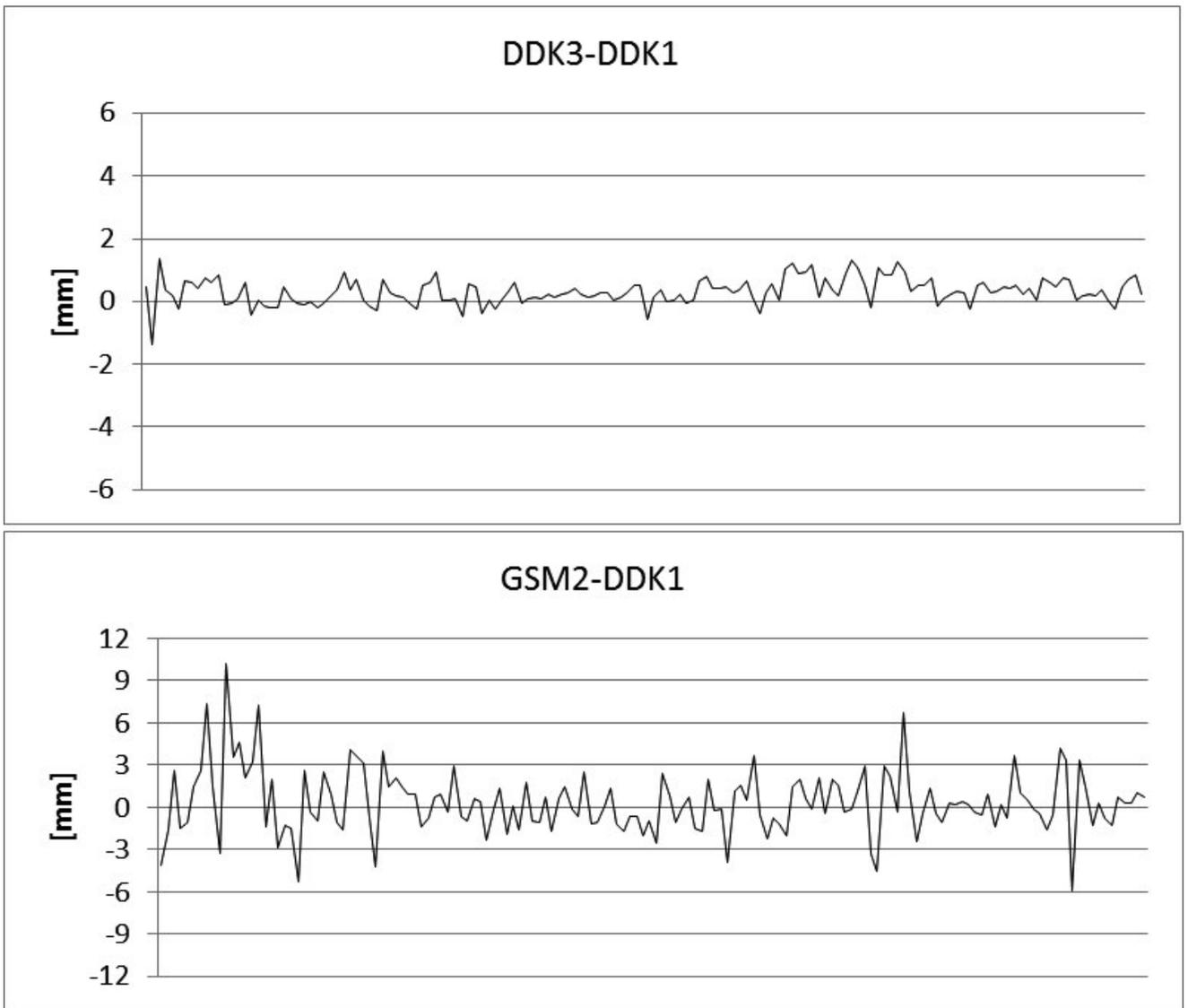

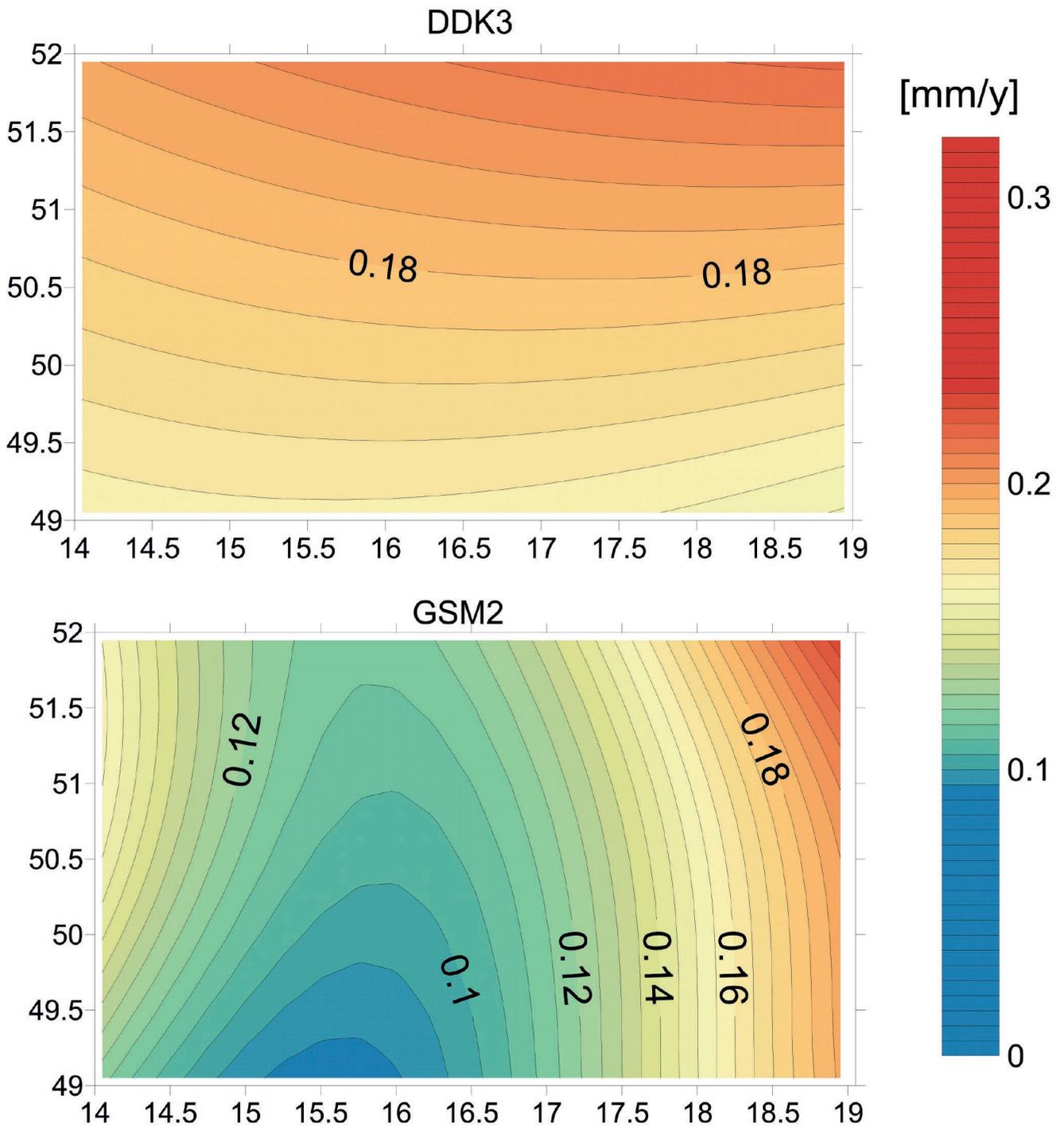**Fig. 9.** Amplitude differences compared to the DDK1 filter [mm].

Fig. 10. Variation in geoid height.

tes area was used. Variant *f* is the combination of variants *b* and *e*.

The interpolation using the minimum curvature method was employed to present the results (Fig. 11). The values of vertical movements in the Sudetes area determined with reference to variant *d* vary from –1.5 mm/y to 3 mm/y (Kowalczyk, 2006b). Taking into account the Sjöberg assumption about the relationship between the change in geoid height over time and movements of the Earth's crust, it can be expected that the change in geoid height over time in the study area is at the level of –0.15 mm/y to –0.30 mm/y. If

the effect of change in mean sea level of the Baltic Sea is removed from the "observed" movements, the values of vertical movements in the Sudetes area fluctuate from 0 mm/y to +1.5 mm/y. Consequently, the change in geoid height would be at the level of 0.0 mm/y to 0.15 mm/y. The models analysed and the Sjöberg assumption are not completely convergent. This can be caused by many factors, such as different epochs of observation, changes in rock mass, changes to the surface of the Earth's crust, and their elimination is a complex process.
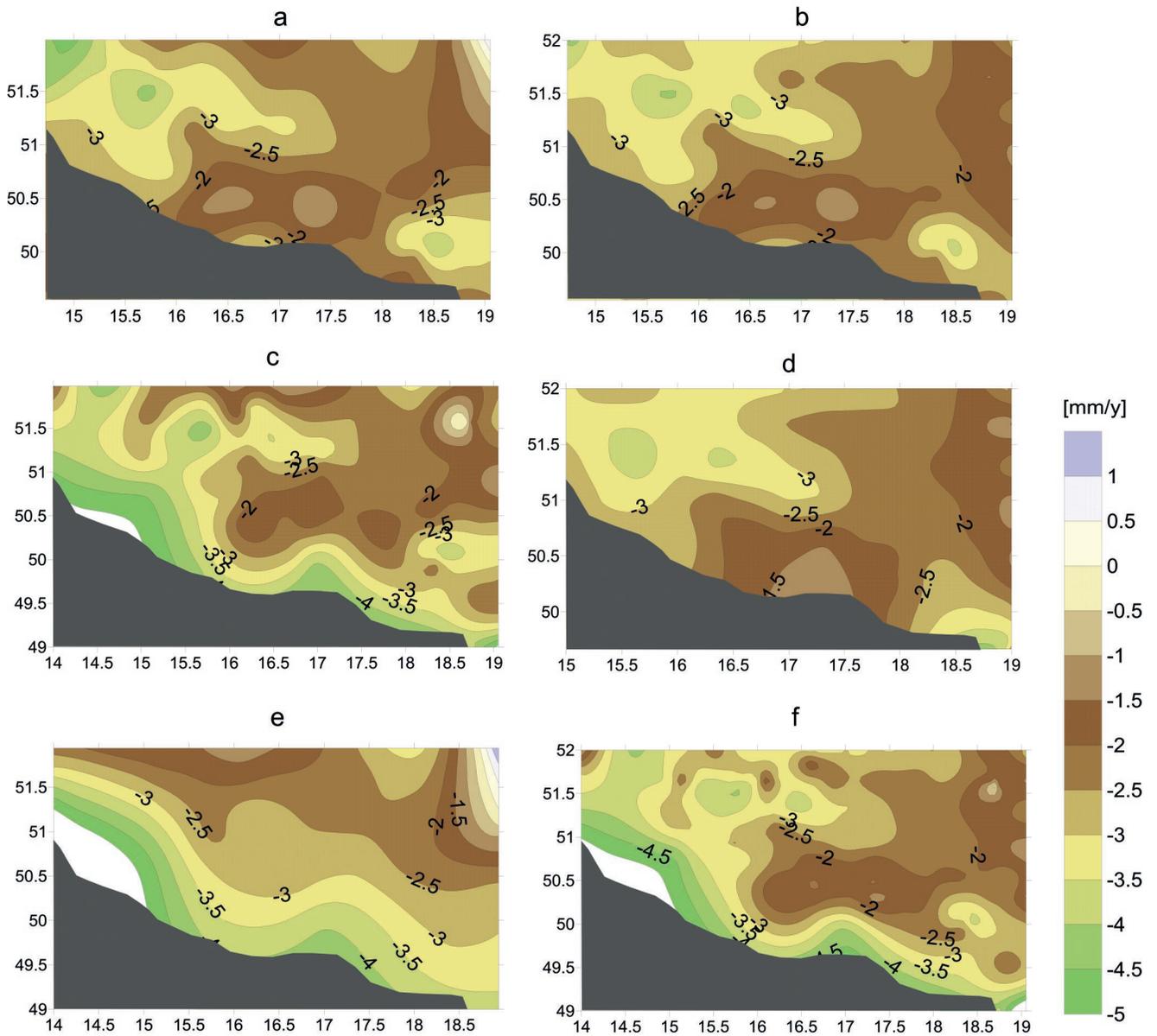
Fig. 11   Observed" vertical movements of the Earth's crust in the Sudetes area (based on Kowalczyk, 2005; Kowalczyk, 2006b; Kowalczyk and Rapinski, 2017).

CONCLUSIONS

GRACE mission data provided the possibility of analysis of geopotential changes. The final results may vary, owing to the processing of raw observations by different computational centres and the possible use of different filters. The value of the trend did not change significantly after removal of the seasonal component (Tab. 2). However, the value of the R^2 coefficient increased slightly, which means that the fit was improved. From a statistical point of view, the results for the Sudetes area are similar: 0.15 mm/y and 0.17 mm/y. The value of R^2 close to zero indicates a poor fit of the regression line to the data, which occurs for all types of filters. The amplitude of the variation in geoid height is equivalent to approximately 1.1 cm, depending on the DDK filter used. In such a small area, the filter used does not significantly af-

fect the value of the trend, but only the horizontal direction of the changes. The values of the change in geoid height over time from the GRACE data have an opposite sign from those that were predicted on the basis of the "observed" vertical movements of the Earth's crust. This confirms the assumptions made in the study by Steffen *et al.* (2015), in which the authors state that this is related to glacial isostatic adjustment (GIA). It can be assumed that the impact of GIA in the Sudetes area is at a level of 0.3 mm/y to 0.4 mm/y.

The results obtained for variation in geoid height do not exceed one-tenth of the vertical movements of the Earth's crust in the Sudetes area. To confirm fully the hypothesis presented in the introduction, further investigations are necessary over a larger area.

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