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Analysis of seasonal position variation for selected GNSS sites in Poland using loading modelling and GRACE data

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ABSTRACT

In this study we compared weekly GNSS position time series with modelled values of crustal deformations on the basis of Gravity Recovery and Climate Experiment (GRACE) data. The Global Navigation Satellite Systems (GNSS) time series were taken from homogeneously reprocessed global network solutions within the International GNSS Service (IGS) Reprocessing 1 project and from regional solutions performed by Warsaw University of Technology (WUT) European Permanent Network (EPN) Local Analysis Center (LAC) within the EPN reprocessing project. Eight GNSS sites from the territory of Poland with observation timespans between 2.5 and 13 years were selected for this study. The Total Water Equivalent (TWE) estimation from GRACE data was used to compute deformations using the Green's function formalism. High frequency components were removed from GRACE data to avoid aliasing problems. Since GRACE observes mainly the mass transport in continental storage of water, we also compared GRACE deformations and the GNSS position time series, with the deformations computed on the basis of a hydrosphere model. We used the output of Water GAP Hydrology Model (WGHM) to compute deformations in the same manner as for the GRACE data. The WGHM gave slightly larger amplitudes than GNSS and GRACE. The atmospheric non-tidal loading effect was removed from GNSS position time series before comparing them with modelled deformations. The results confirmed that the major part of observed seasonal variations for GNSS vertical components can be attributed to the hydrosphere loading. The results for these components agree very well both in the amplitude and phase. The decrease in standard deviation of the residual GNSS position time series for vertical components corrected for the hydrosphere loading reached maximally 36% and occurred for all but one stations for both global and regional solutions. For horizontal components the amplitudes are about three times smaller than for vertical components therefore the comparison is much more complicated and the conclusions are ambiguous.

1. Introduction

The present precision of space and satellite geodetic techniques reached unprecedented accuracy which allows us to study subtle geodynamic phenomena. One of the particular interests in this study is the hydrosphere loading. This process reflects the climatic-driven re-distribution of masses in a hydrosphere. The variable mass loading causes variable crustal deformation [1]. This effect can be observed in geodetic space and satellite techniques as site position variations. The continental water storage loading can be modelled on the basis of the crust elasticity (in terms of load Love numbers or Green's functions) and variable continental water storage mass distribution assessment. One way is to use hydrology models output [1,2]. The other possibility is to use the surface mass transport in Earth system obtained from the inversion of the time-variable gravity field. The global, detailed, time-dependent Earth gravity solution became recently possible with the GRACE mission [3]. The first use of the GRACE solution

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for the crustal deformation and its validation with GNSS measurements was done by Davis et al. [4]. Numerous results for vertical components were presented by other authors showing poor [5] and good agreement [6,7] depending on the processing scheme.

The presented study concentrates on the territory of Poland. It should be underlined that in this area the effect of the continental water storage loading is large and is dominant in seasonal period. The peak-to-peak deformation can reach as much as one centimetre for the vertical component [2]. We compare here the modelled crustal deformation computed on the basis of GRACE results with observed seasonal position variations for selected Polish GNSS sites (see Fig. 1). For the completeness of the studies and to get external validation of our results we include also the hydrological model. The output of WGHM was used in this study.

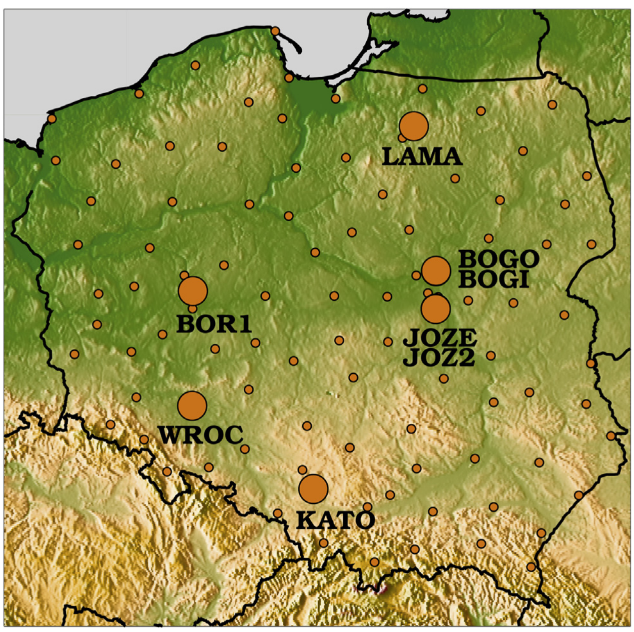

Fig. 1. The map of selected GNSS sites used in this study (big circle) and other permanent GNSS sites in Poland (small circle).

2. Data treatment

The way in which we compared two different techniques (geometric – GNSS and gravimetric – GRACE) demands an explanation. The illustrative description of the data sources and data treatment is given in Fig. 2. This flow chart will be explained in details in consecutive subsections.

2.1. GNSS

To investigate seasonal variations of site positions we selected eight GNSS sites in Poland (in two cases we used collocated sites, see Fig. 1 and Table 1).

The selected stations have observation timespans between 2.5 and 13 years. We also draw other recently installed permanent GNSS sites in Poland to indicate the large number of collecting measurements which, in a near future, can give an additional insight in the subject of loading phenomena in Poland. The other criterion was the availability of International GNSS Service (IGS) global or Warsaw University of Technology (WUT) Local Analysis Center (LAC) regional solutions.

The regional GNSS solutions often show discrepancies with respect to the global results. In this paper we compared both regional (WUT) and global (IGS) GNSS time series with hydrosphere loading models. As a global solution we used weekly solutions from the IGS "repro1" project [8]. The regional solutions used here were computed at the WUT European Permanent Network (EPN) LAC by the authors of this paper within the EPN Reprocessing project [9]. Both IGS and EPN reprocessing projects aimed at reanalysing all the historical GPS data in a fully consistent way, using the latest models and methodology. We reprocessed Global Positioning System (GPS) data of 60 sites using Bernese GPS Software 5.0 [10]. We used IGS "repro1" products (satellite orbits and Earth Rotation Parameters). GPS observations were processed in daily sessions according to guidelines for EPN LACS. We used GPS observations with minimum elevation angle of 5° above the horizon. We estimated zenith tropospheric delays in 1 h intervals as piece-wise linear functions. The hydrostatic part of the Saastamoinen model with the dry Niell mapping function were used as a priori values; corrections to the a priori values were estimated at zenith by using the wet Niell mapping function. Weekly solutions were aligned to the IGS05 reference frame using the no-net-translation minimum constraints conditions.

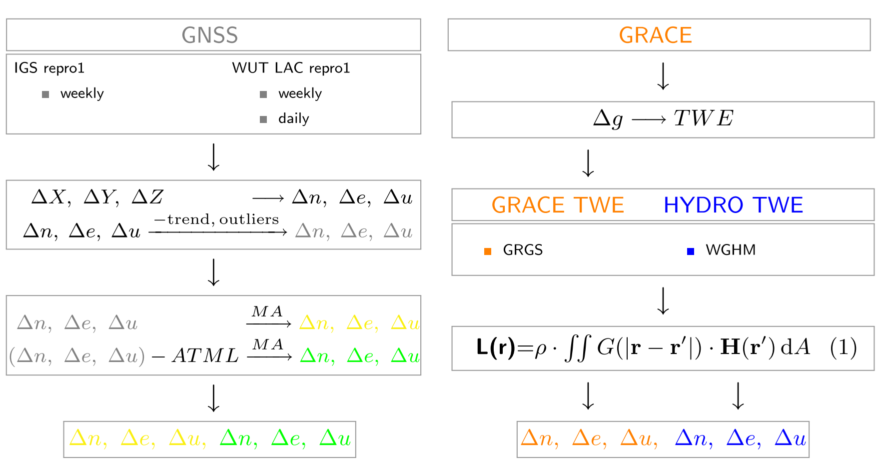

Fig. 2. Flow chart of data treatment. The detailed description is given in text (Section 2). The colours of time series will be consecutively used within this paper.

Table 1
Correlation coefficients for observed and modelled vertical deformation for different sites (chosen examples). The columns have the same headers in the same order as lines. The grey values (below each record) means the higher value for shifted time series. For explanation see text.

(a) **BOGO**(IGS)

GPS	1.00	0.60	0.58	0.54
		0.66	0.60	0.57
GPS2		1.00	0.56	0.43
			0.59	0.53
GRACE			1.00	0.87
				0.87
WGHM				1.00

(b) **BOR1**(IGS)

GPS	1.00	0.74	0.45	0.43
		0.75	0.45	0.44
GPS2		1.00	0.41	0.29
			0.50	0.37
GRACE			1.00	0.85
				0.85
WGHM				1.00

(c) **BOR1**(WUT)

GPS	1.00	0.72	0.68	0.60
		0.74	0.70	0.65
GPS2		1.00	0.58	0.42
			0.59	0.45
GRACE			1.00	0.86
				0.86
WGHM				1.00

(d) **JOZE**(IGS)

GPS	1.00	0.61	0.42	0.37
		0.61	0.52	0.42
GPS2		1.00	0.30	0.12
			0.68	0.60
GRACE			1.00	0.87
				0.88
WGHM				1.00

(e) **WROC**(IGS)

GPS	1.00	0.90	0.49	0.31
		0.90	0.50	0.33
GPS2		1.00	0.50	0.23
			0.53	0.27
GRACE			1.00	0.87
				0.87
WGHM				1.00

(f) **KATO**(WUT)

GPS	1.00	—	0.58	0.82
		—	0.74	0.91
GPS2		—	—	—
			—	—
GRACE			1.00	0.89
				0.90
WGHM				1.00

The geocentric GNSS position time series were firstly detrended and the residuals were transformed to the local system of each station. The trends were estimated using least squares method. Then outliers were detected and removed from the time series. This raw GNSS position time series are shown as grey dots in Figs. 3 and 4. Since we mainly focus on seasonal signals in GNSS position time series, we smoothed them using a simple method of moving average with a window length of 9 weeks. This length was carefully chosen (based on numerical tests) in order to filter out high frequency variations avoiding strong attenuation of seasonal signals. This procedure was applied twice. Firstly, we applied this procedure to our raw position time series (yellow colour in Figs. 3 and 4), and secondly we applied the procedure to the position time series corrected for atmospheric non-tidal loading (ATML) provided by NASA Goddard Flight Space Center [11] (green colour in Figs. 3 and 4). This correction was included to give an overview of the importance of Atmospheric Loading (ATML) when analysing seasonal variations of GNSS site displacements. While the ATML is not the subject of this study we refer to the paper of Petrov et al. [11] for further details on its computation.

2.2. GRACE

The objective of the GRACE satellite mission is to measure the gravity field of the Earth and its variability with unprecedented accuracy of 2–3 mm of the geoid height with spatial resolution of 400 km [3,12]. GRACE consist of two low (~450 km) identical satellites separated by about 220 km. The perturbation of its orbit is measured with the microwave range meter which continuously determines the distance between satellites utilizing low-low Satellite-to-Satellite Tracking (SST) technique. To enhance the low degree harmonic solution each satellite is equipped with a GPS receiver. Onboard accelerometers detect non-gravitational forces (atmospheric drag, solar radiation pressure).

The time dependent Stokes coefficients of the spherical harmonic expansion of the gravity field are inverted into the surface mass variability utilizing formulas given by Wahr et al. [13]. This non-unique problem is possible to be solved with the assumption that all mass transfer are within a thin layer near the Earth's surface. This requirement is satisfied if yearly periods are concerned [14].

The mass variations observed by GRACE within its lifetime are mainly due to variation in land hydrology water storage. The short-term mass variation due to solid Earth tides, ocean tides, oceanic indirect effect and atmospheric signals has to be removed at the processing stage using conventional models due to aliasing effects [15]. The contribution of processes in the mantle has a large amplitude but it occurs slowly relative to human timescales [14]. This detectability of total water storage makes the satellite gravity mission a unique tool which is capable to remotely sense water a few centimetres below the surface. The disadvantage is that particular component cannot be distinguished (feature of no importance in our study). The pre-launch studies indicated the ability of capturing the land hydrology storage variation [16] and was confirmed later in numerous papers when real data was available [3,17,18,19].

The surface mass density is usually expressed as a layer of water - the so called Total Water Equivalent (TWE). In this work we used a product of TWE from Groupe de Recherche en Géodésie Spatiale (GRGS) [20]. The values are given in grid with spatial resolution of 1° both in the latitude and amplitude. The temporal resolution is 10 days. The values of TWE have no significant meaning in terms of local hydrological investigations as they represent regional average. Nevertheless, they are useful for the mass transfer assessment for large scale studies.

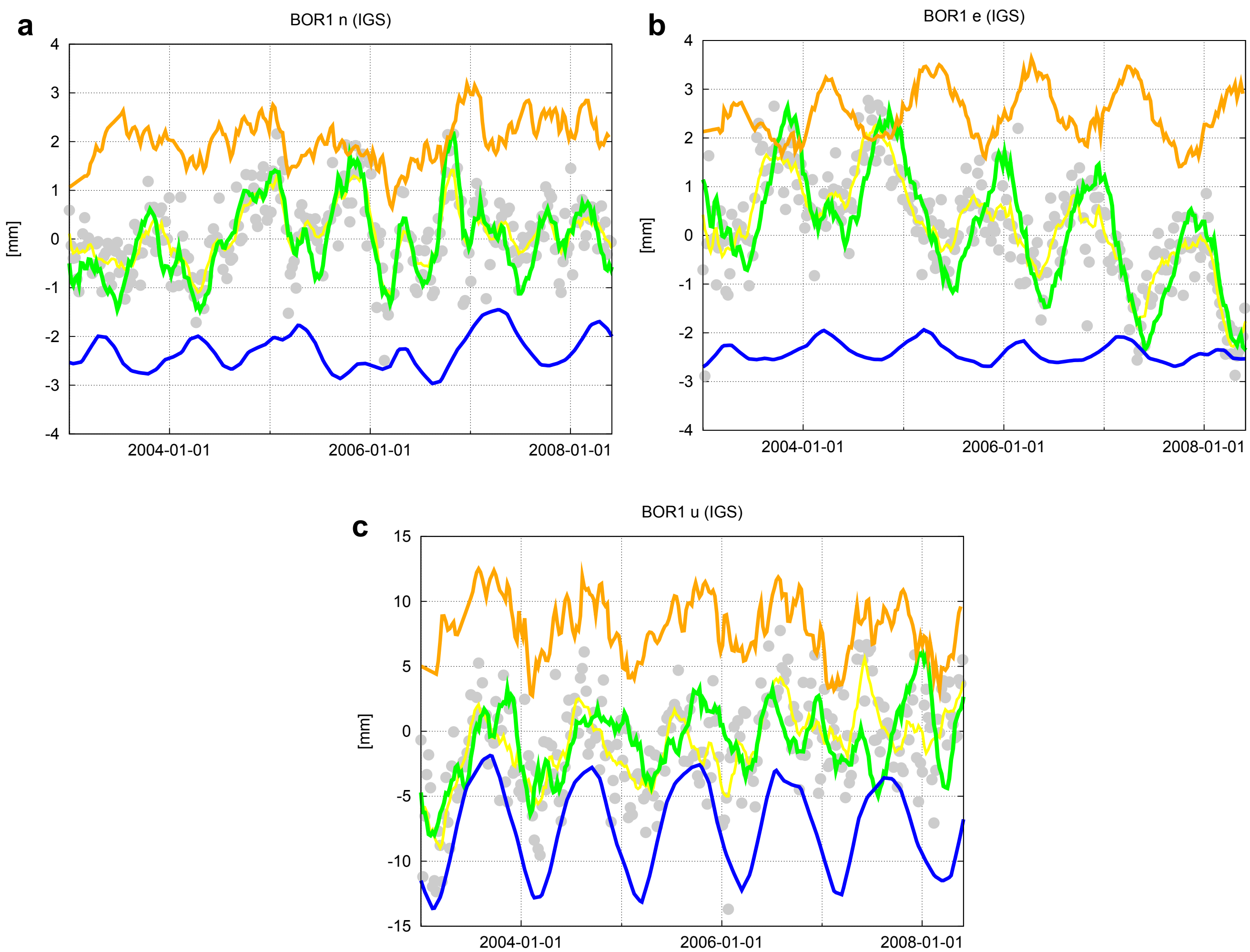

Fig. 3. The time series of GNSS solution (from IGS, grey dots) and smoothed time series using moving average with length of 9 weeks (yellow) and smoothed time series after ATML correction (green). GRACE and WGHM modelled deformations are shown in orange and blue respectively. Time series was shifted for clarity.

On the basis of the TWE data, it is also possible to deduce the crust deformation due to the variable hydrosphere loading. We used Green's function formalism [21] to evaluate this phenomena. The equation presented in Fig. 2 where ρ means water density, G is the Green's function computed on the basis of load Love numbers, H means TWE thickness, $\boldsymbol{r}$ and $\boldsymbol{r}'$ is a position of a site and integrated element, dA is a surface element. Our previous studies [2] showed that the major part of hydrological loading signal for Poland comes from an area of few hundreds of kilometres from considered station but to get a proper value the distribution of masses within whole Earth needs to be taken into account. The convolution was made with modified version of NLOADF program developed for the ocean tidal loading computation as a part of SPOTL package [22].

2.3. WGHM

The GRACE observes mass changes in the continental total water storage as it was explained in the previous subsection. Therefore, it is possible to use an independent hydrological model for computing the hydrological deformations, and to compare them with GRACE-derived deformations and with GNSS position time series. In this study we adopted WGHM [23–25] which is a conceptual model which takes into account all kind of water in a land hydrosphere, i.e. surface water and snow and soil and sub-soil water. It has spatial resolution of 0.5° both in the latitude and longitude and the value of water equivalent is given for every cell in a monthly interval. The Greenland and Antarctica areas are excluded from WGHM.

Currently, a few global hydrological models are available. In general, they are constructed using different conditions and assimilating different data sets. Their uncertainties are still relatively large [19]. Nevertheles, the computed loading is quite consistent. While the comparison of different hydrological loading models is not a goal of this paper we only refer that our analysis for Poland indicated good agreement of amplitudes and phases of computed loading deformations based on WGHM and the GLDAS Noah model (not shown here).

3. Comparison of results

The results of GNSS position time series along with modelled loading deformations for north, east and vertical components in topocentric frame for BOR1 site are presented in Fig. 3. The main features are easily recognizable. The agreement for vertical component in amplitude and in phase is much better for vertical component.

For the height variation, we can see that the result reflects a water storage cycle for the Polish climatic zone (i.e. in spring there is more water stored, the crust is more loaded, therefore the heights

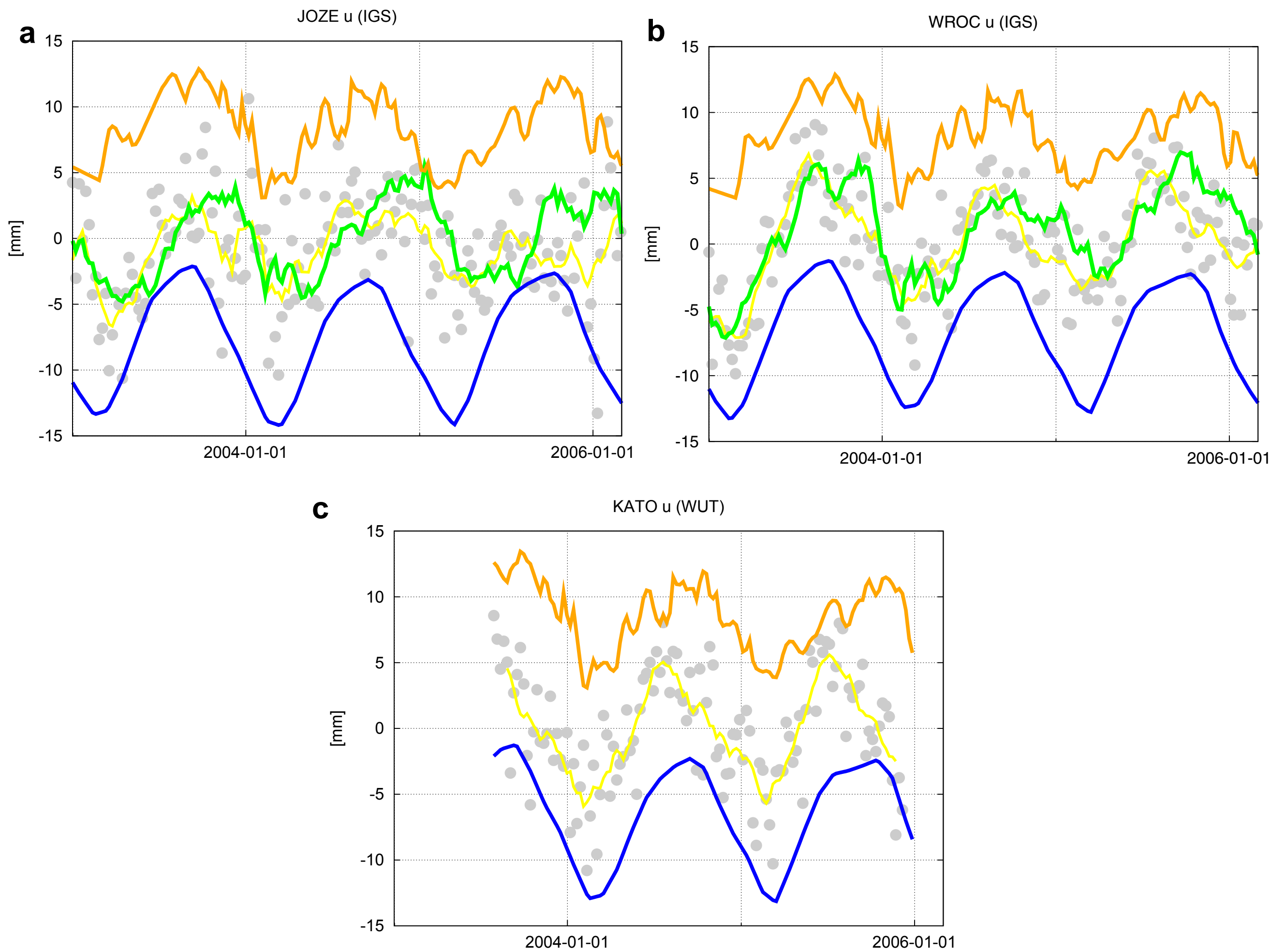

Fig. 4. Observed seasonal deformation for Józefosław (IGS solution), Wrocław (IGS) and Katowice (WUT) along with modelled deformation from GRACE and WGHM. For colour explanation see previous figure.

is minimal, while in late summer/early autumn the height reaches maximum due to the minimum in a water storage). The peak-to-peak variation reaches as much as 10 mm. This value is representative for other considered sites as the vertical deformation due to the continental water storage loading is uniform within a few millimetres for Poland [2]. We see that the hydrological model WGHM gives slightly overestimated values when comparing to GNSS and GRACE results [26] came to the same conclusion for European sites. Other observed feature is that correcting the GNSS results for ATML, changes the observed signal significantly but it is hard to tell whether this correction improves the results or not. This is still a problematic subject due to the complexity of this phenomena [27]. That is the reason why currently this effect is not commonly included in data processing neither recommended by International Earth Rotation and Reference Systems Service (IERS) [28]. However, the improvement in terms of station position repeatability has already been found in previous studies [11,29]. In our work we simply show two time-series with and without ATML correction. The former is more exhibited within this paper.

The periods of disagreement also occur (period from March 2006 till March 2008 for the vertical component in Fig. 3) are clearly visible. The origin of the disagreement has no good explanation yet but problems with repeatability in GNSS time series in seasonal timescale was reported previously in literature. The most likely discrepancies stem from local environmental influence or due to processing artefacts [30,31].

The results for horizontal component are ambiguous and were already reported for European sites [6]. One reason is a much smaller amplitude of observed and modelled variations. These variations are at the level of a few millimetres only which is near the limits of the GNSS positioning accuracy. For the north component some peaks observed with GNSS can be attributed to the mass loading, but the fit is rather poor. One possible explanation is the influence of a land–sea distribution. The oceans and seas are excluded from the hydrological model while the mass variations for these areas are given in the GRGS product (with much smaller variability). This reason and differences in the resolution of GRACE and WGHM are likely to be responsible for discrepancies between modelled deformation for horizontal components. The other explanation could be ATML influence which is particularly pronounced for east component (high pressure variation over continent on the east). The local environmental effect (yearly climate cycle) can be dominant taking into account small amplitudes for horizontal components.

The results and conclusions for BOR1 site can be applied for other selected sites. We give here other examples for vertical components for Józefosław (JOZE), Katowice (KATO) and Wrocław (WROC) sites respectively (Fig. 4).

Table 2 gives some statistics of this comparison in terms of the standard deviation for the vertical component only. Two cases are considered depending on the ATML correction treatment. The reduction of variance for most stations can be observed. Correcting

Table 2
Statistics of comparison (σ, standard deviation) between observed (GNSS) and modelled (GRACE and WGHM) crustal deformation for vertical component. The percent numbers mean standard variation reduction with respect to GNSS (only printed for reduction better than 20%). The additional bottom line in grey shows the same statistic for best reduction of standard deviation shifting GNSS time series (in days, values in square brackets).

		no ATML			**with ATML**		
Site	**Timespan**	σ_{GNSS} $[mm]$	$\sigma_{GNSS-GRACE}$ $[mm]$	$\sigma_{GNSS-WGHM}$ $[mm]$	σ_{GNSS} $[mm]$	$\sigma_{GNSS-GRACE}$ $[mm]$	$\sigma_{GNSS-WGHM}$ $[mm]$
$BOGI_{(IGS)}$	2002.04 – 2009.05	3.9	3.7	3.8	4.8	4.7	5.3
$BOGI_{(WUT)}$	2001.12 – 2005.12	3.0	2.4 2.1 (28%) [35]	2.7 2.3 (23%) [28]	3.0	2.2 (24%) 2.2 (24%) [0]	3.0
$BOGO_{(IGS)}$	1997.01 – 2009.05	2.9	2.5	3.2	3.0	2.5	3.5
$BOR1_{(IGS)}$	1996.01 – 2009.05	3.3	2.6 (20%) 2.6 (20%) [7]	3.6	3.4	2.7 (21%) 2.5 (26%) [−28]	4.1
$BOR1_{(WUT)}$	1996.01 – 2005.12	2.8	2.1 (25%) 2.0 (27%) [14]	2.9	3.1	2.4 (22%) 2.4 (23%) [−14]	3.6
$JOZ2_{(IGS)}$	2002.10 – 2009.05	5.1	4.3	4.9	5.0	4.2	5.0
$JOZ2_{(WUT)}$	2002.10 – 2005.12	3.1	2.5 (20%) 2.4 (23%) [28]	2.6 2.4 (21%) [21]	3.2	2.3 (29%) 2.2 (29%) [−7]	2.8
$JOZE_{(IGS)}$	1996.01 – 2009.05	2.3	2.5	3.5	3.3	3.3 2.3 (30%) [−70]	4.6
$JOZE_{(WUT)}$	1996.01 – 2005.12	2.3	2.5	3.4	2.9	3.1 2.3 (21%) [−70]	4.2
$KATO_{(WUT)}$	2003.07 – 2005.12	3.1	2.7 2.1 (33%) [35]	2.1 (31%) 1.5 (53%) [28]			
$LAMA_{(IGS)}$	1996.01 – 2009.05	7.1	5.0 (29%) 4.5 (36%) [70]	7.4	7.2	5.0 (29%) 5.0 (30%) [14]	7.6
$LAMA_{(WUT)}$	1996.01 – 2005.12	4.4	3.3 (23%) 2.9 (34%) [49]	4.2	4.8	3.5 (26%) 3.3 (29%) [21]	4.7
$WROC_{(IGS)}$	1997.01 – 2009.05	5.5	3.6 (34%) 3.6 (34%) [14]	5.5	5.4	3.4 (36%) 3.4 (37%) [−14]	5.7

GNSS series for ATML increase the number of sites with the reduction of 20% or more not necessarily improving this reduction. This could be attributed to the noise in ATML series. Nevertheless, this numbers prove the loading effect in GNSS results. The GRACE derived deformation fits better than WGHM. This conclusion was already formulated on the basis of the graphical presentation. The increase of the standard deviation can also be found stemming from imperfection of GRACE, WGHM, ATML models, deformation modelling, GNSS data processing or spurious signals in GNSS position time series.

For possible phase shifts between observed and modelled signals (this is especially pronounced for JOZE in Fig. 4, where ATML correction increased the shift) we performed a test. The GNSS position time series were shifted (without amplitude modification) looking for the best standard deviation reduction. The values for estimated shifts at the level of dozen or so days are reasonable taking into account the temporal resolutions of the models.

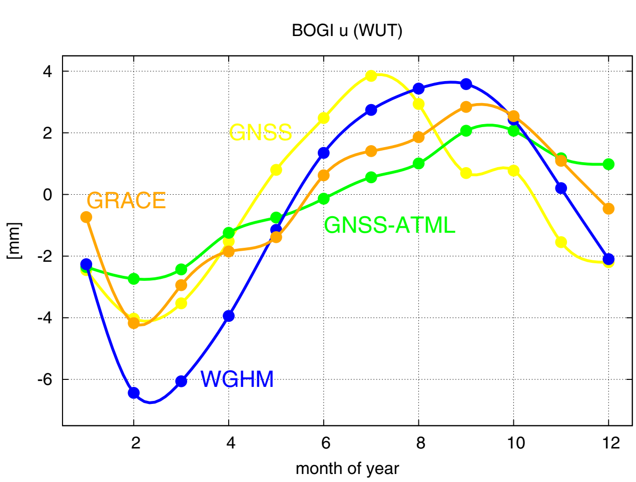

Fig. 5. Yearly variation of observed (GNSS) and modelled (GRACE, WGHM) height variation performed by stacking multiyear time series for Borowa Góra.

The presented test in terms of the position time series standard deviations may not be convincing due to a noise in position time series. The better prove of the presence of the hydrological loading in GNSS position time series can be deduced from presented figures (Figs. 3 and 4). The other proof comes from the time series correlation results (Table 1).

3.1. Stacking time series

In order to get an impression of the yearly cycle in considered observed and modelled time series we performed a stacking method to extract the variations in period of interest. This procedure follows the solution of Refs. [7,32]. We put the multi-year stacking of Borowa Góra (BOGI) site (Fig. 5). For every year the mean value was excluded and for every month all samples were averaged. The results of this procedure allowed us to infer some conclusion. We see that ATML correction can affect observed seasonal signal.

We should be aware that the stacking procedure do not give such clear results and extracted yearly seasonal for some selected sites. Some similarities can be found and presented conclusions are reliable. The further investigation using more robust solution (e.g. Principal Component Analysis, PCA) should be undertaken in order to extract dominant effects for the entire area.

4. Conclusion

In the previous sections we showed that the crust deformation due to the land water storage is the main source of observed seasonal height variations in GNSS position time series. The good agreement for both the amplitude and phase was found comparing to modelled deformations on the basis of water mass redistribution assessments from GRACE satellite data and WGHM model. The discrepancies for horizontal components cannot be definitively explained.

The seasonal vertical variation has complicated pattern for different sites around the world [32]. For the area of Poland the yearly signal is dominated through the water mass loading and can be approximated with a simple cosine harmonic function. For geodetic purposes the hydrological loading influence can be effectively decreased using model given by Ref. [2], which is easy in use without necessity of complex computation.

We obtained slightly different results among analysed sites. Therefore, local effects in GNSS position time series can often lead to misinterpretation. One possible resolution which will be undertaken in future is to spatially smooth the GNSS signal utilizing large amount of permanent site measurements which are now available in Poland.

We also shown that other effects with shorter periods, like ATML, needs to be taken into account when studying seasonal effects in positions time series. This subtle signals could lead to misinterpretation in yearly variations.

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