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Analysis of groundwater storage changes in main Polish river basins using GRACE observations, in-situ data, and hydrological and climate models

Jolanta Nastula[1], Justyna Śliwińska[1], Zofia Rzepecka[2], Monika Birylo[2]

[1]Space Research Centre, Polish Academy of Sciences, Warsaw, Poland

[2]Faculty of Geodesy, Geospatial and Civil Engineering, University of Warmia and Mazury, Olsztyn, Poland

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Abstract

The Gravity Recovery and Climate Experiment (GRACE) measurements have provided global observations of total water storage (TWS) changes at monthly intervals for almost 20 years. They are useful for estimating changes in groundwater storage (GWS) after extracting other water storage components like soil water or snow water.

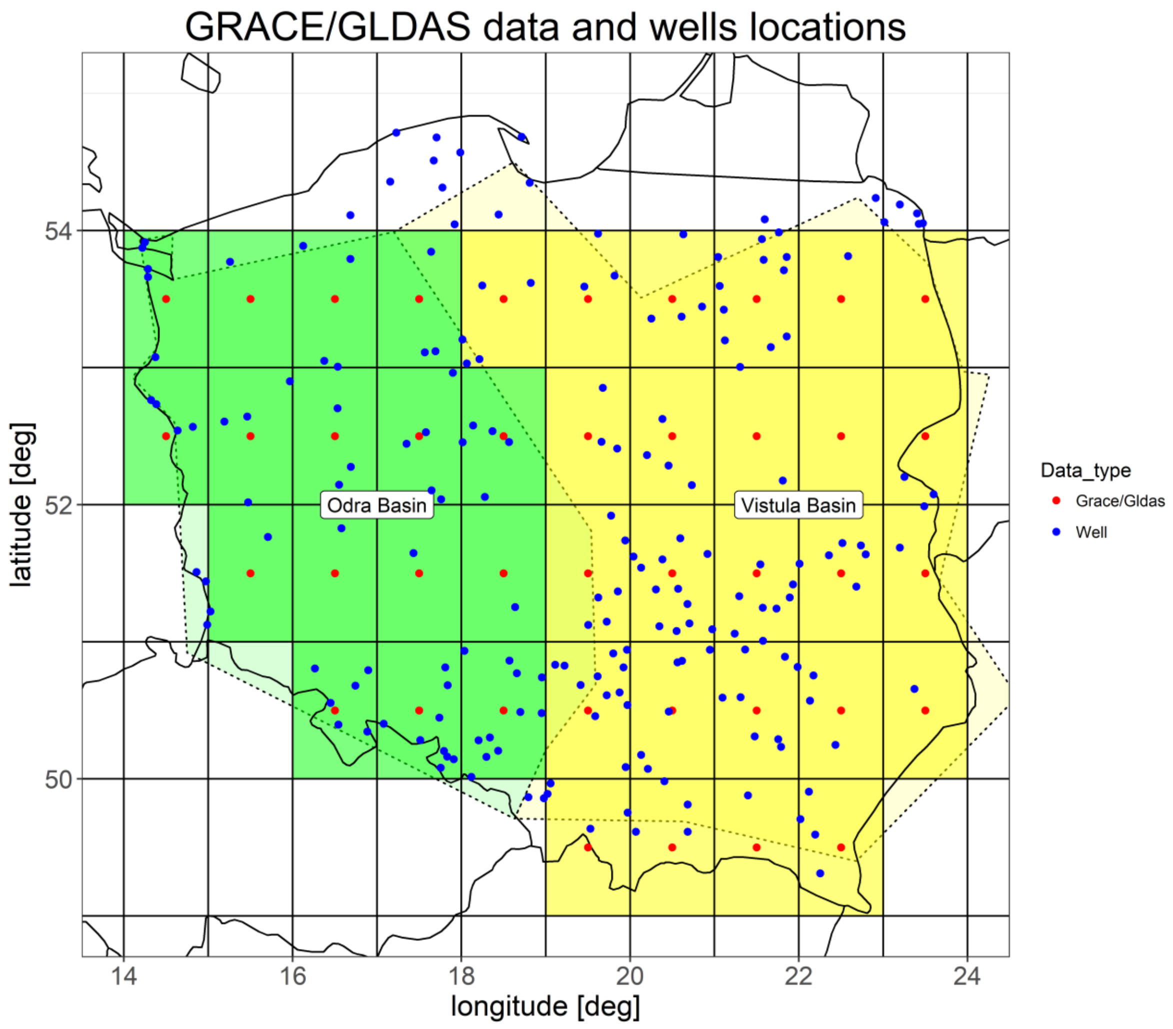
In this study, we analyze the GWS variations of two main Polish basins, the Vistula and the Odra, using GRACE observations, in-situ wells measurements, GLDAS (Global Land Data Assimilation System) hydrological models, and CMIP5 (the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5) climate data. The research is conducted for the period between September 2006 and October 2015.

Here, TWS is taken directly from GRACE measurements and also computed from all considered models. GWS is obtained by subtracting the modelled sum of soil moisture and snow water from the GRACE-based TWS. The resultant GWS series are validated by comparing with appropriately calibrated in-situ wells measurements. For each GWS time series, the trends, spectra, amplitudes, and seasonal components were computed and analyzed. The results suggest that in Poland there has been generally no major GWS depletion. The results can contribute toward selection of an appropriate model that, in combination with GRACE observations, would provide information on groundwater changes in regions with limited or inaccurate in-situ groundwater storage measurements.

Motivation and objectives

- Total water storage (TWS) is an essential element of the hydrological cycle, playing a key role in the Earth's global and regional climate system.
- As one of the TWS components, groundwater storage (GWS) represents the largest freshwater storage in the hydrological system, being a major source of fresh water for domestic, agricultural, and industrial use.
- The aim of this study is to analyze groundwater storage variations in small region (Poland) in a systematic and detailed way.
- We examine spatial and temporal variations of the GWS obtained from GRACE in combination with hydrological models and climate data. We also validate GRACE and model determinations by comparing them with in-situ groundwater measurements at well stations.
- This research also aims to identify which models (in combination with GRACE measurements) provide information on GWS variations that are the most consistent with observations from the groundwater monitoring wells.
- Identifying models that match direct observations is very important in the context of future use of these models for TWS and GWS simulation and prediction. This may be useful especially in regions in which well measurements are unavailable or inaccurate.

Data and methods
Study area



- The study area includes two main rivers in Poland, the Vistula and the Odra.
- The Vistula basin covers about 194,500 km^2 and the area of the Odra basin is about 118,900 km^2.
- These two basins cover almost the entire area of Poland.

Fig. 1. The area of Poland divided into 1° × 1° grid cells belonging to the Odra basin (16 cells) and Vistula basin (25 cells) with the location of the wells used for the study; well locations are indicated with blue dots and GRACE/GLDAS grid centers are indicated with red dots

Data and methods

Data sets

1) GRACE Level-3 data: monthly TWS anomalies accessed from https://grace.jpl.nasa.gov/data/get-data/. For this study we used the mean of solutions provided by official GRACE data centers at Center for Space Research (CSR), Jet Propulsion Laboratory (JPL) and GeoForschungsZentrum (GFZ). All three solutions have a grid resolution of 1°;

2) GLDAS models (4): monthly variations of soil moisture storage (SMS) and snow water storage (SnWS) obtained from the following models: CLM, MOSAIC, NOAH and VIC. All models have a grid resolution of 1°. The data sets were accessed from https://ldas.gsfc.nasa.gov/gldas/GLDASdownload.php;

3) CMIP5 models (10): monthly variations of SMS and SnWS obtained from the following models: FGOALS-g2, GFDL-ESM2G, GISS-E2-H, inmcm4, MIROC5 and MPI-ESM-LR. The models have different spatial resolution, from 1 to 3°. The SMS and SnWS variables from CMIP5 were interpolated into regular 1° × 1° latitude–longitude grids using 3D linear interpolation. The data sets were accessed from: https://esgf-node.llnl.gov/search/cmip5/;

4) in-situ groundwater measurements: monthly observations of well groundwater depths (or groundwater level – GWL) obtained from the Polish Hydrogeological Annual Reports, from 2007 to 2016 (129 wells for Vistula basin and 66 wells for Odra basin). The GWL direct measurement data were recomputed into GWS by inverting the sign of changes and scaling by the porosity coefficients.

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Data and methods

GWS from groundwater level wells

- To enable comparison between measurements from wells and the GRACE data, it is necessary to convert the GWL observed in the well into groundwater storage (GWS), using the porosity coefficients. Porosity coefficient (e) estimations are based on the following formula:

$$e = \left(\frac{\rho_s - \rho_e}{\rho_s}\right),$$

  where ρ_s is the real density of solid phase of the soil and ρ_e is the density of the intact sample of the solid phase of the soil (both given in g/cm^3).

- The porosity coefficients were calculated based on the soil map of Poland. Because the Vistula and Odra basins cover areas with few types of soils, in both basins the proportion of each soil type in terms of total land coverage was estimated, which then was treated as a weight for the average basin porosity coefficient determination.

Soil type	Vistula basin	Odra basin
Brown soils	0.697	0.578
Podzol soils	0. 116	0.251
Organic soils	0.091	0.087
Alluvial soils	0.049	0.050
Black earths	0.033	0.025
Rendzinas	0.012	0.008
Weighted mean	0.41	0.42

Tab. 1. Weights for porosity coefficient calculations based on soil type in the two basins.

Data and methods
GWS from GRACE and models

- On the one hand, the GRACE satellites provide measurements of total changes in TWS in all forms of water stored on and underneath the Earth's surface, but they are not able to reconcile individual TWS components, such as changes in soil moisture (SMS), snow water storage (SnWS), or groundwater storage (GWS).
- On the other hand, all hydrological models provide changes in water storage separately for individual water storage components, but only in layers of thickness defined by model. Consequently, they do not deliver total changes in water storage.
- Therefore, hydrological models can be used to separate the groundwater component from the GRACE TWS variations according the following formula:

$$\mathrm{GWS} = \mathrm{TWS} - \mathrm{SWS} - \mathrm{SnWS}.$$

- In this study, we computed $\Delta\mathrm{GWS}$ according to above equation. In the following:
  - ✓ for ΔGWS obtained by removing SMS and SnWS given in GLDAS models from the GRACE TWS, we use „GWS from GRACE–GLDAS".
  - ✓ for ΔGWS obtained by removing SMS and SnWS given in CMIP5 models from the GRACE TWS, we use „GWS from GRACE–CMIP5".
  - ✓ more generally, for ΔGWS computed by removing model TWS (sum of SWS and SnWS) from GRACE TWS, we use „GWS from GRACE–model".

Data and methods
Time series processing

- Because of different spatial resolution of GWS from GRACE–model and GWS from wells measurements, the time series of GWS in each grid (for GRACE–model) and the time series of GWS in each well (for in-situ measurements) were averaged over area of Vistula and Odra basins.
- To overcome any gaps in the GRACE observations and irregular data time span in well measurements, time series were interpolated into regular 30-day changes in the same period (from November 2006 to November 2015).
- Further analyses comprised of comparison of variations in GWS from different data sources for the Vistula and Odra basins separately.
- Our detailed analyses were conducted for three cases: linear trends, seasonal oscillations, and nonseasonal oscillations.
- Linear trends and seasonal oscillations of TWS and GWS series were computed together using the least-squares method. The fitted model had a following form:

$$\mathrm{y(t)} = a_0 + a_1 \cdot (t - t_0) + \mathrm{a} \cdot \cos\big(\omega_\mathrm{a}(\mathrm{t} - \mathrm{t}_0)\big) + \mathrm{b} \cdot \sin\big(\omega_\mathrm{a}(\mathrm{t} - \mathrm{t}_0)\big) + \\ + \mathrm{c} \cdot \cos\big(\omega_\mathrm{s}(\mathrm{t} - \mathrm{t}_0)\big) + \mathrm{d} \cdot \sin\big(\omega_\mathrm{s}(\mathrm{t} - \mathrm{t}_0)\big) + \mathrm{e} \cdot \cos\big(\omega_\mathrm{t}(\mathrm{t} - \mathrm{t}_0)\big) + \mathrm{f} \cdot \sin\big(\omega_\mathrm{t}(\mathrm{t} - \mathrm{t}_0)\big),$$

  where y is the value of the series for the time t = 1, ..., 108 (number of months), a_0 is the intercept, a_1 is a trend coefficient, a, b, c, d, e, f are coefficients of the fitted sinusoids, t_0 is a reference epoch (here we assumed November 15, 2006), ω_a ω_s ω_t are annual, semiannual, terannual frequency, respectively.
- Nonseasonal changes were obtained after removing trends and seasonal signals.

Results
Time series comparison

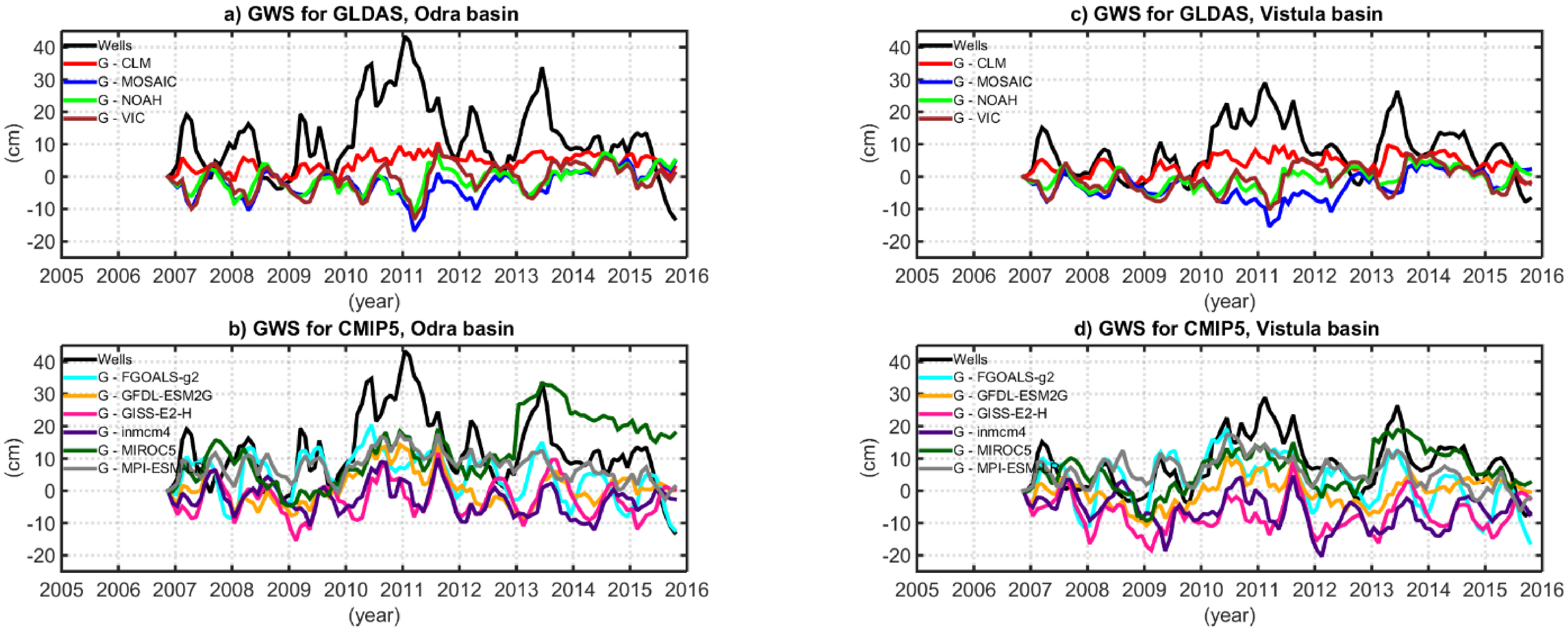
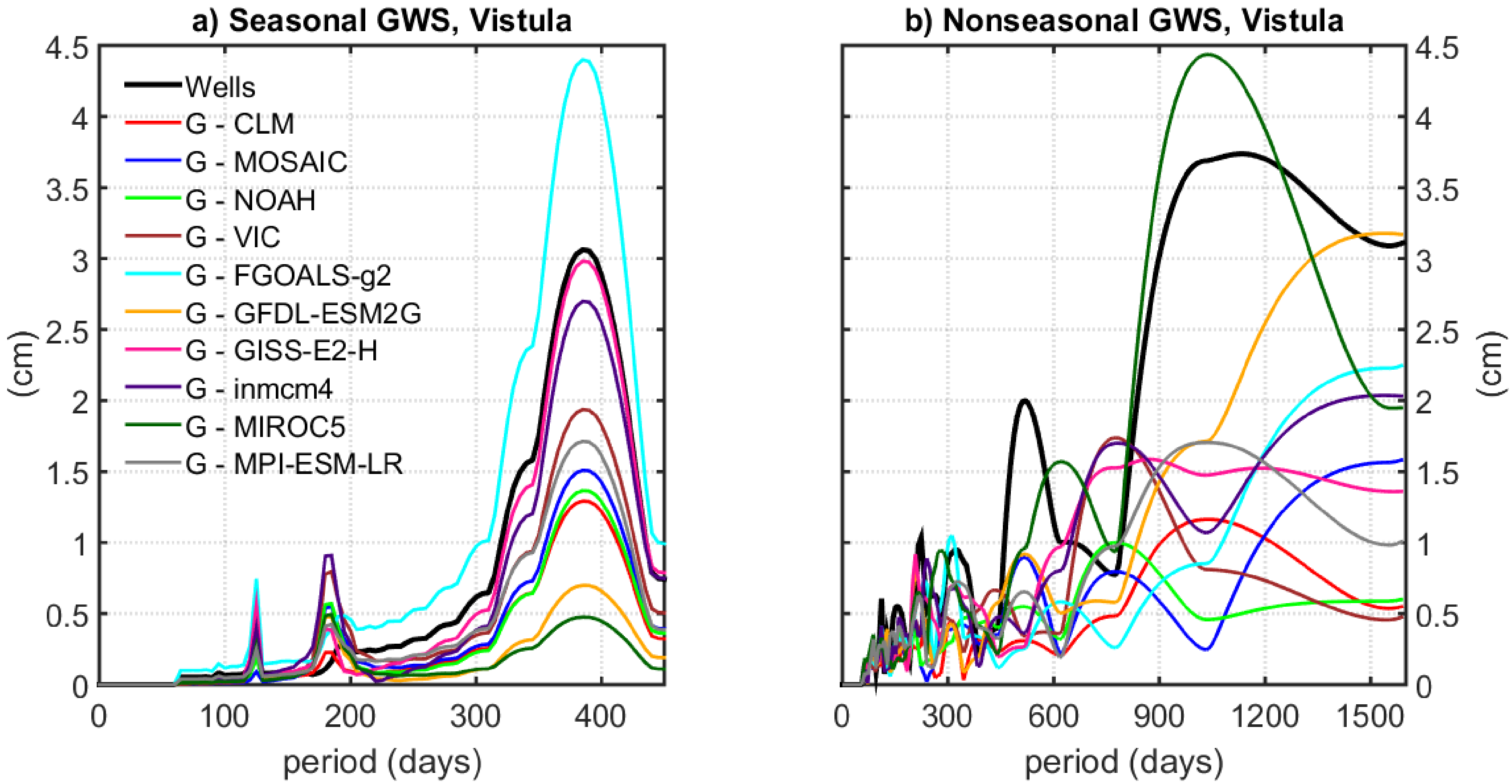


Fig. 2. Comparison of the time series of GWS derived from the wells with GWS series obtained from GRACE–GLDAS (a, c) and GRACE–CMIP5 (b, d) for the Odra (a, b) and Vistula basins (c, d) separately. "G" in the legend is an abbreviation for GRACE

Results

Amplitude spectra of seasonal and nonseasonal variations



- *The annual change dominates in the seasonal frequency range, and its amplitude is several orders greater than semiannual and terannual oscillations. This occurrence is mainly connected with seasonal changes in rainfall.*
- *In the following we will focus only on annual signals.*
- *In nonseasonal spectra band, the strongest are oscillations with periods longer than 3-4 years.*
- *Due to insufficient data length, longer variations cannot be analyzed in this study.*

Fig. 3. Amplitude spectra of seasonal (a) and nonseasonal (b) GWS oscillations obtained from wells measurements and from GRACE–GLDAS and GRACE–CMIP5 for Vistula basin (for Odra the spectra are similar). "G" in the legend is an abbreviation for GRACE

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Results

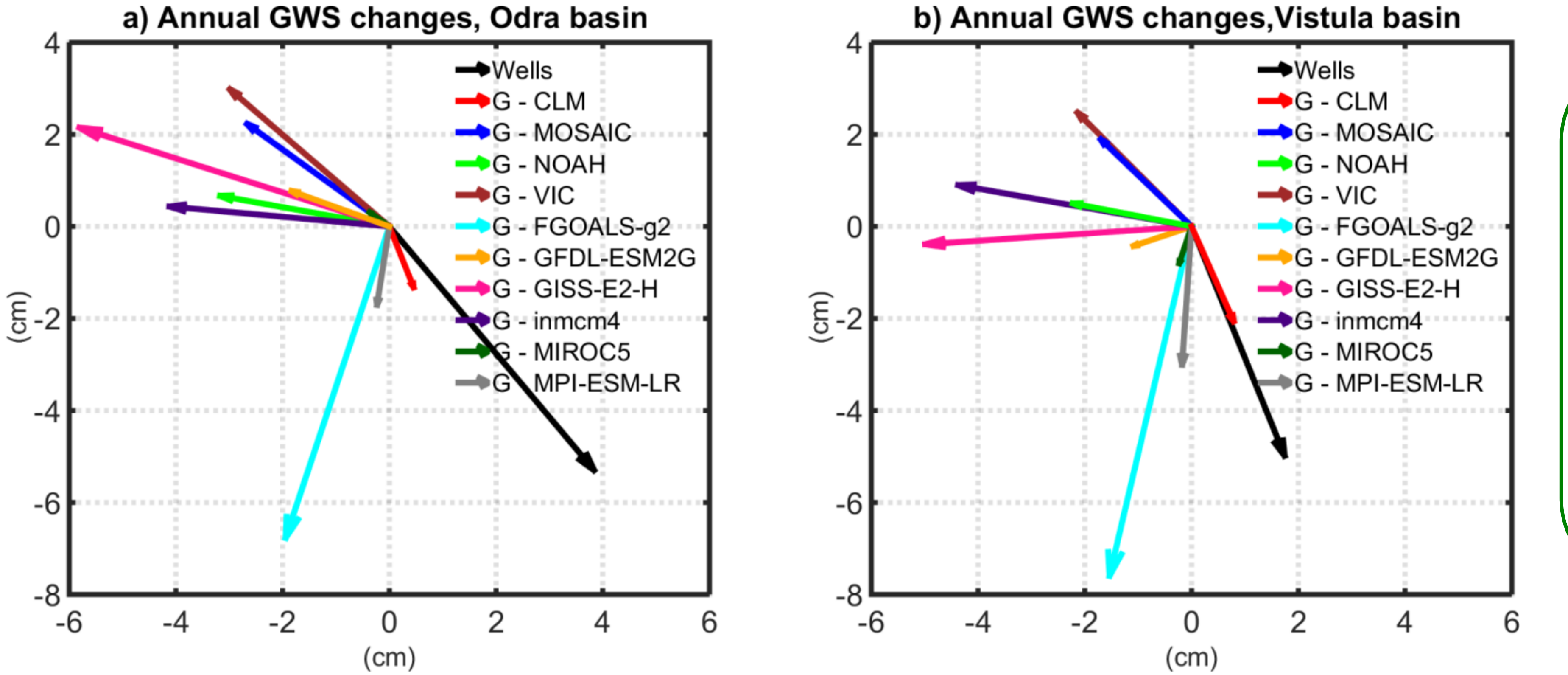
Linear trends

Tab. 2. Linear trends of GWS for Odra and Vistula basins together with their errors and coefficients of determination (R^2). The coefficient of determination is a measure of the quality of the model's fit to the data. It ranges between 0 and 1, with 1 being the best value. The trends and their errors are given in cm/year. The values marked in red indicate the trends with the highest compliance with the trends received from the wells measurements

	Odra basin			Vistula basin		
	Trend	Trend error	Coefficient of determination (R^2)	Trend	Trend error	Coefficient of determination (R^2)
Wells	0.12	0.62	0.99	0.47	0.45	0.97
GRACE – CLM	**0.48**	0.13	0.77	**0.35**	0.16	0.91
GRACE – MOSAIC	0.64	0.22	0.82	**0.50**	0.22	0.88
GRACE – NOAH	0.58	0.19	0.79	**0.46**	0.16	0.82
GRACE – VIC	0.56	0.23	0.87	**0.47**	0.21	0.89
GRACE – FGOALS-g2	–0.82	0.37	0.92	–0.92	0.41	0.91
GRACE – GFDL-ESM2G	**0.06**	0.30	0.99	0.40	0.24	0.93
GRACE – GISS-E2-H	**–0.06**	0.31	0.99	–0.18	0.29	0.99
GRACE – inmcm4	–0.52	0.25	0.94	–0.64	0.28	0.92
GRACE – MIROC5	2.50	0.39	0.53	0.82	0.33	0.88
GRACE– MPI-ESM-LR	–0.28	0.24	0.97	–0.50	0.26	0.93

- *In general, almost all GWS trends are small, as their absolute values are generally not higher than ±1.00 cm/year. However, the attention should be paid to the ratio of trend values to their errors, which may be unfavorable for small trends.*
- *Most of the GWS trends obtained from the GRACE–model agreed well with trends from well measurements in terms of trend sign. The discrepancies between trends from groundwater monitoring wells and GRACE–model did not exceed 1.40 cm/year.*

Results
Seasonal variations



- *None of the GWS data obtained from GRACE–model are fully consistent with the results obtained from groundwater monitoring wells.*
- *The best amplitude agreement with GWS from wells is observed for the GRACE–GISS-E2-H; however, the phase correspondence is poor.*
- *For phases, GWS from GRACE–CLM agrees best with reference data. Nevertheless, this solution possessed one of the smallest amplitudes.*

Fig. 4. Phasor diagrams of annual GWS change derived from wells, GRACE–GLDAS and GRACE–CMIP5 for the Odra (a) and Vistula (b) basins. The reference epoch is November 15, 2006. The length of each vector on a phasor diagram represents the magnitude of amplitude, while the vector direction shows a phase. "G" in the legend is an abbreviation for GRACE

Results

Seasonal variations

Tab. 3. Correlation coefficients between GWS obtained from wells and GWS obtained from GRACE–model, percentage of variance in well-based GWS explained by GWS from GRACE–model, root-mean square errors (RMSE) for annual time series, the months of maximum in annual GWS series, and phases of annual GWS variations for Odra basin. The values marked in red indicate the best results

Odra basin	Correlation coefficients	Relative explained variance (%)	RMSE (cm)	Month of maximum	Phase (days)
Wells	1.00	100	0.00	April	0.0
GRACE–CLM	**0.96**	**36**	**3.70**	**April**	**−17.0**
GRACE–MOSAIC	−0.97	−131	7.04	September	196.9
GRACE–NOAH	−0.74	−98	6.51	August	225.2
GRACE–VIC	−0.99	−169	7.60	October	191.7
GRACE–FGOALS-g2	**0.62**	**18**	**4.20**	June	−52.5
GRACE–GFDL-ESM2G	−0.86	−61	5.88	September	214.1
GRACE–GISS-E2-H	−0.83	−247	8.62	August	216.7
GRACE–inmcm4	−0.67	−125	6.94	August	231.1
GRACE–MIROC5	−0.97	−15	4.96	September	194.3
GRACE–MPI-ESM-LR	**0.73**	**31**	**3.84**	May	−43.4

The relative explained variance (Var_{exp}) describes the variance compatibility between two time series, the first of which is a reference series (r) and the second of which is evaluated (e):

$$Var_{exp} = \left(\frac{Var^{(r)} - Var^{(r-e)}}{Var^{(r)}}\right) \cdot 100\%.$$

The best value for Var_{exp} is 100%.

Results
Seasonal variations

Tab. 4. Correlation coefficients between GWS obtained from wells and GWS obtained from GRACE–model, percentage of variance in well-based GWS explained by GWS from GRACE–model, root-mean square errors (RMSE) for annual time series, the months of maximum in annual GWS series, and phases of annual GWS variations for Vistula basin. The values marked in red indicate the best results

Vistula basin	Correlation coefficients	Relative explained variance (%)	RMSE (cm)	Month of maximum	Phase (days)
Wells	1.00	100	0.00	April	0.0
GRACE–CLM	**1.00**	**66**	**2.17**	**April**	**1.5**
GRACE–MOSAIC	−0.92	−112	5.44	October	205.4
GRACE–NOAH	−0.53	−65	4.79	September	241.2
GRACE–VIC	−0.93	−154	5.95	October	204.2
GRACE–FGOALS-g2	**0.86**	**38**	**2.95**	May	−31.1
GRACE–GFDL-ESM2G	0.03	−3	3.80	July	276.0
GRACE–GISS-E2-H	−0.26	−138	5.77	August	258.5
GRACE–inmcm4	−0.52	−159	6.01	August	242.3
GRACE–MIROC5	**0.82**	23	3.27	June	−34.4
GRACE–MPI-ESM-LR	**0.92**	**38**	**1.95**	May	−22.7

- *Positive correlations and high relative explained variance for both Vistula and Odra basins were indicated for GRACE–CLM, GRACE–FGOALS-g2 and GRACE–MPI-ESM-LR. These series are also characterized by the lowest RMSE. However, the latter two have GWS phases more incompatible with phases of well-based GWS. Taking this fact into consideration, we suggest that GRACE-CLM is the best for annual GWS estimation. However, it should be kept in mind that GRACE–CLM also suffers some weaknesses, e.g. weak signal and visibly smaller amplitudes than for wells and other GRACE-model estimations.*
- *The results are slightly better for Vistula than for Odra.*

Results
Nonseasonal variations

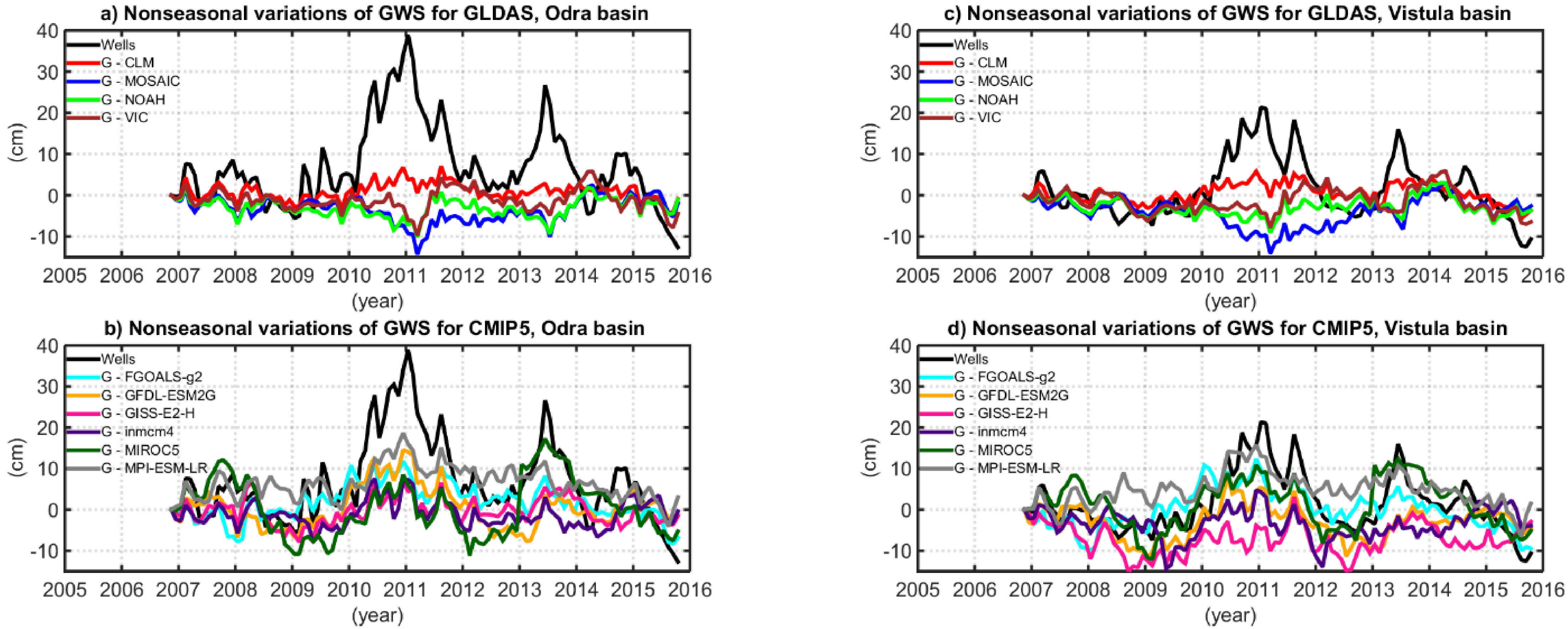


Fig 5. Comparison of nonseasonal GWS time series based on well data with GRACE–GLDAS (a, c) and GRACE–CMIP5 (b, d) models for Odra (a, b) and Vistula (c, d) basins. "G" in the legend is an abbreviation for GRACE

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Results

Nonseasonal variations

Tab. 5. Correlation coefficients between GWS obtained from wells and GWS obtained from GRACE–model as well as percentage of variance in wells-based GWS explained by GWS from GRACE–model for nonseasonal time for Odra and Vistula basins. The values marked in red indicate the best results

	Correlation coefficients		Relative explained variance (%)		RMSE (cm)	
	Odra	Vistula	Odra	Vistula	Odra	Vistula
Wells	1.00	1.00	100	100	0.00	0.00
GRACE–CLM	**0.70**	**0.75**	25	**39**	8.69	**5.53**
GRACE–MOSAIC	−0.59	−0.57	−44	−77	12.02	9.38
GRACE–NOAH	−0.51	−0.23	−29	−26	11.38	7.91
GRACE–VIC	−0.17	−0.01	−16	−17	10.79	7.63
GRACE–FGOALS-g2	**0.70**	**0.69**	**42**	**47**	**7.67**	**5.13**
GRACE–GFDL-ESM2G	**0.74**	**0.67**	**49**	**44**	**7.15**	**5.29**
GRACE–GISS-E2-H	0.62	0.39	30	13	8.45	6.59
GRACE–inmcm4	0.55	0.33	25	8	8.69	6.80
GRACE–MIROC5	0.43	**0.71**	12	**48**	9.42	**5.06**
GRACE–MPI-ESM-LR	**0.73**	**0.72**	**43**	**50**	**7.57**	**4.98**

- *Each GRACE–CMIP5 series provided positive correlations, whereas GRACE–GLDAS series were distinguished by negative values. The only exception was GRACE–CLM, which provided significant positive correlation coefficients for both Odra and Vistula. However, the amplitudes of GWS obtained using this data are lower than those derived from the wells.*
- *Among the climate models, the highest correlations with terrestrial measurements were obtained from GRACE in combination with FGOALS-g2, and MPI-ESM-LR. These three series explain the largest part of well-based groundwater variation (high relative explained variance) and provide the lowest RMSE.*
- *It can be generally concluded that in terms of non-seasonal GWS variations, CMIP5 models are more useful than GLDAS. For the latter, only CLM can be used.*

Conclusions

- In the years 2007–2016, there was not noticeable change in GWS in Poland (the trends are relatively small and generally do not exceed ±1 cm/year).
- The GWS maxima in 2010 and 2013 might be related to the floods that affected the country in these years.
- Although we find a correspondence between wells measurements and GRACE–model determinations, GWS from monitoring wells produced much stronger amplitudes for both basins.
- For annual GWS changes, the best phase agreement with wells measurements as well as satisfactory relative explained variance were found for the GRACE–CLM, GRACE–FGOALS-g2 and GRACE–MPI-ESM-LR.
- For nonseasonal variations, we found that while most GWS from GRACE–CMIP5 produced correlations with GWS from wells above 0.5 and satisfactory relative explained variance, three out of the four GRACE–GLDAS were distinguished by negative correlations and relative explained variances. For GRACE–GLDAS, only GRACE–CLM was found to provide results that were consistent with the data from the wells.
- In general, our study shows better consistency of GRACE–CMIP5 with the results from wells measurements.
- To obtain more consistent results, both models (more ground-based and satellite measurements as input data, better assimilation algorithms, and inclusion of more variables in the models such as surface water and canopy water storage) and terrestrial data (more accurate determination of porosity coefficients and more careful selection of wells) should be improved.

List of acronyms

- CMIP5 – World Climate Research Programme’s Coupled Model Intercomparison Project Phase 5
- CSR – Center for Space Research
- GFZ – GeoForschungsZentrum
- GLDAS – Global Land Data Assimilation System
- GRACE – Gravity Recovery and Climate Experiment
- GWL – groundwater level
- GWS – groundwater storage
- JPL – Jet Propulsion Laboratory
- RMSE – root mean square error
- SMS – soil moisture storage
- SnWS – snow water storage
- TWS – total water storage

Thank you

Note: More results and discussion can be found in the paper:

Śliwińska J, Birylo M, Rzepecka Z, Nastula J. Analysis of Groundwater and Total Water Storage Changes in Poland Using GRACE Observations, In-situ Data, and Various Assimilation and Climate Models. *Remote Sens.* 2019, 11(24), 2949; https://doi.org/10.3390/rs11242949

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[1]Space Research Centre, Polish Academy of Sciences, Warsaw, Poland

[2]Faculty of Geodesy, Geospatial and Civil Engineering, University of Warmia and Mazury, Olsztyn, Poland

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