Variability in Terrestrial Water Storage and its effect on polar motion

Justyna Śliwińska and Jolanta Nastula

Space Research Centre of the Polish Academy of Sciences, Warsaw, POLAND

INTRODUCTION

Our investigations are focused on the influence of Terrestrial Water Storage (TWS) variations obtained from Gravity Recovery and Climate Experiment (GRACE) mission on polar motion excitation functions. The global and regional trend as well as annual, semiannual and 120-day amplitudes of TWS variations are considered here.
We have obtained TWS from the monthly mass grids land GRACE Tellus data. As a comparative dataset, we also used TWS estimates determined from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) as well as from Global Land Data Assimilation System models (GLDAS).
Our studies include two steps:
1. The determination and comparisons of global and regional patterns of TWS obtained from GRACE data, GLDAS and CMIP5 climate models,
2. Comparison of the global hydrological excitation functions of polar motion with a hydrological signal in the geodetic excitation functions of polar motion.

DATA

- **GRACE data.** We used monthly grids of terrestrial water storage anomalies obtained from the Jet Propulsion Laboratory's website (https://grace.jpl.nasa.gov): CSR RL05, JPL RL05 and GFZ RL05 This dataset, with grid resolution of 1° and a time resolution of one month, contains the current surface mass change in units of equivalent water height.
- **GLDAS global hydrological models.** The Global Land Data Assimilation System models contain state variables (soil moisture content, snow water equivalent, canopy surface water) and flux variables (rainfall rate, evaporation, runoff) which can be used for the calculation of terrestrial water storage and terrestrial water storage change. In our analyses we used four GLDAS models: NOAH, VIC, Mosaic (MOS) and CLM (available at https://mirador.gsfc.nasa.gov). Each model has a spatial resolution of 1° and a time resolution of one month (Fang et al., 2008).
- **CMIP5 climate models.** The fifth phase of the Climate Model Intercomparison Procject models contain a complete dataset for providing information about climate variability and climate change (Taylor et al., 2012). The state and flux variables, which are necessary to determine the TWS values, have also been included. We used two CMIP5 models: MIROC and MPI with a grid resolution of 1.40625° and 1.875° respectively. The time resolution for both MIROC and MPI is one month. The models are available at http://cmip-pcmdi.llnl.gov.
- **Geodetic, atmospheric and oceanic polar motion excitation functions (GAM, AAM, OAM).** The hydrological part of the polar motion excitation - geodetic residuals GAO - has been obtained as a difference of observed geodetic excitation functions (Geodetic Angular Momentum GAM - derived from International Earth Rotation and Reference Systems Service IERS) with the sum of Atmospheric Angular Momentum (AAM - NCEP/NCAR model - from Global Geophysical Fluid Center GGFC) and Oceanic Angular Momentum (OAM - model ECCO - from Global Geophysical Fluid Center GGFC) according to the formula:
  GAO=GAM-AAM-OAM.

METHODOLOGY

The Terrestrial Water Storage from GLDAS and CMIP5 climate models has been computed using state variables according to the following formula:

$$TWS_n = SM_n + SN_n + (CWS_n),$$

where n is a number of epoch, *SM* is a soil moisture, *SN* is a snow water equivalent and *CWS* is a canopy water storage component (available only for GLDAS models).
The excitation of polar motion both for GRACE and for GLDAS and CMIP5 models have been computed according to the following formulas (Eubanks 1993):

$$\chi_1 = -\frac{1.098R_e^2}{C-A}\iint \Delta q(\varphi,\lambda,t)\sin(\varphi)\cos(\varphi)\cos(\lambda)dS \qquad \chi_2 = -\frac{1.098R_e^2}{C-A}\iint \Delta q(\varphi,\lambda,t)\sin(\varphi)\cos(\varphi)\sin(\lambda)dS,$$

where $\Delta q(\varphi, \lambda, t)$ are the changes in water storage (in kg/m^2), R_e is the Earth's mean radius, *dS* is the surface element area, *C* and *A* are the Earth's principal moments of inertia.

RESULTS

- **Global changes of Terrestrial Water Storage**

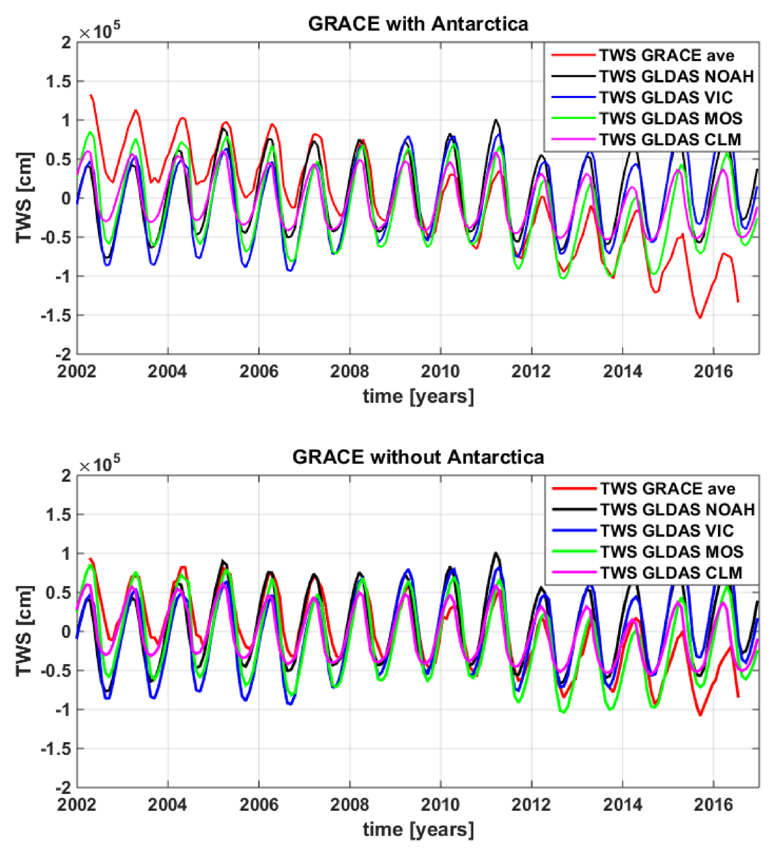

Fig. 1. Time series of global TWS from GRACE and from GLDAS. The GRACE data is an average of CSR, JPL and GFZ solution. TWS for GRACE has been estimated using the data with Antarctica (top panel) and without Antarctica (bottom panel). TWS for GLDAS models has been computed using state variables. The linear trend has not been removed.

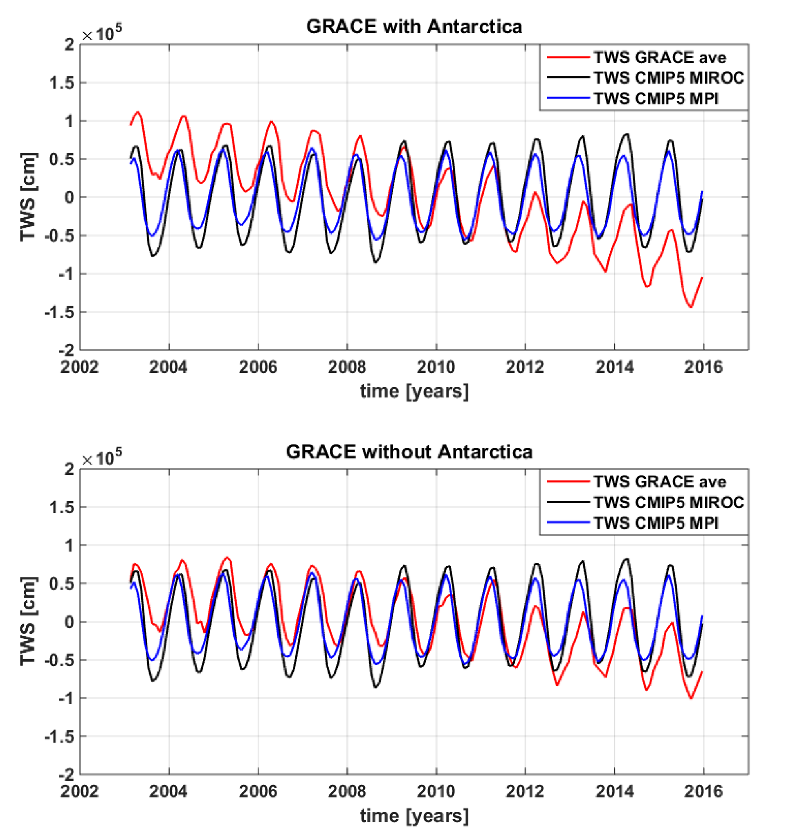

Fig. 2. Time series of global TWS from GRACE and from CMIP5. The GRACE data is an average of CSR, JPL and GFZ solution. TWS for GRACE has been estimated using the data with Antarctica (top panel) and without Antarctica (bottom panel). TWS for CMIP5 models has been computed using state variables. The linear trend has not been removed.

- **Regional patterns of Terrestrial Water Storage**

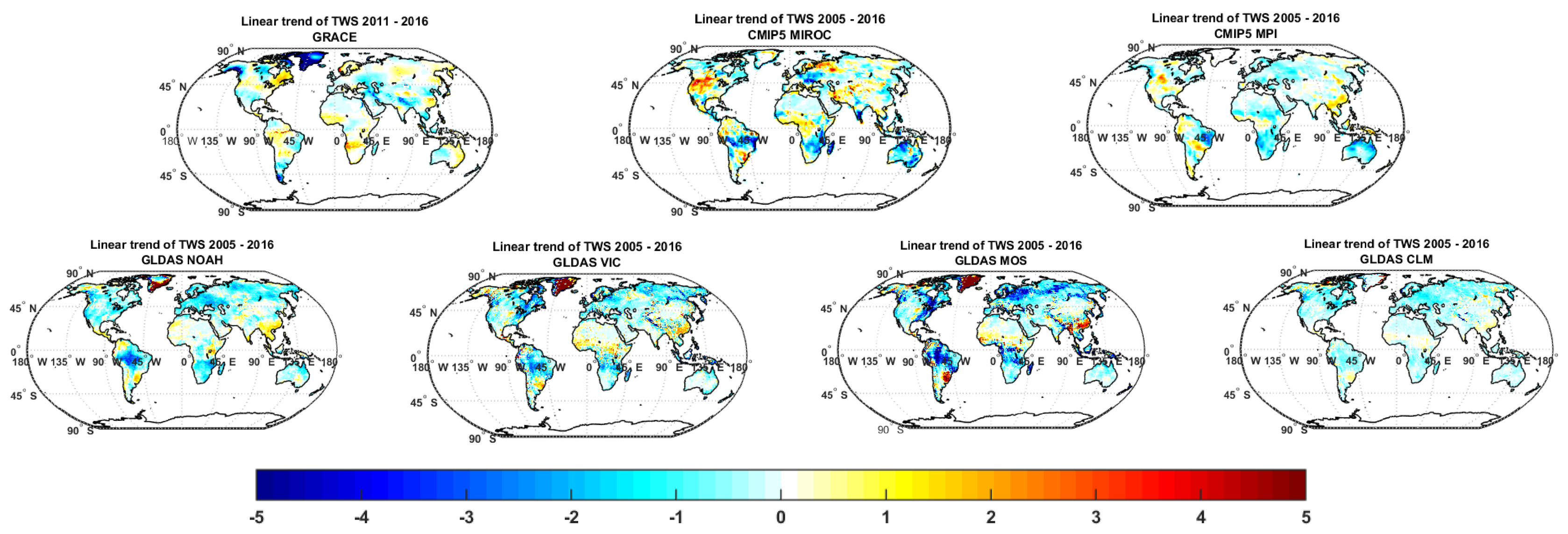

Fig. 3. Linear trend of Terrestrial Water Storage from January 2005 to December 2015 derived from GRACE data (average of CSR, JPL and GFZ solution), CMIP5 climate models (MIROC and MPI) and GLDAS models (NOAH, VIC, MOS and CLM). The values are in cm/year.

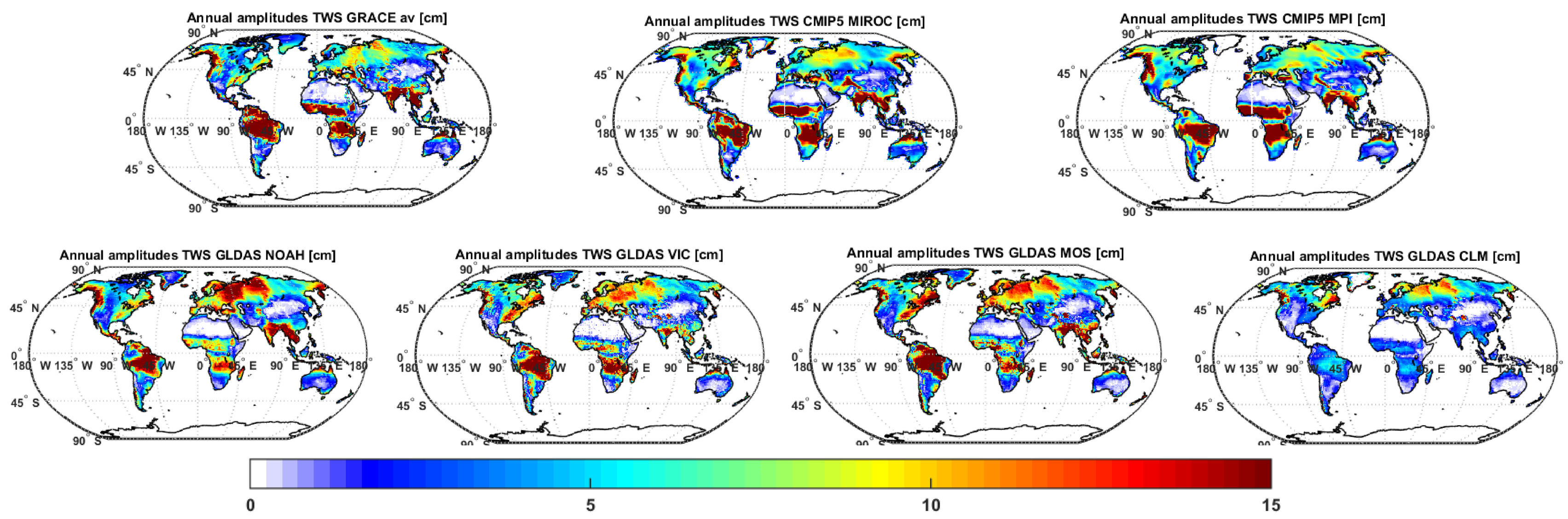

Fig. 4. Annual amplitudes of TWS derived from GRACE data (average of CSR, JPL and GFZ solution), CMIP5 climate models (MIROC and MPI) and GLDAS models (NOAH, VIC, MOS and CLM). The values are in cm.

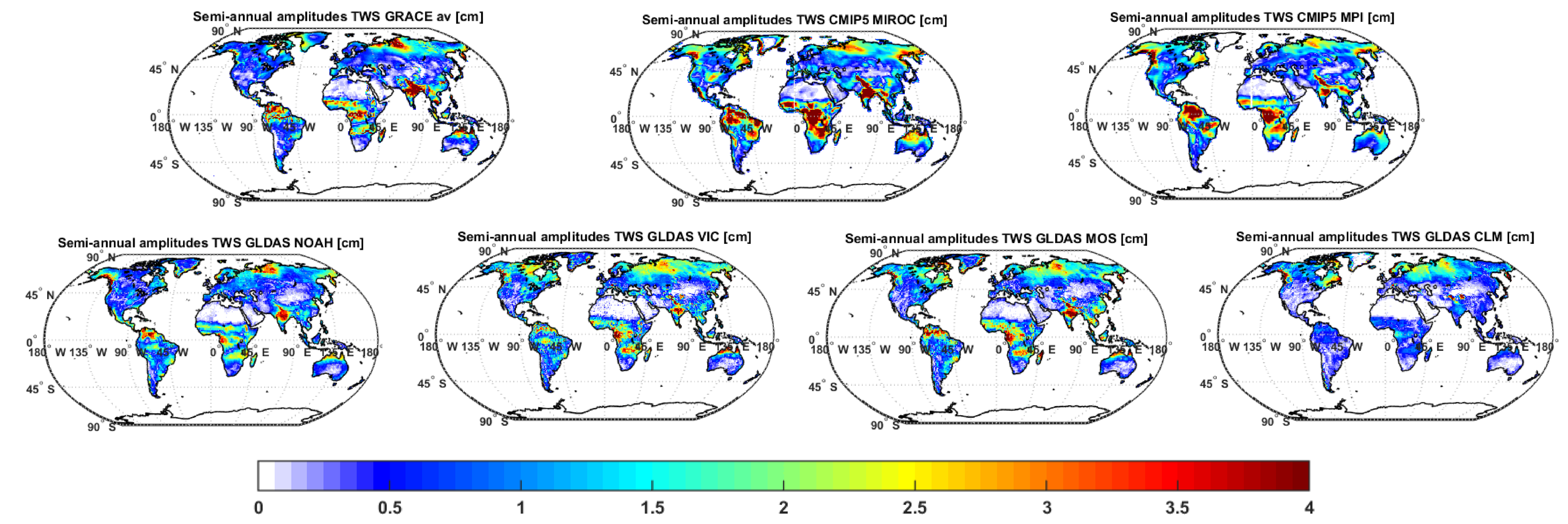

Fig. 5. Semi-annual amplitudes of TWS derived from GRACE data (average of CSR, JPL and GFZ solution), CMIP5 climate models (MIROC and MPI) and GLDAS models (NOAH, VIC, MOS and CLM). The values are in cm.

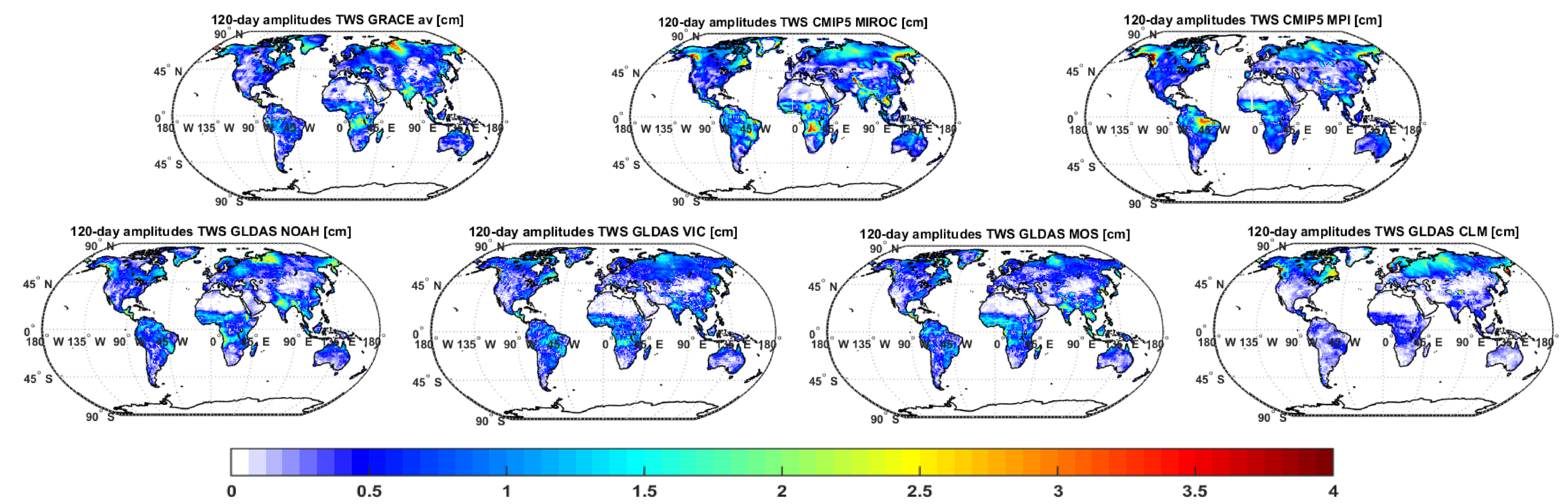

Fig. 6. 120-day amplitudes of TWS derived from GRACE data (average of CSR, JPL and GFZ solution), GLDAS models (NOAH, VIC, MOS and CLM) and CMIP5 climate models (MIROC and MPI). The values are in cm.

- **Polar motion excitation spectra**

In our study we also show the spectra of the complex-valued components of $\chi_1 + i\chi_2$ for the polar motion excitation functions derived from GRACE, GLDAS, CMIP5 as well as for hydrological part of the polar motion HAM (fig. 7). We have used Fourier Transform Band Pass Filter (FTBPF) (Kosek, 1995) with the 50 and 450-day cufoff. Previously, the excitation functions have been filtered with the Butterworth filter in order to remove long period oscillations (with periods longer than 500 days). The plots in fig. 7 show the oscillations both in the prograde and retrograde band.

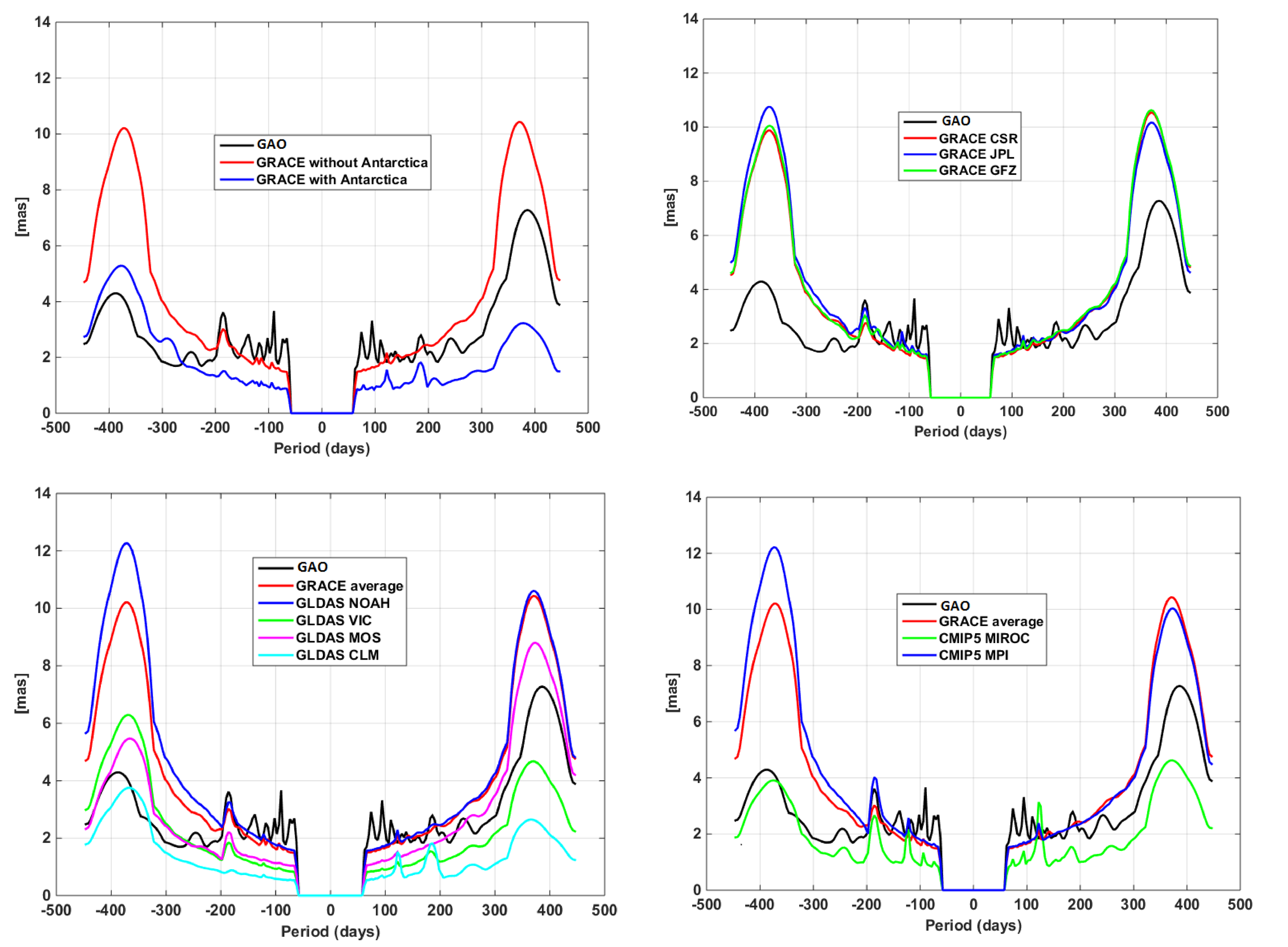

Fig. 7. The Fourier Transform Band Pass Filter (FTBPF) amplitude spectra of excitation functions of polar motion for GRACE average data computed with and without Antarctica (top left panel), for GRACE CSR, JPL and GFZ RL05 solutions (top right panel), for GLDAS models (bottom left panel) and for CMIP5 climate models (bottom right panel). The spectra have been computed with parameter λ=0.01 and a period cutoff 500 days. As a comparative dataset, the spectra for geodetic residuals (GAO=GAM-OAM-AAM) have also been included.

CONCLUSIONS

- In our study we have analyzed different models of land hydrology and we have compared them with GRACE data in terms of global and regional TWS changes as well as their impact on polar motion excitation.
- Time series of TWS obtained from GRACE data show a strong linear trend which cannot be observed for GLDAS and CMIP5 models. This might be caused by the fact that only observations from GRACE include the area of Antarctica. However, even extracting the Antarctica area from GRACE observations does not remove the trend completely.
- Global TWS estimations both for GLDAS and CMIP5 climate models agree in phase with GRACE data. The biggest amplitude among GLDAS models has been observed for NOAH, while the smallest – for CLM. Amplitudes for MIROC are slightly greater than for MPI and they are both stronger than the ones from GRACE estimations.
- All the GLDAS and CMIP5 models show an annual spatial pattern similar to those for the GRACE data. However, the signals estimated from models for area of Siberia are stronger while for tropical zone (Amazonian basin, Congo basin, South-East Asia) are less powerful than derived from satellite observations. Both semi-annual and 120-day amplitudes are the strongest for the MPI and MIROC climate models.
- Power spectra for polar motion excitation functions are dominated by the annual oscillations. The semi-annual signals are observed both for pro- and retrograde components only for GAO and GRACE. While for all land hydrology and climate models (except for CLM) the semi-annual oscillations are noticeable only for retrograde band. 120-day oscillations are observable for GAO and for MIROC model.

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ACKNOWLEDGEMENTS

This work was supported by the Polish national science foundation NCN under grant No. UMO-2013/11/B/ST10/04975.
The data used in this study were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

We would like to thanks the organizers for EGU General Assembly 2017 for the Early Career Scientist's Travel Support.

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