GRACE & GFO satellite gravimetry data for hydrology and Earth rotation

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***Abstract* – The GRACE and GRACE-FO satellites provide data on the Earth's gravitational field changes and are among the most successful NASA/DLR geodetic missions in recent decades. Based on their data, the melting of glaciers, redistribution of masses in the river basins, and changes in the ocean mass are studied. We use multichannel singular spectral analysis (MSSA) to filter these data and separate into principal components. As a result, it is possible to track regional trends associated with floods, droughts, and other climatic anomalies. Geoid monitoring from space also allows to identify global changes in the flattening of the Earth’s figure, related to its rotational velocity. The mass component measured from space affects the drift of the Earth's pole, which has changed in recent decades. The report identifies the connections between the mass redistributions on the planet, climate processes, and Earth's rotation.**

Keywords* – *satellite gravimetry, GRACE, climate change, Earth rotation.

I. INTRODUCTION

Gravity Recovery and Climate Experiment (GRACE) satellites, launched on 17.03.2002 from Plesetsk, finished their work on October 2017. GRACE Follow-on (GFO) mission was launched on May 2018, it is providing a set of monthly Earth’s gravity field observations. The second-order zonal coefficient (C_{20}) of the gravity field decomposition is related to the polar flattening of the Earth figure. Its changes are interrelated to the major component of the Earth’s tensor of inertia, and through it, to the Earth rotation velocity changes. C_{21} and S_{21} coefficients reflect the “misbalance” of the Earth’s mass and are connected with the motion of the pole, well measured by geodetic techniques. The Stokes coefficients of higher degrees and orders can be converted into global maps of monthly mass anomalies. Gravity data reflects changes related to groundwater redistribution, ice melting, and precipitation accumulation. However, de-stripping/filtering is required to use the GRACE/GFO data products. Instead of using Level 3 gridded and preprocessed data, we apply the multichannel singular spectrum analysis (MSSA, or extended EOF) technique to filter Level 2 data by ourselves. The obtained principal components (PCs) of different periods allow study of annual, long-term and other variations of mass in different regions of the world. Below, we briefly present the results of regional averaging of GRACE/GFO signals over the large river basins of Russia, as well as the tendencies in the $C_{20,}$ C_{21} and S_{21} coefficients.

II. DATA AND METHODS

Level 2 GRACE data in form of Stokes coefficients are delivered by many data processing centers, such as CRS, JPL, GFZ, CNES (https://thegraceplotter.com). We used JPL Level-2 RL06 monthly GRACE and GFO spherical harmonic data since 04.2002 till 06.2017 with coefficients complete to degree 60. 21 files (06.02, 07.02, 06.03, 01.11, 06.11, 05.12, 10.12, 03.13, 08.13, 09.13, 02.14, 12.14, 02.12, 05.15, 06.15, 10.15, 11.15, 04.16, 09.16, 10.16, 02.17) were cubically-interpolated (overall *N*=186 files). Similarly, for GRACE-FO we used files from 06.2018 until 12.2023 with interpolation for 08.18. 09.18, overall 67 files. GRACE/GFO are not so precise in measuring C_{20} coefficients (see Fig. 5) [1], thus we replace them with SLR-derived for regional studies. Average field over 15 GRACE years was subtracted. Glacial isostatic adjustment (GIA) effect according to Peltier ICE-6G model was removed. Results are represented in form of equivalent water height (EWH, cm) maps.

For GRACE/GFO data processing we use MSSA (extended EOF) explained in detail in [2, 3]. It is a generalization of singular spectrum analysis (SSA) for the multidimensional (multichannel) time series. Instead of the simple correlation matrix, the lagged trajectory matrix is analyzed. Lag parameter *L* can be chosen heuristically to make singular numbers (SN) of the trajectory matrix separated and capture the major periodicities and trends in the multidimensional time series (Fig. 1). We applied MSSA in frequency domain to the matrix of Stokes coefficients up to degree and order 60. Lag parameter was selected to be *L=48* (4 years) for GRACE and *L=24* (2 years) for GFO.

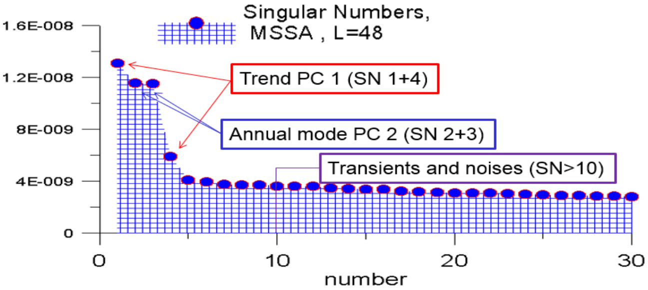

Fig. 1. SN’s grouping for MSSA of GRACE.

III. REGIONAL COMPARISONS

After MSSA we convert the PC’s of satellite gravity data into gridded EWH maps. This quantity represents the thickness of water layer required to compensate the gravity anomaly in the region. The GRACE trends (PC 1) shown in Fig. 2 over Eurasia reflect the melting of glaciers in Himalayas, degradation of permafrost in Siberia, Caspian sea mass decrease, and other trends in the mass redistribution.

We averaged data in the basins of large Russian rivers using Simulated Topological Networks (STN-30p) river mask. Some of the obtained time series are given in Fig 3. They show annual oscillations and changes related to hydrology and climate. Among them: the heat wave in 2011 and large snow accumulation in 2013 over European part of Russia, Amur flood in 2013, etc. It is interesting to compare gravity field from satellites with the absolute gravimeter GABL-M measurements in Moscow, see Fig. 4.

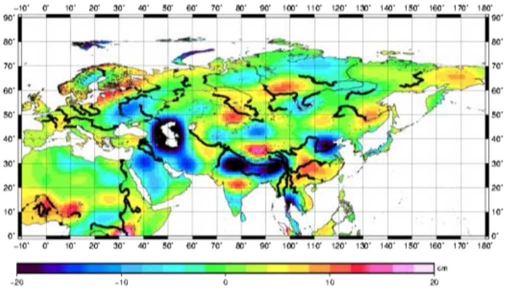

Fig. 2. Mass changes (trends, PC 1) from GRACE for 2003-2017 over Eurasia obtained through MSSA.

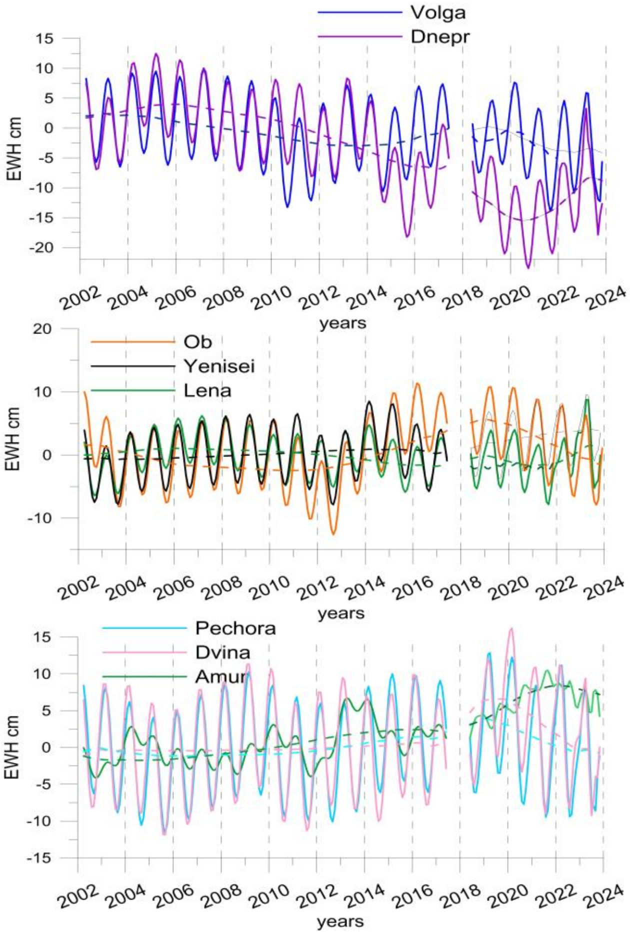

Fig. 3. Sum of SNs 1-10 and PC 2 (trends) averaged over large Russian river basins from GRACE and GFO.

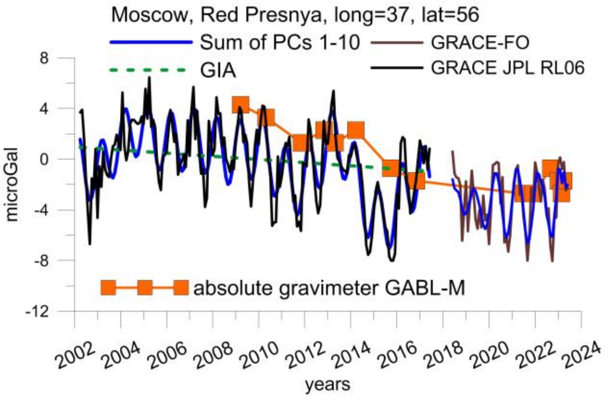

Fig. 4. Comparison of absolute gravimetry with GRACE/GFO data for Moscow region.

IV. GLOBAL TENDENCIES AND EARTH ROTATION

Gravity field coefficient C_{20} can be easily recalculated into the form-factor J_2, characterizing the geoid flattening. Its values for GRACE, GFO are compared with satellite laser ranging (SLR) ones (1976-now) in Fig. 5. The decrease of flattening changed to increase around 2000’s. It could have relation to glacial melting and Earth rotation velocity changes, but has not found an explanation yet [4].

The trends in C_{21}, S_{21} gravity coefficients since 2002, shown in Fig 6, correspond well to the drift of the Earth’s pole, which means that the climate change causes mass displacements on Earth, and results in the drift of its pole of rotation [5]. Such anomalies as the acceleration of the Earth rotation, Atlantic Multidecadal Oscillation turnover, and Chandler wobble disappearance [6,7], observed in 2020s, present interest for geodesists and require precise continuous monitoring of the Earth’s gravity field.

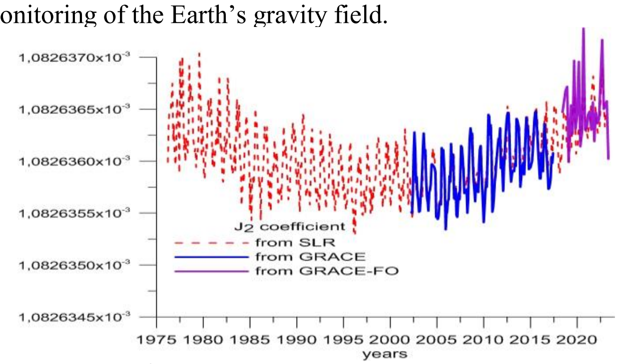

Fig. 5. J_2 variations from GRACE/GFO and SLR.

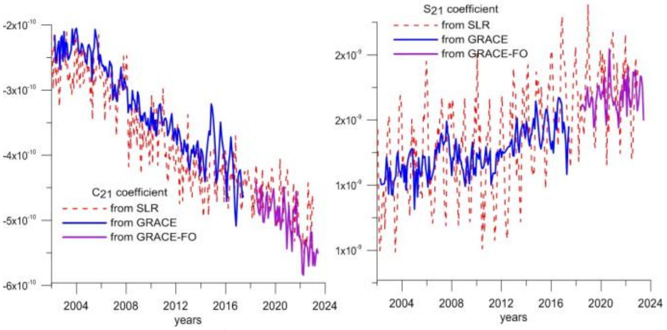

Fig. 6. C_{21}, S_{21} variations from GRACE/GFO and SLR.

REFERENCES

[1] Zotov, L.V., C.K. Shum, N.L. Frolova Gravity changes over Russian rivers basins from GRACE / Planetary Exploration and Science: Recent Results and Advances, Edt. by Sh. Jin, Springer, 2015.

[2] Zotov, L. Earth rotation and climate processes / Moscow, MIEM NRU HSE, 2022 – 306 p. (in Russian).

[3] Golyandina, N., Nekrutkin V., Zhigljavskyet A. Analysis of time series structure: SSA and related techniques / Chapman & Hall/CRC, N.Y. London. 2001.

[4] Zotov, L., Ch. Bizouard, C.K. Shum, Ch. Zhang, N. Sidorenkov, V. Yushkin Analysis of Earth’s Polar Motion and Length of Day Trends in Comparison with Estimates Using Second Degree Stokes Coefficients from Satellite Gravimetry // Advances in Space Research, 2022, N 69 – P. 308-318, https://doi.org/10.1016/j.asr.2021.09.010

[5] Bizouard, Ch. Geophysical modelling of the polar motion / De Gruyter 2020.

[6] Zotov L., N. Sidorenkov, Ch. Bizouard Anomalies of the Chandler Wobble in 2010s, // Moscow University Physics Bulletin, 2022 – Vol. 77 (3) – P. 55-58. doi:10.3103/S0027134922030134

[7] Agnew D.C., A global timekeeping problem postponed by global warming, // Nature, 628, 333–336, 2024 doi:10.1038/s41586-024-07170-0