Mass changes over Russia from GRACE and GRACE-FO

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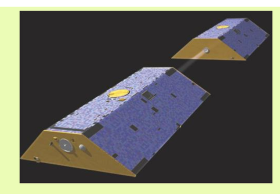
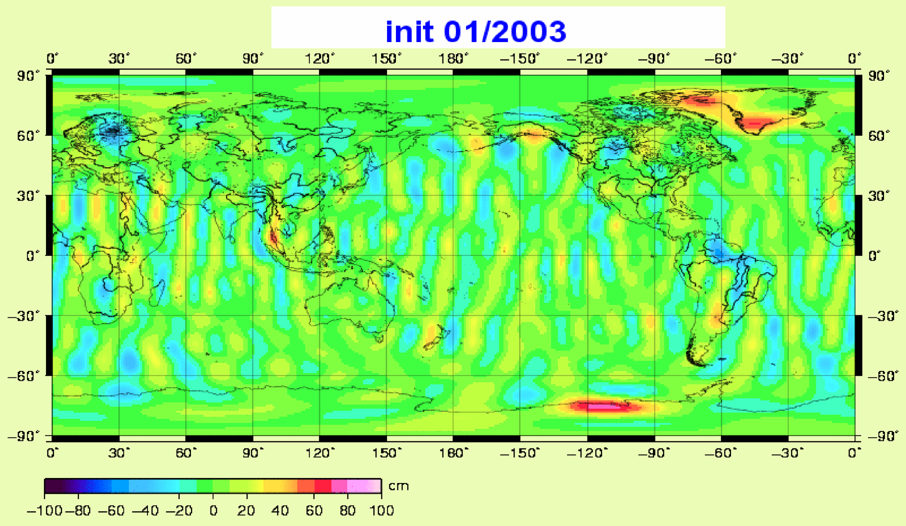


Abstract: Gravity Recovery and Climate Experiment (GRACE) satellites, launched 17.03.2002 from Plesetsk, finished their work 10.2017. 05.2018 GRACE-Follow-on mission was launched, it is providing a set of monthly Earth's gravity field observations. They present a big interest for hydrological studies. Gravity data reflect changes, related to the groundwater redistribution, ice melting, and precipitation accumulation. However, de-stripping/filtering is required to use the GRACE data products. We apply Multichannel Singular Spectrum Analysis (MSSA, or extended EOF) technique to filter GRACE data and separate the principal components (PCs) of different periods. We performed data averaging over the large river basins of Russia and present some comparisons with ground measurements by absolute gravimeter and water level gausge stations.

Data: We used JPL Level-2 RL06 monthly GRACE 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 06.2012 till 06.2023 with interpolation for 08.18. 09.18, 02.19, overall 66 files. C_{20} coefficients were replaced by SLR-derived. Average field over 12 years was subtracted. GIA effect according to Peltier ICE6G model was removed. Results are represented in form of equivalent water height (EWH, cm) maps.

Fig 1. → Vertical "stripes" manifest as high-frequency correlated errors dominates each of the monthly temporal gravity field solutions. Initial data contains mostly stripes, and illustrates constant (geographically-correlated) spatial behavior. MSSA can be used for de-striping.



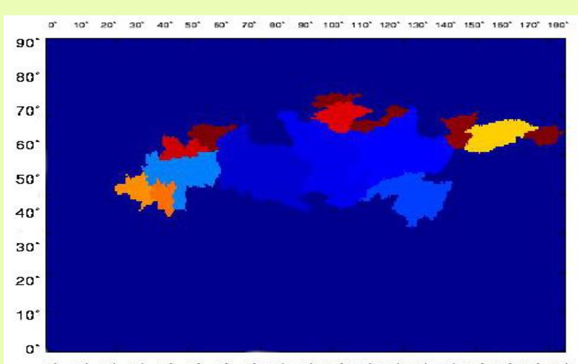
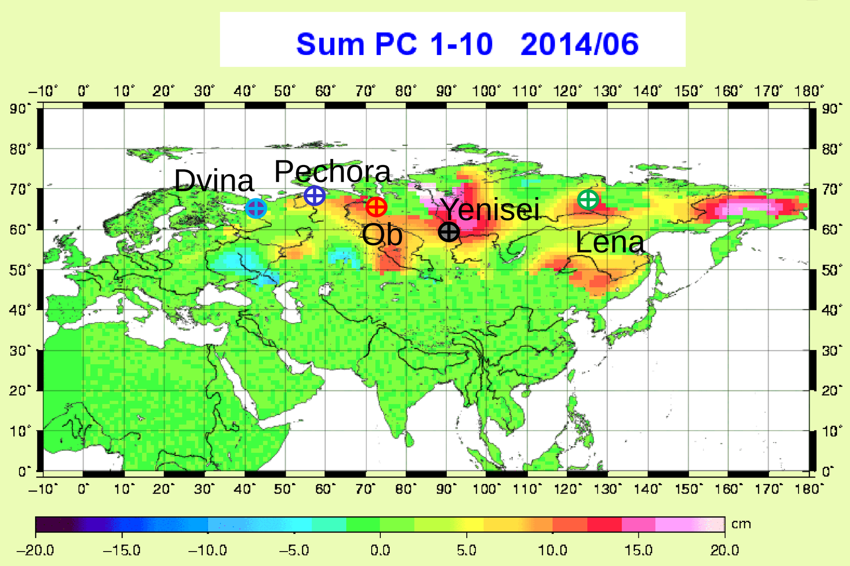


Fig 2. ← Sum of MSSA PCs 1-10 represent main signal variability (energy). Stripes are mostly removed (they go to larger PCs). Simulated Topological Networks (STN-30p) database is used to constrain the region of study to the basins of 15 large Russian rivers.
↓ The map for 06.2014 is presented.



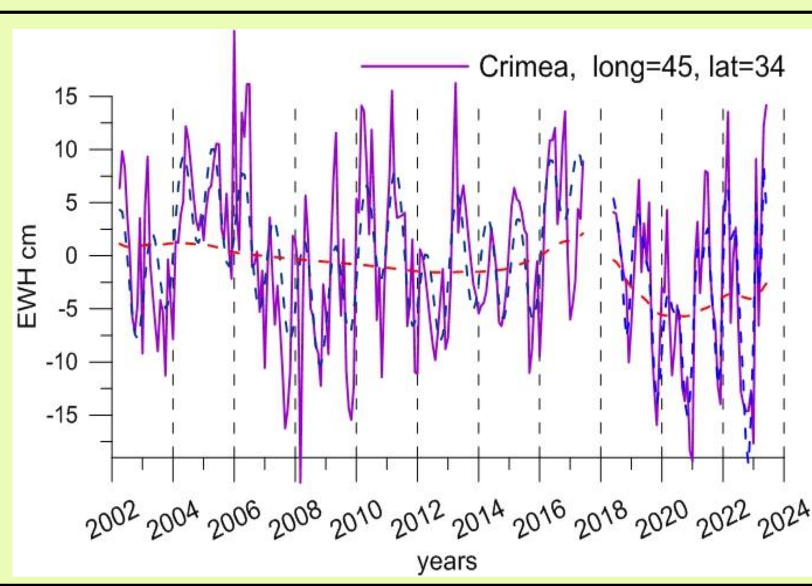
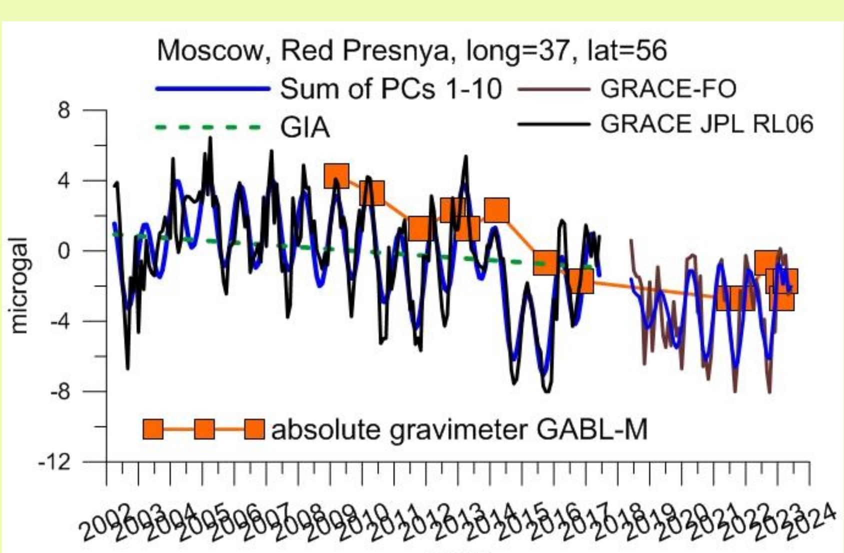


Fig 3. ↑ C_{20} Crimea's territory is a steppe with mountings and only a few small rivers. There were difficulties in 2014-2022, when water supply from Dnepr was blocked.



← **Fig 4.** Results of comparison of GRACE and GFO data with measurements made with absolute gravimeter GABL at the former Main gravity station of USSR in Moscow.

MSSA Method: Multichannel Singular Spectrum Analysis (MSSA), also called Extended EOF, is a generalization of Singular Spectrum Analysis (SSA) for the multidimensional (multichannel) time series. SSA, in its turn, is a Principal Component Analysis, generalized for the time series in such way, that instead of the simple correlation matrix, the trajectory matrix is analyzed. It is obtained through the time series embedding into the *L*-dimensional space. Parameter *L* is called lag or "caterpillar" length. When *L=1*, SSA becomes PCA. In every point *ij* on the map we have time series $A_{ij}(t_k)$ of length *N*. The trajectory matrix for every $X_{A_{ij}}$ should be build and incorporated into large block matrix *X* as follows:

$$X_{A_{ij}} = \begin{pmatrix} A_{ij}(t_0) & A_{ij}(t_1) & \ldots & A_{ij}(t_{K-1}) \\ A_{ij}(t_1) & A_{ij}(t_2) & \ldots & A_{ij}(t_K) \\ \ldots & \ldots & \ldots & \ldots \\ A_{ij}(t_{L-1}) & A_{ij}(t_L) & \ldots & A_{ij}(t_{N-1}) \end{pmatrix} \quad X = [X_{A_{1,1}}, X_{A_{2,1}}, X_{A_{1,2}} \ldots, X_{A_{ij}}, \ldots, X_{A_{P-1,Q}}, X_{A_{P,Q}}]^T$$

$K = N - L + 1$ SVD: PC-i matrix:

$$X = USV^T \qquad X^i = s_i u_i v_i^T$$

Then Singular Value Decomposition (SVD) should be applied to *X*. As a result, a sequence of singular numbers (SN) s_i standing along the diagonal of matrix *S* in order of decreasing values and the corresponding eigenvectors u_i, v_i are obtained. The Principal Components (PCs) can be reconstructed from them, knowing the structure of the matrix X^i. Some of SNs may be related to one and the same PC and represent similar behavior. Than SN-components should be grouped together and reconstructed as one PC. As a result, the set of PCs with decreasing amplitudes representing different modes of time series variability are obtained.

MSSA is more flexible for recognition of trend, modulated oscillations of different periods, denoising of multidimensional time series, then simple EOF. Different channels "help" each other to capture spatio-temporal correlation patterns. We applied MSSA in frequency domain to the matrix of Stokes coefficients. Lag parameter was selected to be *L=48* (4 years) for GRACE and *L=24* (2 years) for GRACE-FO.

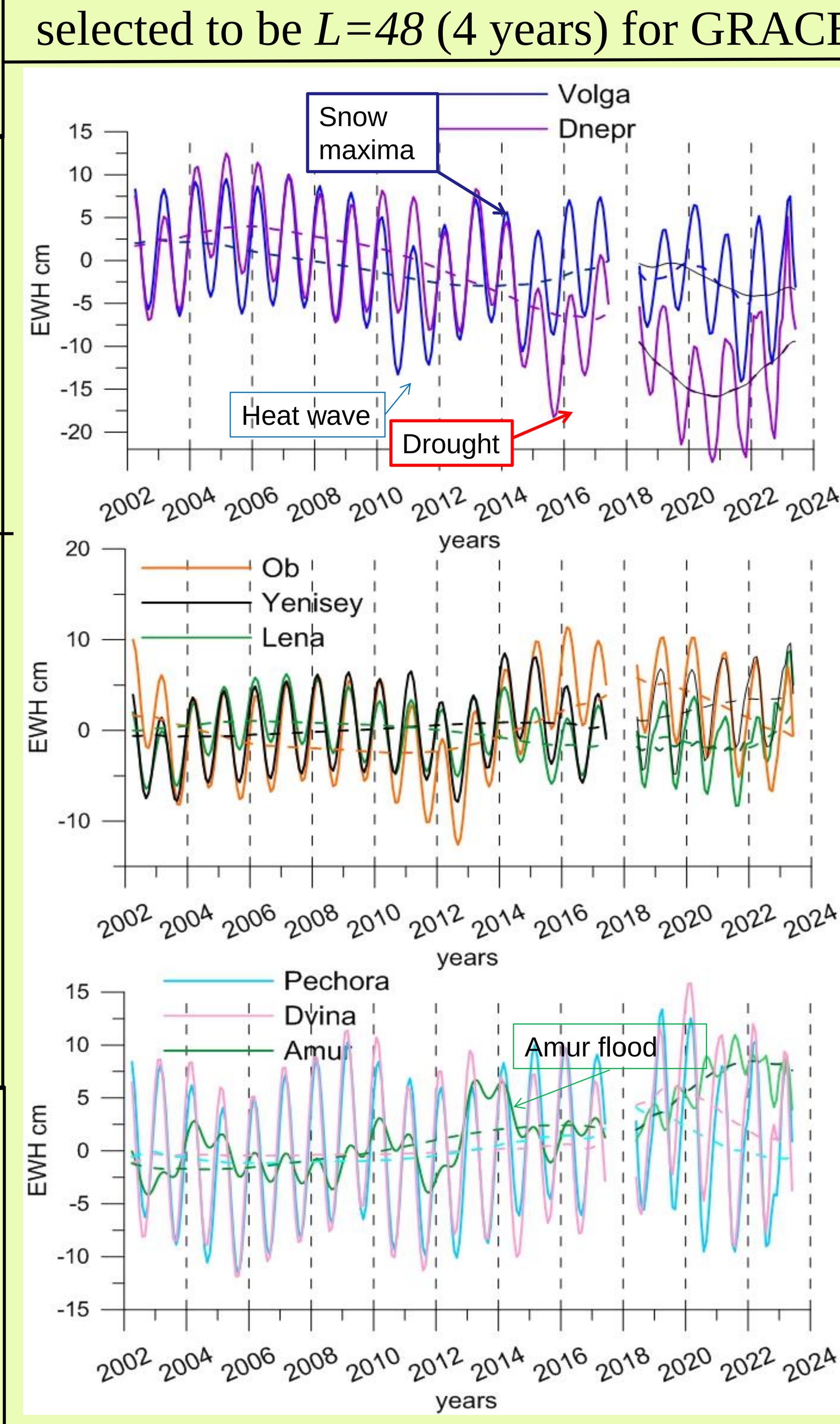


Fig 4.↓ Singular numbers for MSSA with parameter *L=48*

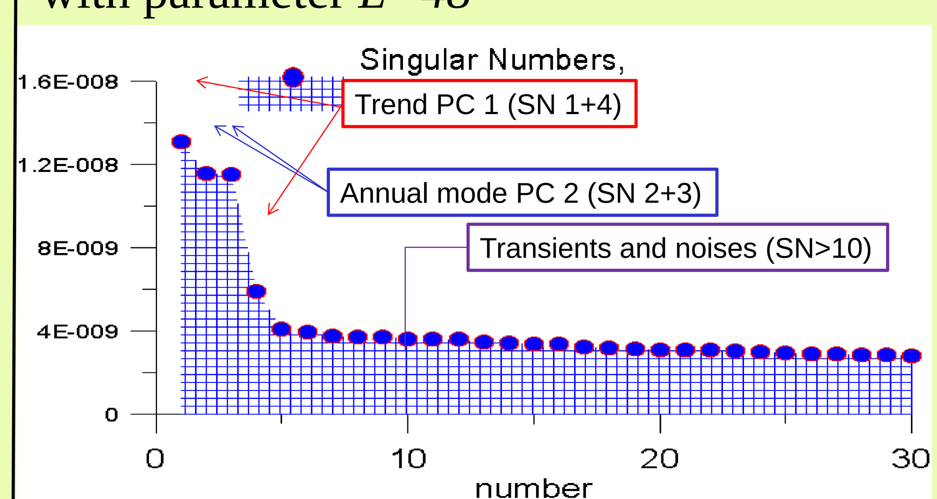


Fig 5.↓ Difference between 2018 and 2002 for the trend component (PC 1).

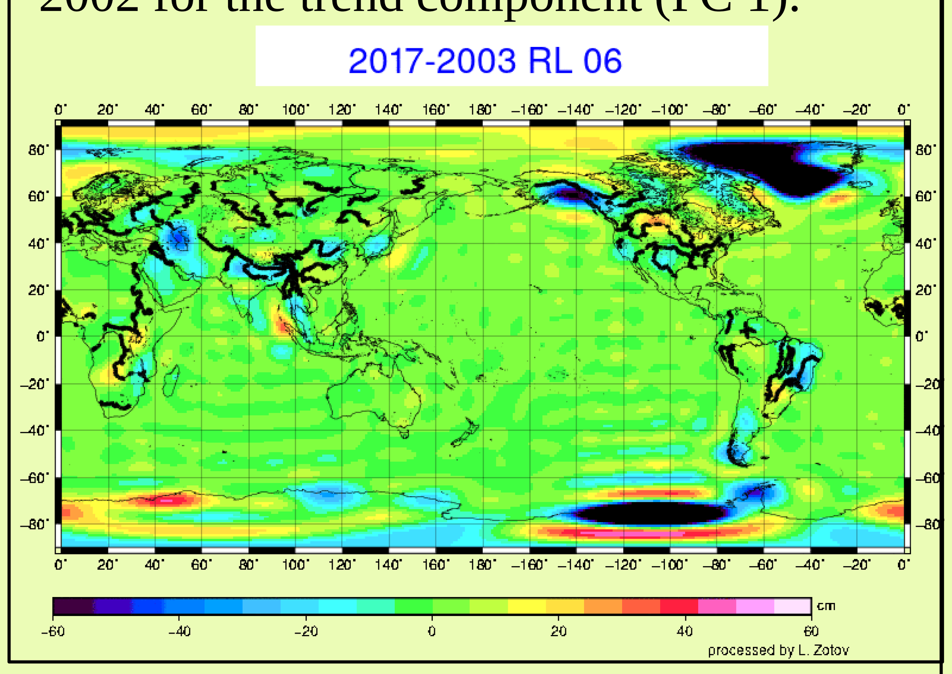
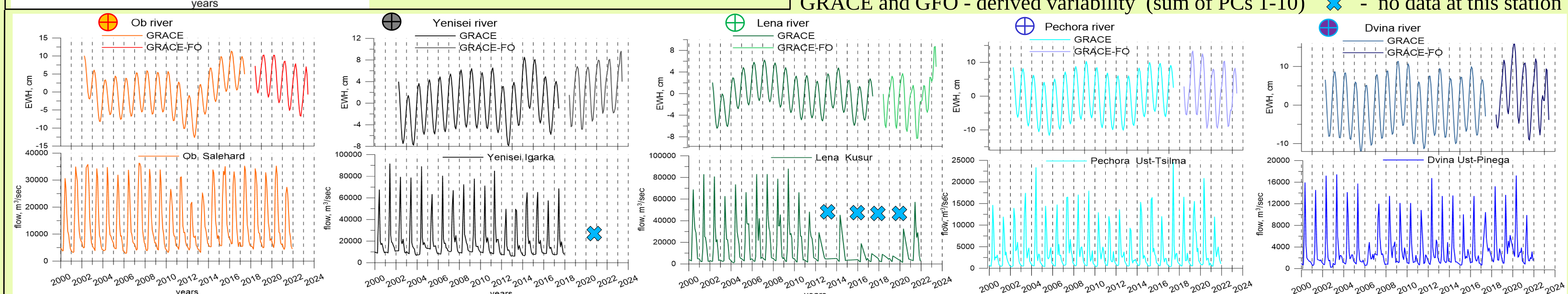


Fig 6. ↑ Sum of PCs 1-10 for particular river basins from GRACE and GFO. Different trends' behavior for European and Siberian rivers is seen.

Fig 7. ↓ Comparison of changes of the large Russian river's flows since 2000 with GRACE and GFO - derived variability (sum of PCs 1-10) ✖ - no data at this station



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Conclusion: GRACE and GRACE-FO data is very useful for hydrological and climatological studies, especially over large territory, not completely covered by the meteorological and hydrological networks, like Russia. MSSA is now a widely-used method for GRACE&GFO data processing, de-striping, filtering, and Principal Components (PCs) separation.

The comparisons with in-situ gauge data and gravity measurements are important for satellite data validation and hydrological applications. We presented some simple comparisons and are open for future collaboration and development.

XXI..281 "СОВРЕМЕННЫЕ ПРОБЛЕМЫ ДИСТАНЦИОННОГО ЗОНДИРОВАНИЯ ЗЕМЛИ ИЗ КОСМОСА"