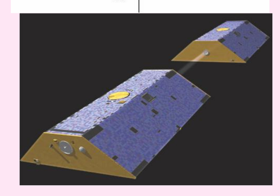
# Gravity changes over Russian rivers basins from GRACE

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**Abstract:** Gravity Recovery and Climate Experiment (GRACE) satellites, launched 17.03.2002 from Plesetsk, provide 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. Spring 2013 can be characterized by the extremely large snow accumulation occurred in Russia. Melting of this snow induced large floods and river levels increase. The exceptional maxima are seen in the curves obtained from GRACE, they can be compared to the hydrological models, such as GLDAS or WGHM, and ground observations.
Long-periodic climate-related changes were separated into PC 2. Gravity field increase in Siberia and decrease around Caspian sea are seen. Overall trend over Russia demonstrates growth until 2009, when it has maximum, following by the decrease.


**Data**: We used JPL Level-2 RL05 monthly GRACE spherical harmonic data since 01.2003 till 06.2013 with coefficients complete to degree 60. Six files (06.03, 01.11, 06.11, 05.12, 10.12, 03.13) were linearly interpolated (overall $N$=126 files used). $C_{20}$ coefficients were replaced by SLR-derived. Average field over 10 years was subtracted. GIA effect according to Paulson 2007 model was removed. Results are represented in form of equivalent water height (EWH) level (cm) animated 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.

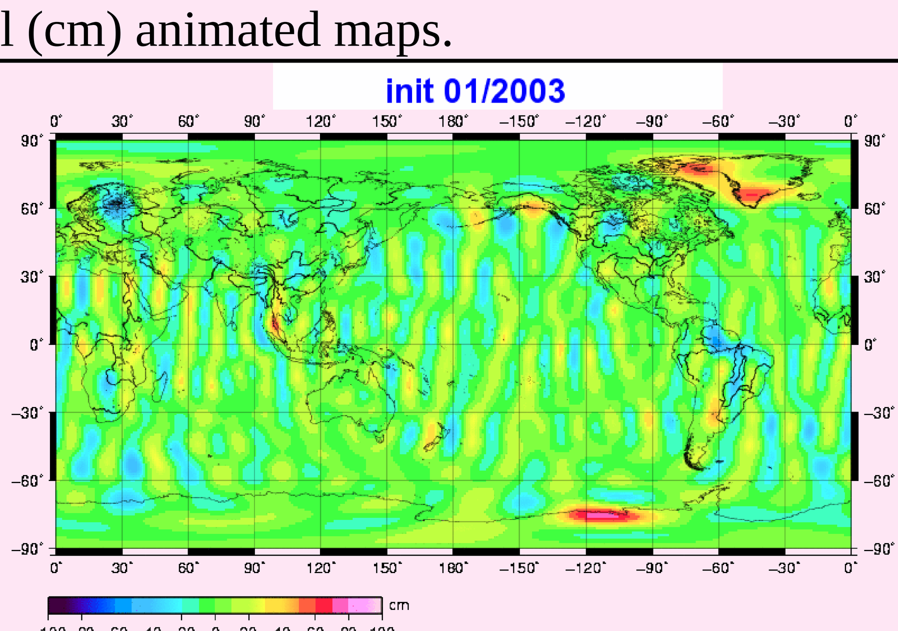



**Fig 2.** ↓ Sum of MSSA PCs 1-10 ($L$=36) represent main signal variability (energy). Stripes are mostly removed (they go to larger PCs). Simulated Topological Networks (STN-30p) database is used to constrain the region of study to the basins of 15 large Russian rivers (left). Two maps for the beginning (01.2003) and end (06.2013) of the data span are presented (right).

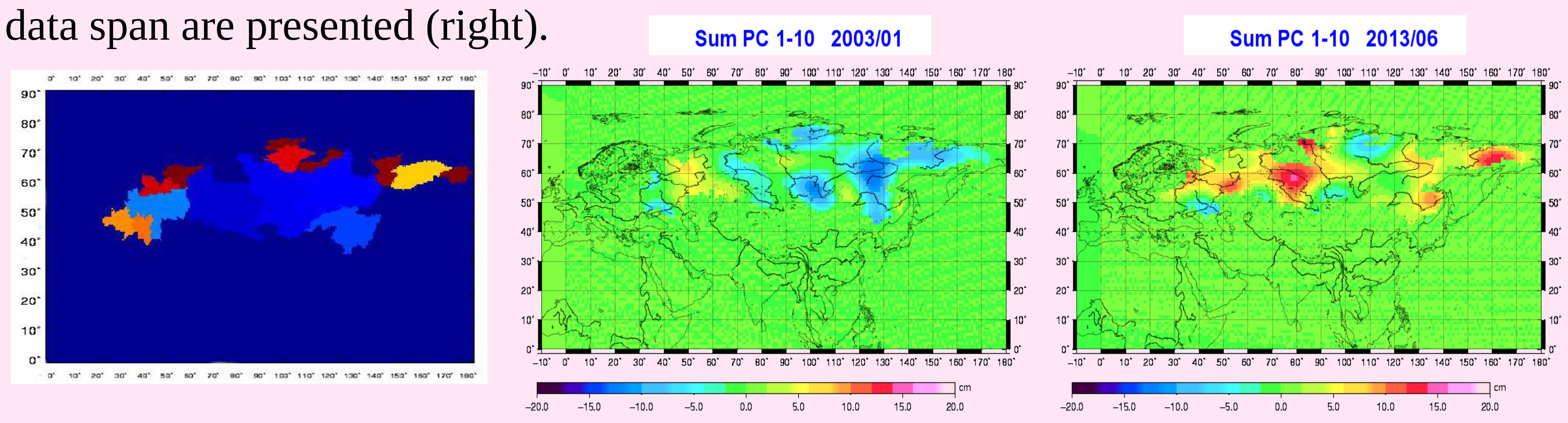
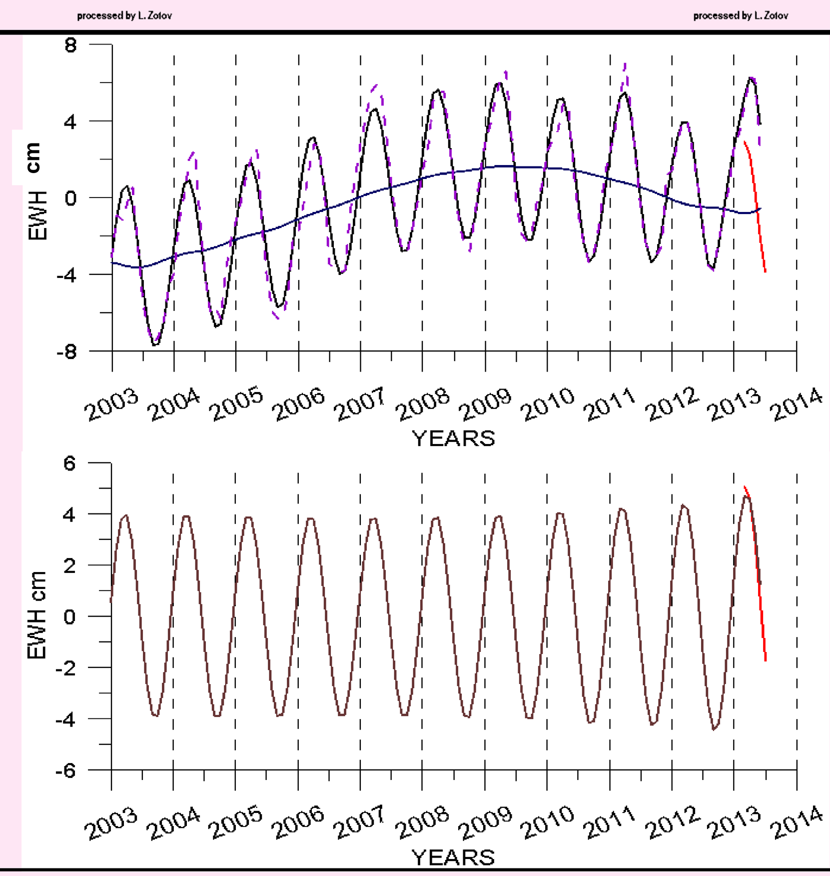



**Fig 3.** → **Top:** Results of averaging over the basins of large Russian rivers. Black curve is sum of PCs 1-10. Purple curve - initial data (sum of all PCs). The trend (PC 2) is shown in blue. It has maximum in 2009, then goes down. Red curve depicts the prediction made 03.2013 by Neural Network. The observed level of gravity anomaly sufficiently surpasses the prediction. Unprecedented maxima is related to huge snow accumulation over Russia by spring 2013. **Bottom:** Average for annual oscillation captured by PC 1 demonstrates amplitude increase since 2009. →




**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:

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

$K = N - L + 1$

SVD: $$X = USV^T$$

PC-i matrix: $$X^i = s_i u_i v_i^T$$

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 behaviour. Then 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 $L=36$ (3 years).

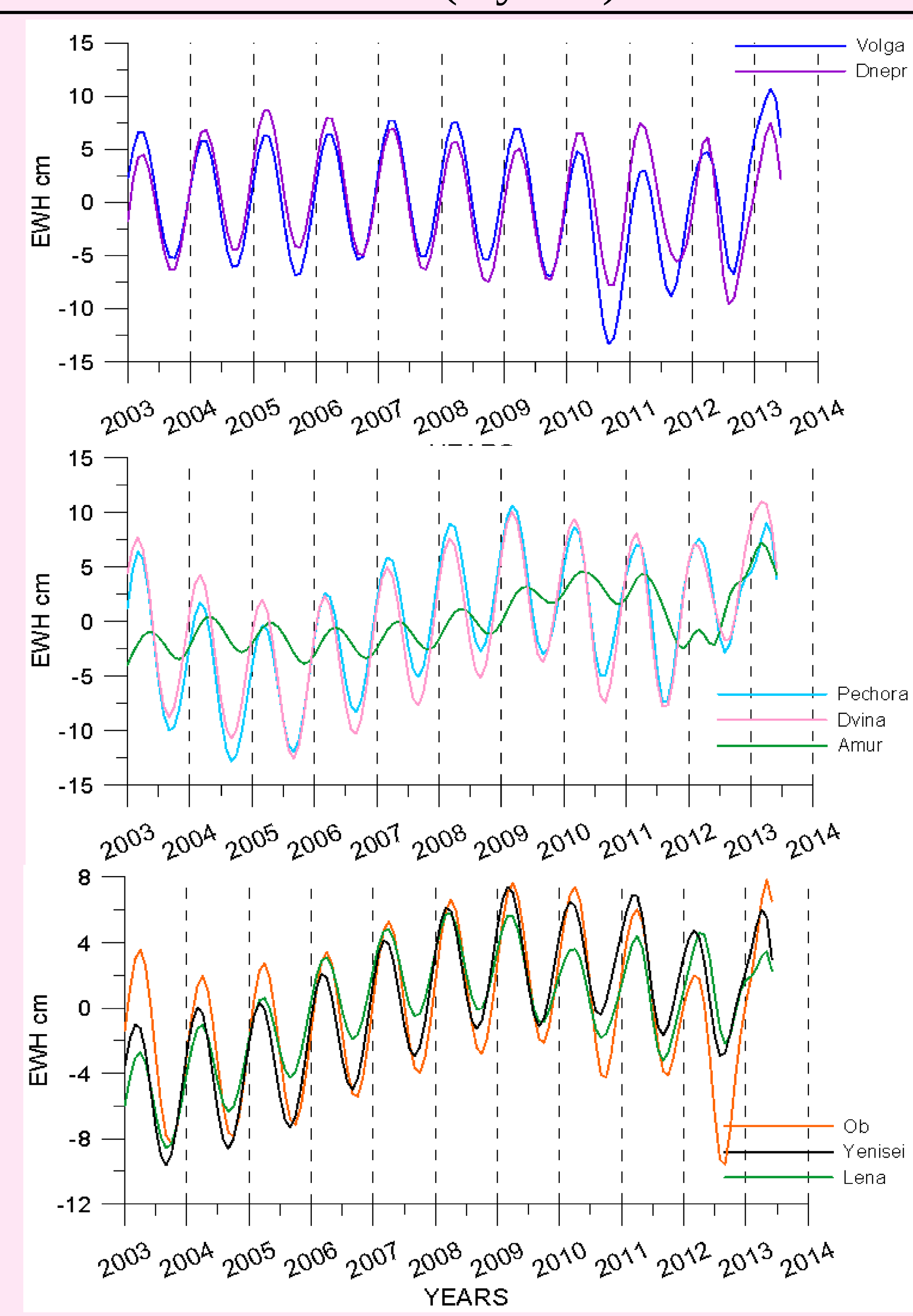



**Fig 4.**↓ Singular numbers for MSSA with parameter $L=36$

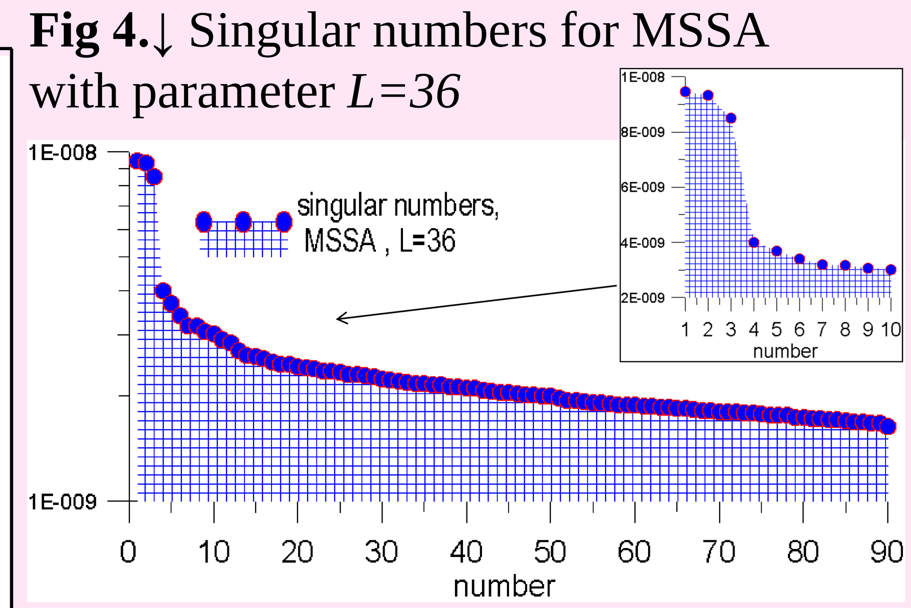



**Fig 5.**↓ Difference between 2013 and 2003 for the trend component (PC 2).

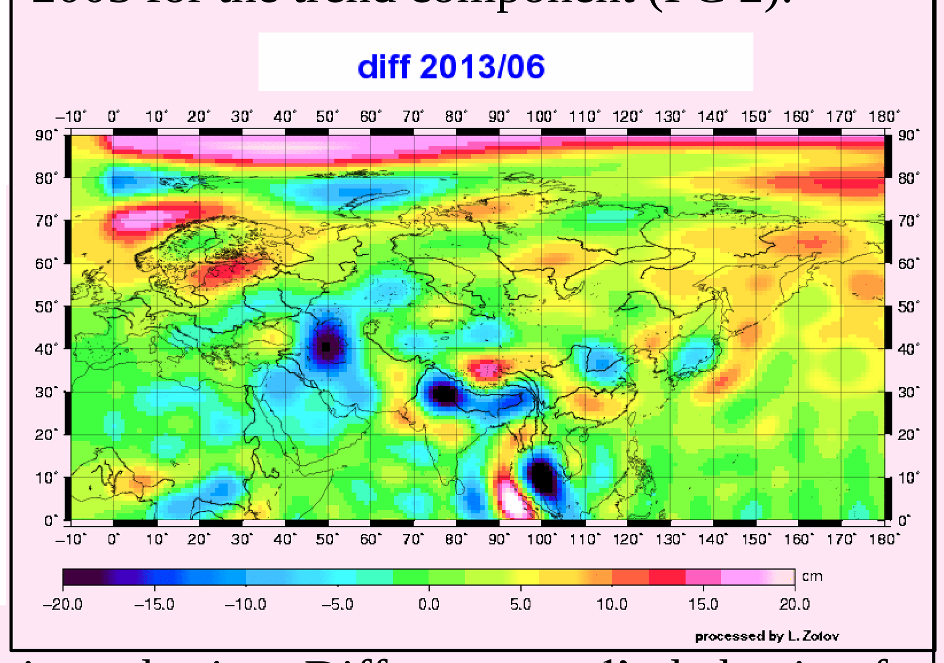
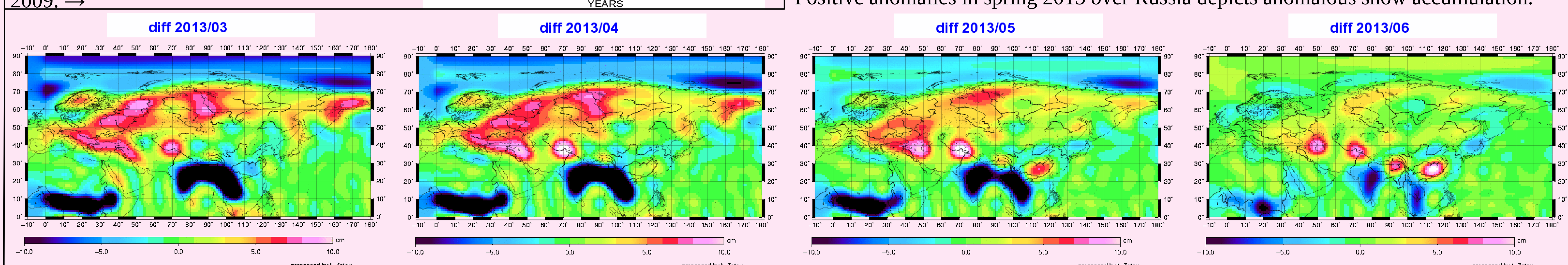



**Fig 6.** ↑ Sum of PCs 1-10 for particular rivers basins. Different trend's behavior for European and Siberian rivers is seen together with the unprecedented maxima in summer 2013. Minimum in summer 2010 for Volga river corresponds to the heat wave.

**Fig 7.** ↓ The differences for the annual PC 1 between monthly (March-June 2013) maps and average maps over 9 years (2003-2012) for the corresponding months. Positive anomalies in spring 2013 over Russia depicts anomalous snow accumulation.





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**Conclusion**: GRACE 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 a promising method for GRACE data processing, de-striping, filtering, and Principal Components (PCs) separation.
After averaging over 15 large Russian rivers basins annual component shows amplitude increase since 2009 (Fig. 3). Unprecedented maximum in spring 2013 is caused by the huge snow accumulation over the territory of Russia (Fig. 6,7). Trend component shows increase since 2003, maximum in 2009, following by the decrease. Map for the trend (Fig. 5) show gravity field increase in Siberia and decrease over Caspian sea since 2003.


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