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Challenges from North to South
Des défis du Nord au Sud

How reliable is the mass variation in the Siberian permafrost region as observed by GRACE?

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ABSTRACT

Permafrost generally and in Siberia (Russia) especially plays a key role for global hydrological mass transport, climate change and the eco-system of the Earth. In this study, surface and sub-surface mass variations in the Siberian permafrost region based on the gravitational approach (i.e. from GRACE mission) are estimated, and investigated to what extent the mass transport estimates are reliable and realistic. On the other hand, hydrological mass variations in this region are determined based on the geometrical approach using satellite (radar/laser) altimetry re-tracking data (e.g. Jason-2, ICESat) and satellite imagery (e.g. LandSat). In addition, hydrological surface mass variations are extracted from global hydrological water cycle models based on various in-situ hydrological observations, e.g. precipitation, evapotranspiration and run-off data. In this study, we quantify and asses the signal errors and its contributions to the integral mass variations in Siberia including error bars and determine to what extent GRACE results can provide mass variations which are caused by permafrost changes.

RÉSUMÉ

Le Pergélisol généralement et en particulier en Sibérie (Russie) joue un rôle clé pour le transport mondial de masse hydrologique, le changement climatique et l' éco-système de la Terre. Dans cette étude, les variations de masse de la surface et du sous-sol dans la région du permafrost sibérien basée sur l'approche gravitationnelle (de la mission GRACE) sont estimées et étudié dans quelle mesure les estimations de transport de masse sont fiables et réalistes. En outre, nous quantifions et examinons les erreurs de signal et ses contributions aux variations de masse intégrale en Sibérie, y compris les barres d'erreur, et nous déterminons dans quelle mesure les résultats de GRACE peuvent fournir des variations de masse qui sont causées par les changements du pergélisol.

1 INTRODUCTION

Over the past few years significant advance has been made on the understanding of the Earth's gravity filed based on satellite missions CHAMP (Challenging Mini-Satellite Payload, GRACE (Gravity Recovery And Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer). From those missions, the GRACE satellite mission specially is mapping the time variable part of the Earth's gravity field at monthly, weekly as well as daily intervals. Here, the monthly solutions are used to estimate monthly variations in the distribution of water on land after removing the background models such as atmospheric, oceanic, ice and solid mass changes (Flechtner; Dobslaw 2014).

Most GARCE-related studies have been focused on the estimation of time-variable mass variations in the Earth system with only little focusing on the effect of GRACE satellite observation errors and spherical harmonic coefficients errors on the mass variations derived by GRACE L2 products (Wahr et al. 2006). After sophisticated error estimations, the accuracy of estimated mass variations can be used to see how real the mass variations in a certain region are. This information is especially used to calibrate hydrological mass variations from hydrological models such GLDAS (Global Land Data Assimilation System) (Rodell et al. 2009) or WaterGap Global Hydrological Model (WGHM) (Döll et al. 2014). It should be mentioned that GRACE has no vertical resolution; therefore based on only GRACE results it is not possible to decide to which layers of the Earth mass variations belong. Therefore, GRACE-based estimated mass variations have to be adequately separated for better understanding of the individual signal contributions. For example, we cannot distinguish if mass variations are caused by atmospheric mass changes including changes in precipitation or evapotranspiration rates, or by water storage changes on the ground or underground. Therefore, to separate mass variation signals from GRACE, we have to employ some complementary models (e.g. GLDAS model) for understanding each contribution.

Using GRACE observations from 2012 to 2015, mass variation signals including secular and (long-)periodical contributions in different regions can be precisely estimated. One of the challenging regions, which is not sufficiently investigated so far, is the permafrost region in Siberia, Russia. During the past decades, the permafrost regime in the Siberian region has experienced significant changes in terms of permafrost thawing due to climate warming. In the permafrost region of Siberia, the most temporal mass variations are related to hydrological processes including thawing of permafrost layers. In addition, permafrost layers with different thickness cover about 80% of Siberia. These frozen sheets play an important role for sea level rise and the global hydrological water cycle in the Earth system.

In this study, integrated mass variations in terms of hydrological mass variations and the uncertainties of the results in the permafrost region of Siberia with focus on the error propagation of hydrological signals are precisely estimated based on the new release of GRACE (RL05a) from GeoForschungsZentrum (GFZ) in Potsdam in the period of 2002-2015. It will be discussed how the GRACE errors are propagated to the whole mass variation signals, and how accurate and reliable the secular trend estimation based on GRACE products is.

2 ERRORS IN GRACE MONTHLY SOLUTIONS

Estimated total water storage changes from GRACE are suffering from signal degradation due to the GRACE-type orbit configuration, observation errors and noise (Velicogna; Wahr 2013). The random errors on the GRACE products are increasing as a function of spherical harmonic degree and the systematic errors are correlated within a particular spectral order of the Stokes coefficients (Swenson; Wahr 2006). Over the past few years, significant progress has been made to design an optimal filter either to reduce, to remove or to isolate such errors in the GRACE products. It should be noticed that filters are not only reducing the high-frequency errors, but also are modifying or removing true geophysical signals. Therefore, filter design focuses on the trade-off to minimize the loss of signals of interest and to maximize noise reduction in the target region (Swenson; Wahr 2011). Figure 1 shows the systematic error and random noise in estimated mass variations based on GRACE data in April 2002 (the first month of GRACE data). It shows that the errors dominate. Therefore, the signal of interest cannot be distinguished from the noise.

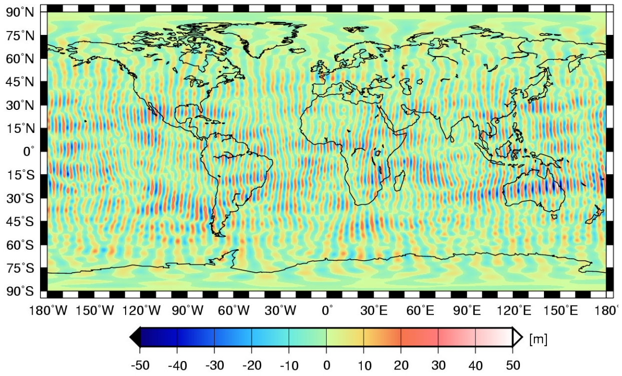

Figure 1: Estimated mass variations in terms of Equivalent Water Thicknesses relative to the mean gravity field from GRACE in April 2002.

2.1 Systematic errors

If not specially considered in post-processing GRACE products show correlated errors due to the GRACE type orbit configuration that are represented as longitudinal stripes. These products suggest a certain kind of correlations especially in the spherical harmonic order of the Stokes coefficients. It should be mentioned that significant correlations are found only for the higher orders. The striping errors can be damped by a polynomial fit to the spherical harmonic coefficients of higher orders (Swenson; Wahr 2011). Figure 2 shows the filtered spherical harmonic coefficients before and after de-striping. The coefficients are fitted (i.e. filtered) with a polynomial of degree 4 staring from order 15.

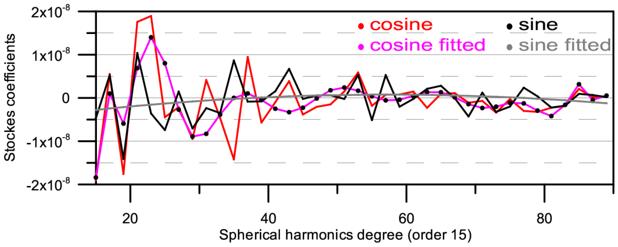

Figure 2: Cosine and sine spherical harmonic coefficients and the corresponding smoothed (de-stripped) coefficients after applying a de-striping filter (with a polynomial of degree 4, starting from order 15).

2.2 Random errors

The monthly gravity field products are affected by correlated noise at higher frequencies. Due to that short-wave noise in the GRACE products, applying an optimized spatial filter is indispensable. The correlated noise shows up in terms of striping effects in the mass variation results, when represented in a geographical plot. The striping errors are caused by the orbit design of GRACE-type configurations, incomplete reduction of non-tidal high frequencies of mass variations and limitation in the data processing of the Earth gravity field. Therefore, an effective filter has to be applied to separate signal from noise. The normalized spherical harmonic coefficients can be smoothed in many different ways (Davis et al. 2008; Jekeli 1981; Klees et al. 2008; Kusche 2007; Swenson; Wahr 2006) of which we have tested several for Siberia (Shabanloui; Müller 2015). Depending on the location of the Region Of Interest (ROI), one or more Signals Of Interest (SOI) can be related to the mass changes, which are strongly depended on the applied filter in the ROI. Therefore, the filter design plays a key role in the estimation of realistic mass variations in the target region.

Figure 3 shows the effect for mass variations in April 2015 after applying an isotropic Gaussian filter with a radius of 350 km and a de-striping filter starting from order 15 with a polynomial degree of 4. It can be seen that, after application of the Gaussian filter, some mass variations in terms of EWT, which are not detectable in Figure 1, appeared.

3 MASS VARIATION ESTIMATION

3.1 Data

We used the new released GFZ solutions from Jan. 2002 to April 2015 (144 months). In addition, due to GRACE orbit design, configuration and polar gaps, the lower degrees of the Earth's gravity field are not estimated with an acceptable accuracy. Therefore, for our processing, the zonal term $\bar{c}_{2,0}$ of the monthly gravity field coefficients is replaced by the solution from Satellite Laser Ranging observations (Cheng et al. 2013).

3.2 Estimation of hydrological mass variations

GRACE Satellite-to-Satellite Tracking (SST) observations include all gravity changes caused by variations in the atmosphere, ocean, continental hydrology, ice as well as solid Earth in the Earth system (AOHIS). The tidal and non-tidal variations in the atmosphere and ocean are removed by using current ECMWF and baroclinic ocean model in the processing of GRACE raw observations (Flechtner; Dobslaw 2014). In the reduced data, time variable gravity signals on land will be visible. These signals are related to mass transport in the Earth system. Time-variable monthly gravity solutions from GRACE consist of fully normalized spherical harmonic coefficients complete to degree and order of $n_{\max}$. The maximum degree and order of GRACE solutions are variable from different official analysis centres (ACs). It depends on the quality of the observations, processing strategies which are used in the analysis centres. For example, the most current release of GRACE solutions in 2015 are up to degree order (d/o) of 90 processed by GeoForschungsZentrum (GFZ) in Potsdam (Germany), up to d/o 60 and 90 processed by Jet Propulsion Laboratory (JPL) at Pasadena and up to d/o 96 released by Centre of Space Research (CSR) at Austin, USA (Flechtner; Dobslaw 2014; Tapley et al. 2004).

Gravity variations expressed in equivalent water thickness (EWT) can be computed as (Wahr et al. 1998):

$$EWT(\lambda,\varphi,t)=\frac{R_e\rho_e}{3\rho_w}\sum_{n=0}^{n_{\max}}\frac{2n+1}{1+k_n}\sum_{m=0}^{n}\left(\Delta\bar{c}_{nm}^{f}\cos(m\lambda)+\Delta\bar{s}_{nm}^{f}\sin(m\lambda)\right)P_{nm}(\sin\varphi). \quad (1)$$

$EWT(\lambda,\varphi,t)$ represents the mass variations relative to mean gravity field in terms of equivalent water thickness at the node position (λ,φ) at time t, R_e is the Earth's equatorial radius of the gravity model, ρ_e and ρ_w are the mean density of the Earth and fresh water, and P_{nm} are the fully normalized associated Legendre polynomials. $\Delta\bar{c}_{nm}^{f}$ and $\Delta\bar{s}_{nm}^{f}$ are the reduced Stokes' coefficients after applying the optimized filter (e.g. Gaussian filter). They indicate the deviation from mean Stokes' coefficients (as static field or mean of all time-variable coefficients) for a certain month.

Our goal of analysing GRACE products is to estimate mass variations in Siberia and relating those mass variations to Total Water Storage Changes (TWSC). Finally, we will show how uncertainties in GRACE Stokes coefficients propagate to TWSC. As a first step, mass variations expressed in EWT on the globe are estimated based on GRACE monthly solutions after applying a de-striping filter starting from order 15 with a polynomial degree of 4, and a Gaussian filter with radius 350 km as well as replacing $\bar{c}_{2,0}$ from SLR solutions. Figure 3 shows the derived mass variations relative to a mean gravity filed in EWT on the globe.

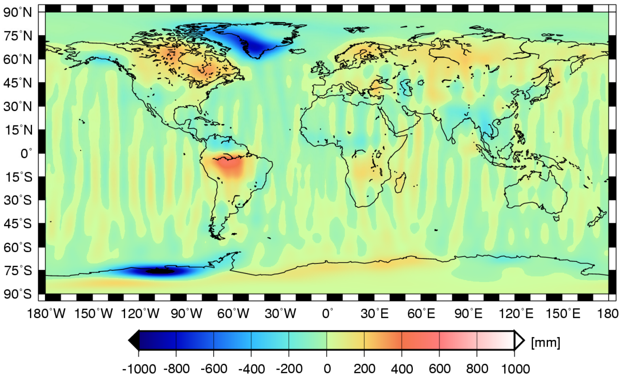

Figure 3: Mass variations in EWT in April 2015 [after applying a Gaussian filter with radius 350 km, replacing $\bar{c}_{2,0}$ with SLR solutions and using a de-striping filter with a polynomial degree of 4 starting from order 15].

3.3 Time series analysis of mass variation signals

Integral mass variations estimated from GRACE contain ice, hydrology and solid Earth changes as potential sources. Depending on the location of the ROI, one or more SOI can be related to the mass changes. For example, mass variations in the Siberian permafrost region are related to hydrological (water) variations that are only partly caused by permafrost thawing but also by precipitation and run-off variations. To estimate secular and periodical contributions, the following equation is used as (Ogawa 2010):

$$EWT(\lambda,\varphi,t)=a+bt+\sum_{f=1}^{4}\left(c_f\cos(\omega_f t)+s_f\sin(\omega_f t)\right)+\varepsilon \quad (2)$$

with mass variations expressed in $EWT(\lambda,\varphi,t)$ at the node position (λ,φ) at time t. The parameters a and b are bias and secular trend. The periodical signals are expressed in terms of cosine and sine coefficients c_f and s_f. The amplitudes c_f and s_f correspond to the angular frequency ω_f. In this study, the expansion term for the periodical signals is chosen as 4. The periods of 161 days, 1, 2.5 and 3.7 years are taken into account. Ray et al. (2003) showed that aliasing terms exist for the S_2, K_2 and K_1 tide components that result in 161-day, 3.7-year and 7.4-year periods. Contribution of K_1 is not well retrievable due to its long aliasing period and the shorter time span of available GRACE monthly solutions. It is not considered further on. Schmidt et al. (2008) found a long-periodic wave of about 2.5 years on the global scale in GRACE data and the hydrological models for the GRACE period. They also showed that the 2.5-year period is also retrievable in hydrological models for a longer period of data. Seasonal and annual (and inter-annual) mass variations are usually related to the (sub-)surface water storage changes that can be considered as the largest contribution to the temporal gravity changes (Ray et al. 2003). Noise and other un-modeled terms are characterized by ε. Eq. (2) is solved by some standard least-squares adjustment by using the variance-covariance information from error propagation of spherical harmonic coefficients on mass variations in terms of EWT. The quality of estimated secular trends and periodical terms strongly depend on the GRACE time span (interval) and the number of selected periodical terms. In other words, the modeled periodical terms should absorb all existing significant periodical signals in the (pseudo)-observations. Figure 6 shows the estimated secular trend in the permafrost region of Siberia, after applying a Gaussian filter with radius 350 km, replacing $c_{2,0}$ from SLR solutions and using a de-striping filter from order 15 with a polynomial degree of 4 in the period of 2002 – 2015. The northern part of the permafrost region shows mass decrease, where the southern part indicates mass increase for the period of 2012 – 2015.

3.4 Uncertainty in the mass variation estimation

In this section, the error propagation of spherical harmonic coefficients to the mass variations in terms of EWT is derived. The precision of EWT estimation depends on the accuracy of the spherical harmonic coefficients $\sigma_{\Delta\bar{c}^f_{nm}}$ and $\sigma_{\Delta\bar{s}^f_{nm}}$ which are available as formal or calibrated errors in the GRACE L2 products. The precision of estimated mass variations expressed in EWT can be written as:

$$\sigma_{EWT(\lambda,\varphi,t)} = \left[\sum_{n=0}^{n_{\max}}\left(\sum_{m=0}^{n}\left(\left(\frac{\partial EWT(\lambda,\varphi,t)}{\partial\Delta\bar{c}^f_{nm}}\right)^2\sigma^2_{\Delta\bar{c}^f_{nm}}+\left(\frac{\partial EWT(\lambda,\varphi,t)}{\partial\Delta\bar{s}^f_{nm}}\right)^2\sigma^2_{\Delta\bar{s}^f_{nm}}\right)\right)\right]^{1/2} \tag{3}$$

with

$$\frac{\partial EWT(\lambda,\varphi,t)}{\partial\Delta\bar{c}^f_{nm}} = \frac{R_e\rho_e}{3\rho_w}\frac{2n+1}{1+k_n}\cos(m\lambda)P_{nm}(\sin\varphi) \tag{4}$$

and

$$\frac{\partial EWT(\lambda,\varphi,t)}{\partial\Delta\bar{s}^f_{nm}} = \frac{R_e\rho_e}{3\rho_w}\frac{2n+1}{1+k_n}\sin(m\lambda)P_{nm}(\sin\varphi) \tag{5}$$

as derivative relative to cosine and sine terms of the spherical harmonic coefficients.

Figure 4 shows the propagation of GRACE monthly spherical harmonic coefficient errors on the globe. The accuracy of mass variations varies between 4-20 mm EWT. It can be seen that the propagated errors only depend on the latitude and the applied filter radius to remove high frequency uncertainties in the Stokes coefficients. Due to the GRACE orbit design, the higher latitudes of the Earth (e.g. north and south poles) are tracked by GRACE more frequently than the lower latitudes (e.g. equator). Therefore, the higher latitudes have higher spatial resolution and higher accuracy than other regions. Figure 5 represents the uncertainty estimation in the GRACE mass variations after applying a Gaussian filter with radius of 350 km in the permafrost region of Siberia. It can be seen that the accuracy of mass variations in Siberia varies between 4 and 8 mm EWT, which is approximately 60% more accurate than the equator region.

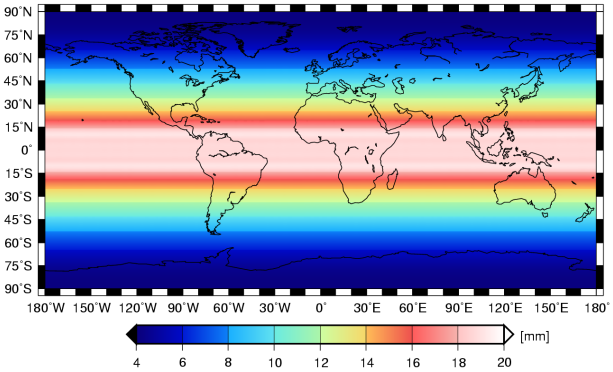

Figure 4: Global uncertainty estimation of GRACE mass variations in mm EWT after applying Gaussian filtering with a radius of 350 km.

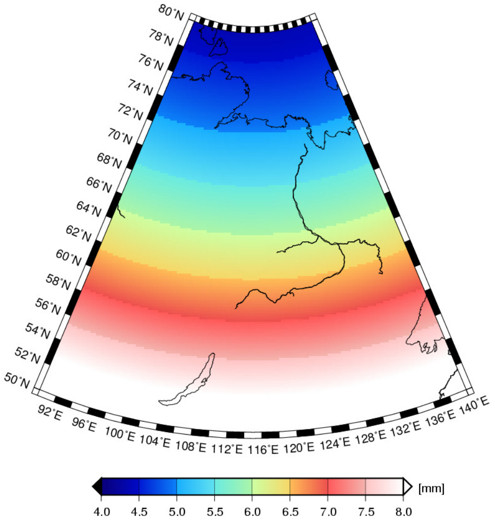

Figure 5: Uncertainty estimation of GRACE mass variations in mm EWT after applying Gaussian filtering with a radius of 350 km in the permafrost region of Siberia.

3.5 Mass variations in Siberia

After successful application of corrections due to the zonal coefficient $\bar{c}_{2,0}$, appropriate filtering based on Gaussian and de-striping filter, the mass variations expressed in EWT are computed at the nodes of an equiangular grid with $1^{\circ} \times 1^{\circ}$ taking into account the maximum degree of 90. Figure 6 shows the secular mass variations the Siberian permafrost region by applying an isotropic 1D Gaussian filter with radius 350 km for the period of 2002-2015 (144 months). The double peak features in terms of minimum and maximum surface mass variations (i.e. EWT changes) of -11 mm/a and 11 mm/a are visible in Siberia. The minimum occurs in the northern part of Siberia, where the maximum appears in the southern part of the permafrost region. The basins of Lena and Yenisei rivers clearly show mass increase. It should be mentioned that weaker smoothing (e.g. Gaussian filter with a radius of 200 km) would obviously leave an unrealistically strong variability in GRACE results. Therefore, after more testing of different filters, the Gaussian filter with the radius of 350 km seems to be an appropriate filter for this region.

To study the estimated surface mass variations in the Siberian permafrost region in more detail, the station Vilyuysk located near the Vilyuy river on the left tributary of the Lena river is selected as an example. Velicogna et al. (2012)) showed a mass increase for the whole Lena basin using the CSR solution in the period of 2002–2010. We also estimated a mass increase based on the new release of GFZ-RL05a solution for the Vilyuysk region in the period of 2002–2015. Figure 7 shows a positive secular trend (mass increase) of 5.28 mm $\pm$ 0.17 mm/a for the station Vilyuysk in the period of 2002 - 2015. But the trend is not constant. It was stronger until 2008 and is almost zero since then with some periodic variations.

If more data are available, we will test the secular trend rate to see if the acceleration of mass variations in this region can be realistically estimated for the period beyond 2015.

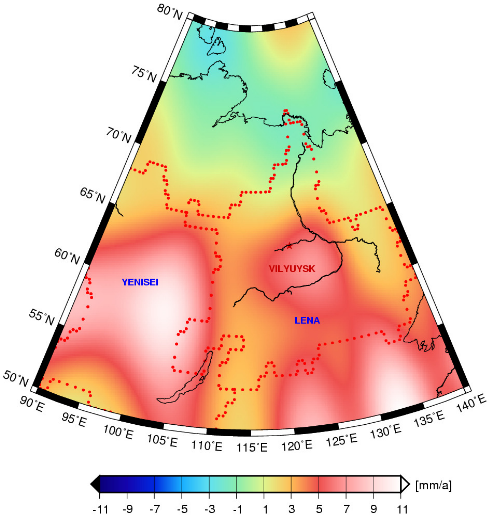

Figure 6: Secular trend estimation in the permafrost region of Siberia in the period of 2002 – 2015, after applying a Gaussian filter with radius 350 km, replacing $\bar{c}_{2,0}$ with SLR solutions and a de-striping filter with a polynomial degree of 4 starting from order 15 (Two river basins Lena and Yenisei in Siberia are indicated by red color and the station Vilyuysk is marked with a red star).

4 CONCLUSIONS

Our investigations of mass variations and their uncertainties in Siberia from GRACE products for the period of 2002-2015 mainly focused on the permafrost regime. It should be noted that removing of order-dependent correlations, high-frequency dependent filtering and replacing of the lower degree of the spherical harmonics (i.e. zonal term $\bar{c}_{2,0}$) have a significant impact on the mass variation and the error estimations. The lower latitudes are suffering more than high latitudes in terms of accuracy of estimated mass variations. In the permafrost region of Siberia, the maximum achievable accuracy based on applied Gaussian filter with the radius of 350 Km are 4 mm EWT in the northern part, and 8 mm EWT in the southern part. Therefore, in the Lena basin, mass variations (i.e. mass increases) can be estimated with an accuracy of 6 mm EWT. These uncertainties have some impact on the estimated secular trend. For the station Vilyuysk, a secular trend of 5.28 mm/a $\pm$ 0.17 mm/a was estimated for the period of 2002-2015. This mass increase may be related to permafrost thawing in the Lena basin, but hydro-climatic changes of permafrost layers in Siberia are very complex and also include non-stationary pattern changes. Therefore by increasing the time span and accuracy of GRACE observations (e.g. with the launch of GRACE follow-on in 2017) as well as the availability of more precise complementary new missions and new observations (e.g. Satellite Altimetry) and hydrological models, permafrost thawing processes in Siberia might be better determined and physically interpreted in future. Future studies of temporal mass variations should include data from further space-borne missions, e.g. satellite altimetry and satellite imagery, to constrain hydrological mass variations and to improve of signal separation in the Siberian permafrost region.

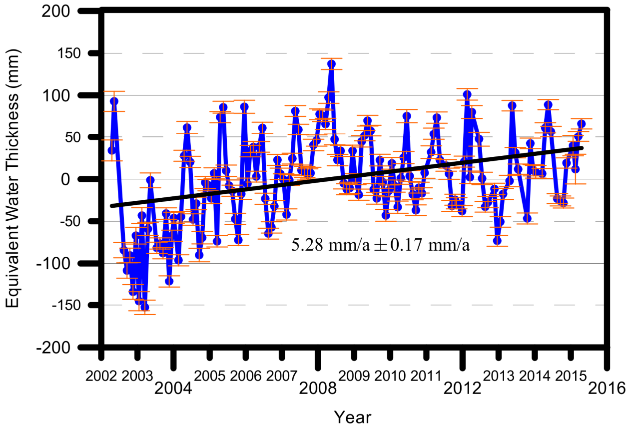

Figure 7: Hydrological mass variations in mm EWT at the Vilyuysk station for the period of 2002–2015 including uncertainty estimation [after applying a Gaussian filter with a radius of 350 km, applying a de-striping filter with a

polynomial degree of 4 starting from order 15 and replacing $\overline{c}_{2,0}$ with SLR solutions].

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REFERENCES

Cheng, M., B. D. Tapley, and J. C. Ries, 2013: Deceleration in the Earth's oblateness. Journal of Geophysical Research: Solid Earth, 118, 740-747.

Davis, J. L., M. E. Tamisiea, P. Elósegui, J. X. Mitrovica, and E. M. Hill, 2008: A statistical filtering approach for Gravity Recovery and Climate Experiment (GRACE) gravity data. Journal of Geophysical Research: Solid Earth, 113.

Döll, P., M. Fritsche, A. Eicker, and H. Müller Schmied, 2014: Seasonal Water Storage Variations as Impacted by Water Abstractions: Comparing the Output of a Global Hydrological Model with GRACE and GPS Observations. Surv Geophys, 35, 1311-1331.

Flechtner, F., and H. Dobslaw, cited GRACE 327-750 (GR-GFZ-AOD-0001): AOD1B product description document for product release 05 (Rev. 4.2, May 20, 2014)

Jekeli, C., 1981: Alternative Methods to Smooth the Earth's Gravity Field. Ohio State University, Department of Geodetic Science and Surveying.

Klees, R., E. A. Revtova, B. C. Gunter, P. Ditmar, E. Oudman, H. C. Winsemius, and H. H. G. Savenije, 2008: The design of an optimal filter for monthly GRACE gravity models. Geophysical Journal International, 175, 417-432.

Kusche, J. r., 2007: Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type gravity field models. Journal of Geodesy, 81, 733-749.

Ogawa, R., 2010: Transient, seasonal and inter-annual gravity changes from GRACE data: Geophysical modelings, Dept. Natural History Sciences, Graduate School of Science, Hokkaido University.

Ray, R. D., D. D. Rowlands, and G. D. Egbert, 2003: Tidal Models in a New Era of Satellite Gravimetry. Space Science Reviews, 108, 271-282.

Rodell, M., I. Velicogna, and J. S. Famiglietti, 2009: Satellite-based estimates of groundwater depletion in India. Nature, 460, 999-1002.

Shabanloui, A., and J. Müller, 2015: Mass variations in the Siberian permafrost region based on new GRACE results and auxiliary modeling. Interntial Associate Geodesy Symposia, Accepted.

Swenson, S., and J. Wahr, 2006: Post-processing removal of correlated errors in GRACE data. Geophysical Research Letters, 33, L08402.

Swenson, S. C., and J. M. Wahr, 2011: Estimating signal loss in regularized GRACE gravity field solutions. Geophysical Journal International, 185, 693-702.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber, 2004: The gravity recovery and climate experiment: Mission overview and early results. Geophysical Research Letters, 31, L09607.

Velicogna, I., and J. Wahr, 2013: Time-variable gravity observations of ice sheet mass balance: Precision and limitations of the GRACE satellite data. Geophysical Research Letters, 40, 3055-3063.

Velicogna, I., J. Tong, T. Zhang, and J. S. Kimball, 2012: Increasing subsurface water storage in discontinuous permafrost areas of the Lena River basin, Eurasia, detected from GRACE. Geophysical Research Letters, 39.

Wahr, J., M. Molenaar, and F. Bryan, 1998: Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. Journal of Geophysical Research: Solid Earth, 103, 30205-30229.

Wahr, J., S. Swenson, and I. Velicogna, 2006: Accuracy of GRACE mass estimates. Geophysical Research Letters, 33, L06401.