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Increasing subsurface water storage in discontinuous permafrost areas of the Lena River basin, Eurasia, detected from GRACE

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[1] We use monthly measurements of time-variable gravity from the GRACE (Gravity Recovery and Climate Experiment) satellite mission to quantify changes in terrestrial water storage (TWS) in the Lena river basin, Eurasia, during the period April 2002 to September 2010. We estimate a TWS increase of 32 ± 10 km^3/yr for the entire basin, equivalent to an increase in water thickness of 1.3 ± 0.4 cm/yr over a basin of 2.4 million km^2. We compare TWS estimates from GRACE with time series of precipitation (P) minus evapotranspiration (ET) from ERA-Interim reanalysis minus observational river discharge (R). We find an excellent agreement in annual and inter-annual variability between the two time series. Furthermore, we find that a bias of $-20 \pm 10\%$ in P-ET is sufficient to effectively close the water budget with GRACE. When we account for this bias, the time series of cumulative TWS from GRACE and climatological data agree to within ±3.8 cm of water thickness, or ±9% of the mean annual P. The TWS increase is not uniform across the river basin and exhibits a peak, over an area of 502,400 km^2, centered at 118.5°E, 62.5°N, and underlain by discontinuous permafrost. In this region, we attribute the observed TWS increase of 68 ± 19 km^3 to an increase in subsurface water storage. This large subsurface water signal will have a significant impact on the terrestrial hydrology of the region, including increased baseflow and alteration of seasonal runoff. **Citation:** 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, *Geophys. Res. Lett.*, *39*, L09403, doi:10.1029/2012GL051623.

1. Introduction

[2] Recent studies show substantial changes in the Arctic terrestrial hydrological system [e.g., *Rawlins et al.*, 2010]. Most of these analyses have focused on precipitation (P), evapotranspiration (ET), and river discharge (R) [*Serreze et al.*, 2002, 2006; *White et al.*, 2007; *Rawlins et al.*, 2010]. Comparatively less attention has been paid to terrestrial water storage (TWS), which is calculated as a residual of these other water balance components. Changes in the Arctic terrestrial water cycle, especially the storage component, alter soil moisture and thermal regimes, and thus affect plant communities and land-atmosphere water, energy and trace gas exchanges, with potentially large climate feedbacks. Recent warming over northern land areas has altered regional atmosphere circulation and precipitation patterns, deepening the soil active layer and destabilizing the upper permafrost layers [*Zhang et al.*, 2005].

[3] In this study, we directly address the issue of changes in TWS using time-variable gravity data from the GRACE mission. We focus our analysis on the Lena river basin, Eurasia, a region of about 2,400,000 km^2 in size. Most of the Lena river basin is underlained by permafrost: about 79% with continuous permafrost, and the remainder with discontinuous permafrost [*Zhang et al.*, 2005]. Previous studies using GRACE data have revealed an increase in TWS in the Lena basin [*Muskett and Romanovsky*, 2009; *Troy et al.*, 2011] and found a qualitative agreement between TWS estimated using GRACE and ancillary climatological data [*Landerer et al.*, 2010]. Here, we present a more detailed, quantitative analysis and attribution of these changes in the water budget. We examine if the GRACE data can be used to estimate the bias in net precipitation (P-ET) from reanalysis output, and quantify the agreement between TWS from GRACE versus TWS from climatological data and observational river discharge. We discuss the spatial patterns of TWS revealed by GRACE, determine the partitioning of the sources of the change in TWS and their impact on the hydrological cycle.

2. Data and Methodology

[4] We use 99 monthly GRACE gravity field solutions, in the form of spherical harmonic coefficients, generated at the Center for Space Research at the University of Texas between April 2002 and September 2010 [*Tapley et al.*, 2004]. Each solution consists of spherical harmonic (Stokes) coefficients up to degree 60. GRACE does not recover degree-1 coefficients. We calculate these coefficients by combining GRACE data with ocean model output as in *Swenson et al.* [2008]. We replace the GRACE C_{20} coefficients with values derived from satellite laser ranging [*Cheng and Tapley*, 2004]. The GRACE data directly reveal anomalies in TWS, because this is the largest source of mass change within our area of interest; other mass changes such as glacial isostatic adjustment (GIA) are of much lower magnitude. TWS anomalies are calculated relative to the period August 2002–August 2009, which is the longest period common to all observations used in our analysis. To reduce the influence of seasonal variability on the long-term trend, we apply a 13-month moving average to the monthly

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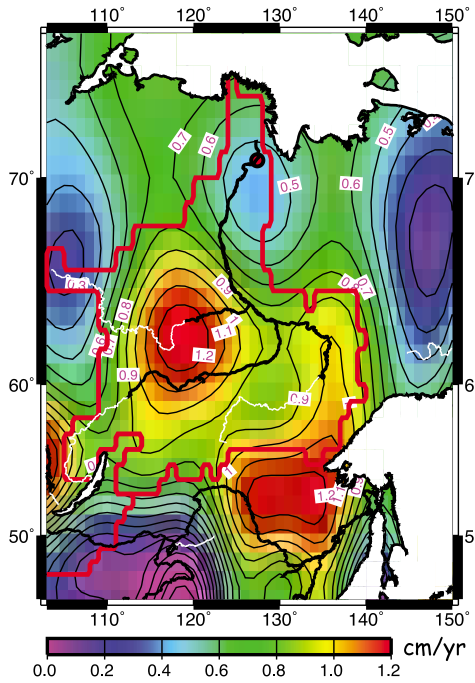

Figure 1. Rate of change of Terrestrial Water Storage (TWS), in cm/yr of water thickness, determined from GRACE data for April 2002–September 2010. River basin boundaries (red line) and river gauge location (red circle) are shown.

Stokes coefficients. This yields a smoothed time series where seasonal variations are reduced. We simultaneously fit an annual, a semiannual, and a linear trend to the smoothed Stokes coefficient time series. To reduce the random error component, which increases as a function of decreasing wavelength, we smooth the data using a Gaussian filter with a 350 km radius [*Wahr et al.*, 1998]. To isolate the TWS signal, the GRACE data are corrected for the GIA signal following *Paulson et al.* [2007]. The correction is less than 2% of the GRACE signal. We then generate an evenly spaced latitude-longitude grid. The trend in TWS is shown in Figure 1.

[5] GRACE Stokes coefficients can be used to estimate water storage variations averaged over a specific region by constructing an averaging function optimized for the region. To calculate monthly TWS averaged over the Lena basin we construct an averaging kernel convolving a 250 km half-width Gaussian function with the basin mask (1 inside the basin and 0 outside) and we apply the kernel to the GRACE data. Because the signal we are interested in recovering is not uniform across the region boundaries and across the basin, the choice of the kernel is critical. We construct various kernels corresponding to Gaussian functions of different halfwidth (from 300 km to 0 km). We discard the kernels that produce an uneven sampling of the basin. For each of the remaining kernels, we calculate a scaling factor and a mass estimate error. The scaling factor is calculated assuming a synthetic mass change equal to the GLDAS-NOAH model TWS trend [*Rodell et al.*, 2004] over the study region, processing it in the same manner as the GRACE data, i.e., converting it to the spectral domain, truncating it to degree 60 and spatially averaging it using the averaging kernel, and comparing the retrieved signal with the original synthetic. Uncertainties in the Stokes coefficients are determined by assuming that the scatter of the monthly values about their seasonal cycle is due entirely to errors [*Wahr et al.*, 2006]. This represents the upper bound on the random component of the error. The 1-σ error estimates in the spatially averaged GRACE time series are then calculated from the uncertainty in the individual Stokes coefficients. We choose the kernel that produces the smallest mass error and the most uniform sampling of the basin. The corresponding scaling factor is 1.3, and the mass errors for the averaged monthly TWS and for the trend are ±22 km^3 and ±6 km^3/yr, respectively. Figure 2 shows the rescaled monthly averaged TWS anomalies.

[6] Errors in the GRACE TWS signal are a combination of errors in the GRACE gravity fields, leakage from other geophysical sources and procedure errors. The uncertainty caused by leakage from outside the region is estimated by applying our solution process to the GRACE signal, after first removing our best-fitting monthly estimates for the Lena, and then fitting a trend to the residual [*Tiwari et al.*, 2009]. We calculate the total uncertainty in the GRACE TWS as the root-sum-square of errors in the GRACE gravity field solutions, GIA correction, leakage, averaging process and fit errors.

[7] The increase in TWS (Figure 1) exhibits a strong anomaly near the center of the basin at 118.5°E and 62.5°N, in a region 502,400 km^2 in size, and characterized by discontinuous permafrost; hereafter referred to as the Lena subregion. To calculate the monthly TWS averaged over this subregion, we generate an averaging kernel following the procedure described above. We define a mask for the subregion (1 inside a region corresponding to a 400 km disc centered at 118.5°E and 62.5°N and 0 outside), and we select an exact (radius = 0-km) averaging function, i.e., no Gaussian averaging, as it samples the subregion uniformly and we find that GRACE measurements errors are not significantly larger in the case of $R = 0$ compared to $R > 0$. Note that truncation to degree 60 produces some smoothing of the signal, even in the case of $R = 0$. For this kernel we estimate a scaling factor of 1.15. In this case, because the TWS is

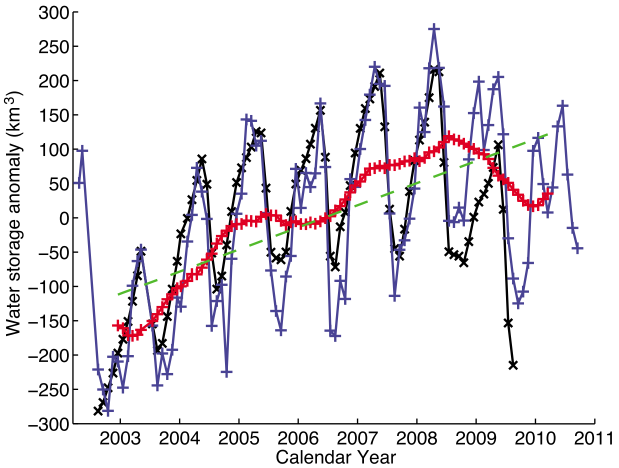

Figure 2. Time series of terrestrial water storage (TWS) changes for the Lena basin from GRACE monthly mass solutions (blue crosses) and from accumulated P-ET-R from ERA-interim reanalysis and river discharge data (black crosses). GRACE data filtered for seasonal dependence are denoted as red crosses; the best fit linear trend for the GRACE time series is shown as a green line.

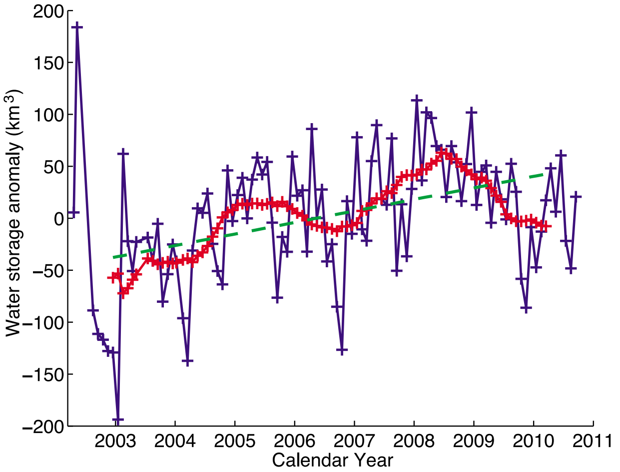

Figure 3. Time series of GRACE terrestrial water storage (TWS) changes for the Lena subregion. Unfiltered data are denoted as blue crosses. Data filtered for seasonal dependence are denoted red crosses. The best-fitting trend is shown as a green line.

uniform across the region, the scaling factor is calculated by applying the averaging function to a uniform 1-cm water mass change spread evenly over the subregion. We evaluate the uncertainty in the scaling factor associated to the spatial distribution of the mass change within the subregion by calculating the sensitivity to different mass distributions. We find an uncertainty of 1% which we include in our final error budget. Figure 3 shows the resulting monthly spatially averaged TWS anomalies for the Lena subregion.

[8] Independently, we estimate monthly TWS changes for the Lena basin from climatological data, i.e., P-ET-R. We use ERA-Interim forecast monthly P and ET [e.g., *Simmons et al.*, 2007] and monthly R data for the Lena river gauge at Kusur (station Code: 3821, Lat/Lon: 70.68°N/127.39°E) located at the Lena river delta [*Lammers et al.*, 2001]. Discharge data are available only through August 2009. Estimated errors in river discharge range from 3 to 8% [*Shiklomanov et al.*, 2006]; here we assume a conservative error of 10%. For P-ET, we use an error estimate of 25% based on previous studies [*Serreze et al.*, 2006; *Rawlins et al.*, 2010]. The climatological data are processed in the same manner as the GRACE data, i.e., converted to the spectral domain, truncated to degree 60, and spatially averaged.

3. Results

[9] We calculate a TWS gain of 32 ± 10 km^3/yr for the Lena basin from December 2002 to March 2010, which is equivalent to an average water thickness of 1.3 ± 0.4 cm/yr. The mean annual P-ET from ERA-Interim is 19.2 cm for the basin. In the Lena subregion, the GRACE data reveal a TWS gain of 11 ± 6 km^3/yr (2.2 ± 1.2 cm/yr equivalent water thickness) and a cumulative storage increase of 80 ± 16 km^3 (16 ± 3 cm equivalent water thickness) over the entire study period.

[10] We estimate the component of the TWS change in Lena subregion. The TWS change estimated from GRACE includes mass contributions from groundwater, soil water, surface water (lakes), snow, ice, and vegetation biomass. The vegetation biomass signal has been shown to be well below the detection limits of GRACE [*Rodell et al.*, 2005], so biomass is not a factor here, especially in the case of the Lena basin which is dominated by tundra. To estimate the TWS contribution from snow cover changes, we use 25 km EASE-Grid monthly snow water equivalent (SWE) data from the Advanced Microwave Scanning Radiometer on EOS Aqua (AMSR-E) (http://nsidc.org/data/amsre/) [*Derksen et al.*, 2003]. The retrieval accuracy for SWE from satellite passive microwave sensors, including AMSR-E, is generally higher for flatter regions with less vegetation cover. This is the case of the Lena subregion which is relatively flat and largely covered by tundra. We estimate that changes in snow mass represent only 10% of the total TWS increase in the Lena during the entire 7-year period (i.e., 1 km^3/yr, or 7 km^3 for the entire period). This result is similar to station observation based cold season precipitation trends for the region [*Rawlins et al.*, 2009]. If we remove the SWE contribution from the GRACE TWS estimates, we obtain an adjusted storage trend of 10 ± 7 km^3/yr for the Lena subregion. We assume a conservative estimate of SWE error of 1 km^3/yr, or 100%.

[11] We estimate the TWS signal leakage from outside the subregion to be 5 km^3 for the entire analyzed period. After correction for leakage, we obtain an adjusted TWS trend of 9 ± 7 km^3/yr (1.8 ± 1 cm/yr) and total storage increase of 68 ± 19 km^3 (13.6 ± 3.8 cm) for the 7-year period for the subregion.

[12] We estimate an upper bound of lake water storage contribution using increasing surface inundation trends for the Lena subregion detected from the satellite microwave (AMSR-E) remote sensing record. We calculate the total increase in land fractional cover of open water during summer (JJA) non-frozen conditions using a global daily land parameter record from AMSR-E from 2002 to 2008 [*Jones and Kimball*, 2010]. In the Lena subregion, the AMSR-E record shows an average inundation increase of 0.02% per year that corresponds to a total increase in inundated area of 600 km^2 for the 7-year period. Even assuming a 5 m depth increase in water storage over the 600 km^2 region (this represents an upper bound for the increase in lake storage given the flat terrain of the Lena basin), the entire inundated area should only account for 3 km^3 of the observed 68 km^3, or 5% of the observed signal. We conclude that the GRACE-derived positive TWS trend is largely due to an increase in soil and groundwater storage, which we denote hereafter as subsurface water storage.

[13] Turning to the TWS from climatological data, we may assume that discharge (R) observations from gauges are unbiased [*Shiklomanov et al.*, 2006]. On the other hand, there is an unknown bias in P-ET from reanalysis that is difficult to estimate [*Serreze et al.*, 2006]. A bias in P-ET represents an offset in the P-ET time series but an offset and a trend in the cumulative time series. If we do not remove the bias, it is not possible to compare the trend of the accumulated TWS from P-ET-R and GRACE. Hence we compare the de-trended time series of monthly TWS from GRACE and accumulated P-ET-R, and we find that they agree to within ±19% and ±14% with and without accounting for the autocorrelation, respectively. Both time series show strong seasonal variability which coincides in phase but the P-ET-R signal has a smaller amplitude.

[14] We have high confidence that the GRACE-derived TWS is not affected by residual bias because we remove all biases in our analysis. If we assume conservation of water mass, we may estimate the average annual bias in P-ET that

best matches TWS from GRACE plus R. We find an average annual bias of −4.5 ± 2.4 cm of water for the entire basin, or −20 ± 10% of the average annual P-ET. This value is within the error bounds in P-ET from the reanalysis data and agrees in magnitude and sign with an independent estimate from *Serreze et al.* [2006].

[15] Figure 2 shows the time series of accumulated P-ET-R corrected for the bias. The data agree to within ±1.9 cm of equivalent water thickness with GRACE when we account for auto-correlation. When we account for all sources of error, we effectively close the water budget to within ±9% of the mean annual precipitation (∼47 cm).

4. Discussion

[16] GRACE measurements of time-variable gravity reveal a TWS increase of 32 ± 10 km^3/yr in the Lena basin during the period April 2002–September 2010. Previous studies using GRACE data showed evidence of a TWS increase for the Lena basin but did not quantify the magnitude of TWS increase [*Landerer et al.*, 2010; *Troy et al.*, 2011; *Sahoo et al.*, 2011] and did not account for bias effects or leakage from surrounding regions on the GRACE water storage signal [*Muskett and Romanovsky*, 2009]. Here, we quantify the TWS increase for the Lena and find a strong agreement between independent storage trends derived from GRACE and climatological data.

[17] Several studies have identified biases in P-ET from re-analysis data [*Serreze et al.*, 2006; *Simmons et al.*, 2007]. Due to sparse ground observations and regional water budget uncertainties, it is difficult to estimate the bias. Here, we estimate this bias using GRACE data, assuming that the bias is constant over the period of record and applying water mass conservation. In reality, the bias may be time dependent [*Serreze et al.*, 2006; *Landerer et al.*, 2010], but this is beyond the scope of the paper. Here, our goal is to close the regional water budget over 7 years.

[18] Previous analysis by *Sahoo et al.* [2011] reports water budget closure for the Lena basin to within ±25% of the mean annual precipitation, with the uncertainty attributed mainly to P and storage terms from GRACE. The authors used monthly GRACE TWS gridded data averaged with a 750 km gaussian smoothing, but did not correct for the bias in the GRACE data caused by smoothing and leakage. Here, we correct for GRACE errors and for the bias in P-ET to close the regional water budget to within ±9% of the mean annual precipitation, i.e., an error reduction by a factor 3.

[19] The observed TWS increase for the Lena subregion is twice as large as in the rest of the basin and is associated with an increase in subsurface water storage of 9 ± 7 km^3/yr (1.8 ± 1 cm/yr) and cumulative storage increase of 13.6 ± 3.8 cm from December 2002 to March 2010. We have no measurement of the groundwater table within the active layer in that region. We estimate that a potential 10 cm rise of the groundwater table toward the surface corresponds to an average groundwater storage increase of 2.4 cm in the Lena subregion, assuming a specific yield of 0.24 typical of tundra soils [*Johnson*, 1967]. A 56 cm rise in the groundwater table from 2002 through 2010 would be required to account for the subsurface water storage increase measured by GRACE. An increase in the active layer thickness (ALT) may also increase groundwater storage in this subregion. *Zhang et al.* [2005] analyzed regional soil temperature measurements and estimated a mean ALT of 1.9 m, and ranging from 1.2 to 2.9 m for the Lena basin; they also identified a 31 ± 9 cm increase in mean ALT from 1956–1990. Since the 1990s, air temperatures over Siberia have increased significantly so the ALT should have increased at an even greater rate than for previous decades. The relatively conservative 1956–1990 trend would produce an ALT increase of 8 cm for the 7-year study period. An 8 cm decrease in ground water level over the same period represents 1.9 cm of potential additional soil water storage averaged over the region, but would account for only 14% of the TWS change detected by GRACE. However, much of the upper permafrost layer is generally ice rich [*Brown et al.*, 1997]. When the active layer thickens, meltwater from ground ice near the permafrost table keeps the newly thawed layer saturated and leaves little or no room for lowering the groundwater table within the active layer, resulting in little or no change in ground water storage. Therefore, we conclude that changes in ALT have relatively little impact on the observed TWS change.

[20] Over the Lena subregion, the fractional area of discontinuous permafrost ranges from 30 to 40%, with non-permafrost areas covering from 15,000 to 100,500 km^2. In non-permafrost areas, surface water can easily infiltrate into groundwater at a rate of 10 to 70 cm/yr. *Ye et al.* [2004] find that the ratio of maximum to minimum monthly discharge has decreased from 1937 through 2000 in the upper Lena river basin, concurrent with the Lena subregion. They also find that the recession coefficient, the ratio of monthly discharge in April to monthly discharge in December, during cold seasons increased over the same period. These results imply that more surface water is infiltrating as groundwater and increasing base flows; they also speculate that regional permafrost degradation plays an important role in these changes.

[21] Subsurface water storage that remains within the active layer and is accessible to vegetation will strongly impact terrestrial water, energy and carbon cycle processes under a warming climate by providing additional moisture for ET (latent energy flux) and plant growth. These changes are consistent with positive vegetation growth and ET trends for the Lena basin as derived from the global satellite record [*Zhang et al.*, 2008]. However, the net effect of these changes on regional soil carbon stocks will depend upon sub-grid scale variability in surface soil moisture conditions, which are strongly interactive with local terrain and permafrost.

[22] Besides representing a significant change in terrestrial hydrology, the overall positive trend in TWS is consistent with increasing precipitation trends and intensification of the Arctic freshwater cycle with climate warming [*White et al.*, 2007; *Rawlins et al.*, 2010].

5. Conclusion

[23] This study quantifies the increase in TWS in the Lena river basin during a 7-year period using a rigorous analysis of GRACE data. We find that TWS increases twice as rapidly as in the rest of the basin in an area of discontinuous permafrost near the center of the basin. We attribute most of this observed change in TWS to an increase in subsurface water storage. The estimated TWS increase in the Lena subregion implies an average increase in the groundwater table of 56 ± 9 cm or groundwater recharging through areas not underlain by permafrost, while changes in active layer

thickness likely have little impact. We also estimate the bias in P-ET using GRACE data to close the water budget. After correcting for this bias, the TWS change from GRACE is largely explained by an increase in P-ET. Our approach to evaluate the bias in P-ET can be applied to other river basins and provide important feedback on the accuracy of reanalysis products.

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