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1 Increasing subsurface water storage in discontinuous permafrost 2 areas of the Lena River basin, Eurasia, detected from GRACE

3 I. Velicogna,^{1,2} J. Tong,¹ T. Zhang,^{3,4} and J. S. Kimball⁵

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5 [1] We use monthly measurements of time-variable gravity
6 from the GRACE (Gravity Recovery and Climate Experi-
7 ment) satellite mission to quantify changes in terrestrial
8 water storage (TWS) in the Lena river basin, Eurasia, during
9 the period April 2002 to September 2010. We estimate a
10 TWS increase of $32 \pm 10 \text{ km}^3/\text{yr}$ for the entire basin, equiv-
11 alent to an increase in water thickness of $1.3 \pm 0.4 \text{ cm/yr}$
12 over a basin of 2.4 million km^2 . We compare TWS estimates
13 from GRACE with time series of precipitation (P) minus
14 evapotranspiration (ET) from ERA-Interim reanalysis minus
15 observational river discharge (R). We find an excellent
16 agreement in annual and inter-annual variability between the
17 two time series. Furthermore, we find that a bias of $-20 \pm 10\%$
18 in P-ET is sufficient to effectively close the water budget with
19 GRACE. When we account for this bias, the time series of
20 cumulative TWS from GRACE and climatological data agree
21 to within $\pm 3.8 \text{ cm}$ of water thickness, or $\pm 9\%$ of the mean
22 annual P. The TWS increase is not uniform across the river
23 basin and exhibits a peak, over an area of 502,400 km^2 ,
24 centered at 118.5°E, 62.5°N, and underlain by discontinuous
25 permafrost. In this region, we attribute the observed TWS
26 increase of $68 \pm 19 \text{ km}^3$ to an increase in subsurface water
27 storage. This large subsurface water signal will have a sig-
28 nificant impact on the terrestrial hydrology of the region,
29 including increased baseflow and alteration of seasonal run-
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34 1. Introduction

35 [2] Recent studies show substantial changes in the Arctic
36 terrestrial hydrological system [e.g., *Rawlins et al.*, 2010].
37 Most of these analyses have focused on precipitation (P),
38 evapotranspiration (ET), and river discharge (R) [*Serreze*
39 *et al.*, 2002, 2006; *White et al.*, 2007; *Rawlins et al.*, 2010].

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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 ter-
restrial 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 underlain by permafrost: about 79%
with continuous permafrost, and the remainder with dis-
continuous 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 reanal-
ysis output, and quantify the agreement between TWS from
GRACE versus TWS from climatological data and obser-
vational 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 coeffi-
cients. 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

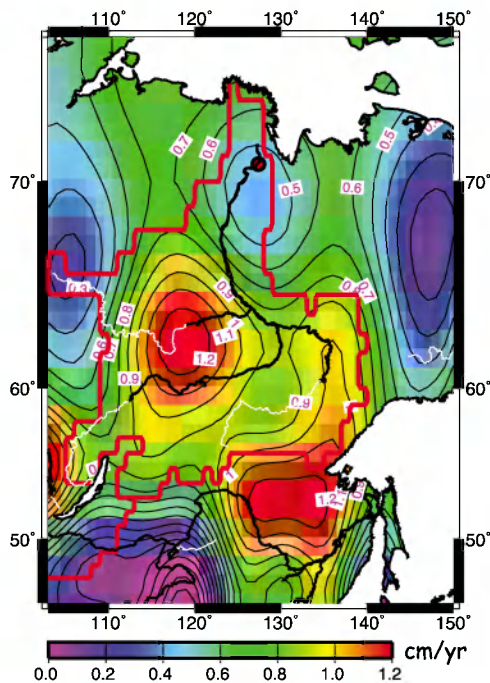


Figure 1. Rate of change of Terrestrial Water Storage (TWS), in cm/yr of water thickness, determined from GRACE data for April 2002–September 2010. River basin boundaries (red line) and river gauge location (red circle) are shown.

91 Stokes coefficients. This yields a smoothed time series where
 92 seasonal variations are reduced. We simultaneously fit an
 93 annual, a semiannual, and a linear trend to the smoothed
 94 Stokes coefficient time series. To reduce the random error
 95 component, which increases as a function of decreasing
 96 wavelength, we smooth the data using a Gaussian filter with a
 97 350 km radius [Wahr et al., 1998]. To isolate the TWS signal,
 98 the GRACE data are corrected for the GIA signal following
 99 Paulson et al. [2007]. The correction is less than 2% of the
 100 GRACE signal. We then generate an evenly spaced latitude-
 101 longitude grid. The trend in TWS is shown in Figure 1.

102 [5] GRACE Stokes coefficients can be used to estimate
 103 water storage variations averaged over a specific region by
 104 constructing an averaging function optimized for the region.
 105 To calculate monthly TWS averaged over the Lena basin we
 106 construct an averaging kernel convolving a 250 km half-
 107 width Gaussian function with the basin mask (1 inside the
 108 basin and 0 outside) and we apply the kernel to the GRACE
 109 data. Because the signal we are interested in recovering is
 110 not uniform across the region boundaries and across the
 111 basin, the choice of the kernel is critical. We construct var-
 112 ious kernels corresponding to Gaussian functions of differ-
 113 ent halfwidth (from 300 km to 0 km). We discard the kernels
 114 that produce an uneven sampling of the basin. For each of
 115 the remaining kernels, we calculate a scaling factor and a
 116 mass estimate error. The scaling factor is calculated assum-
 117 ing a synthetic mass change equal to the GLDAS-NOAH
 118 model TWS trend [Rodell et al., 2004] over the study region,
 119 processing it in the same manner as the GRACE data, i.e.,
 120 converting it to the spectral domain, truncating it to degree
 121 60 and spatially averaging it using the averaging kernel, and
 122 comparing the retrieved signal with the original synthetic.
 123 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 $\pm 22 \text{ km}^3$ and $\pm 6 \text{ km}^3/\text{yr}$, 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 $502,400 \text{ km}^2$ in size, and characterized by dis-
 continuous 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 sub-
 region (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 sig-
 nificantly 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

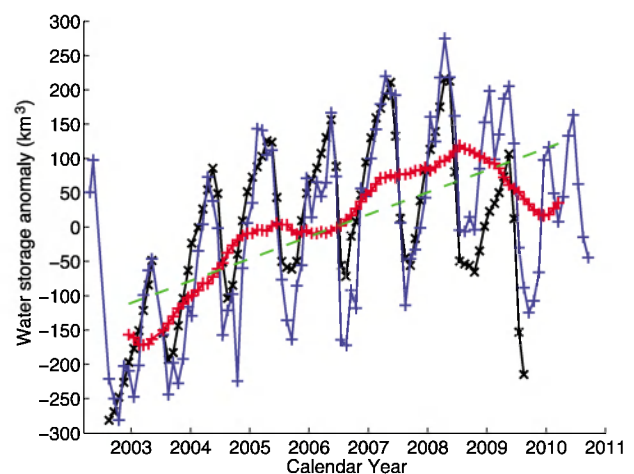


Figure 2. Time series of terrestrial water storage (TWS) changes for the Lena basin from GRACE monthly mass solutions (blue crosses) and from accumulated P-ET-R from ERA-interim reanalysis and river discharge data (black crosses). GRACE data filtered for seasonal dependence are denoted as red crosses;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

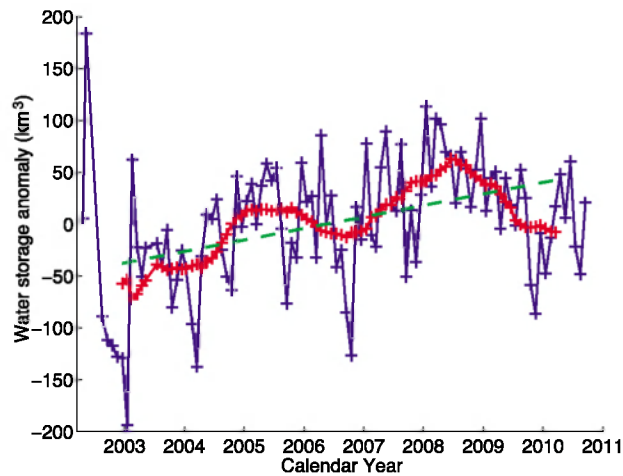


Figure 3. Time series of GRACE terrestrial water storage (TWS) changes for the Lena subregion. Unfiltered data are denoted as blue crosses. Data filtered for seasonal dependence are denoted red crosses. The best-fitting trend is shown as a green line.

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

171 [8] Independently, we estimate monthly TWS changes for
 172 the Lena basin from climatological data, i.e., P-ET-R. We use
 173 ERA-Interim forecast monthly P and ET [e.g., *Simmons*
 174 *et al.*, 2007] and monthly R data for the Lena river gauge at
 175 Kusun (station Code: 3821, Lat/Lon: 70.68°N/127.39°E)
 176 located at the Lena river delta [*Lammers et al.*, 2001]. Dis-
 177 charge data are available only through August 2009. Esti-
 178 mated errors in river discharge range from 3 to 8%
 179 [*Shiklomanov et al.*, 2006]; here we assume a conservative
 180 error of 10%. For P-ET, we use an error estimate of 25%
 181 based on previous studies [*Serreze et al.*, 2006; *Rawlins et al.*,
 182 2010]. The climatological data are processed in the same
 183 manner as the GRACE data, i.e., converted to the spectral
 184 domain, truncated to degree 60, and spatially averaged.

185 3. Results

186 [9] We calculate a TWS gain of $32 \pm 10 \text{ km}^3/\text{yr}$ for the Lena
 187 basin from December 2002 to March 2010, which is equiva-
 188 lent to an average water thickness of $1.3 \pm 0.4 \text{ cm}/\text{yr}$. The
 189 mean annual P-ET from ERA-Interim is 19.2 cm for the basin.
 190 In the Lena subregion, the GRACE data reveal a TWS gain of
 191 $11 \pm 6 \text{ km}^3/\text{yr}$ ($2.2 \pm 1.2 \text{ cm}/\text{yr}$ equivalent water thickness)
 192 and a cumulative storage increase of $80 \pm 16 \text{ km}^3$ ($16 \pm 3 \text{ cm}$
 193 equivalent water thickness) over the entire study period.

194 [10] We estimate the component of the TWS change in
 195 Lena subregion. The TWS change estimated from GRACE
 196 includes mass contributions from groundwater, soil water,
 197 surface water (lakes), snow, ice, and vegetation biomass.
 198 The vegetation biomass signal has been shown to be well
 199 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., $1 \text{ km}^3/\text{yr}$, 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 $10 \pm 7 \text{ km}^3/\text{yr}$ for the Lena subregion. We assume a con-
 servative estimate of SWE error of $1 \text{ km}^3/\text{yr}$, 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
 $9 \pm 7 \text{ km}^3/\text{yr}$ ($1.8 \pm 1 \text{ cm}/\text{yr}$) and total storage increase of
 $68 \pm 19 \text{ km}^3$ ($13.6 \pm 3.8 \text{ cm}$) 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 sum-
 mer (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 accumu-
 lated 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 $\pm 19\%$ and $\pm 14\%$ 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

263 best matches TWS from GRACE plus R. We find an average
264 annual bias of -4.5 ± 2.4 cm of water for the entire basin, or
265 $-20 \pm 10\%$ of the average annual P-ET. This value is within
266 the error bounds in P-ET from the reanalysis data and agrees
267 in magnitude and sign with an independent estimate from
268 *Serreze et al.* [2006].

269 [15] Figure 2 shows the time series of accumulated P-ET-R
270 corrected for the bias. The data agree to within ± 1.9 cm of
271 equivalent water thickness with GRACE when we account
272 for auto-correlation. When we account for all sources of
273 error, we effectively close the water budget to within $\pm 9\%$
274 of the mean annual precipitation (~ 47 cm).

275 4. Discussion

276 [16] GRACE measurements of time-variable gravity
277 reveal a TWS increase of 32 ± 10 km³/yr in the Lena basin
278 during the period April 2002–September 2010. Previous
279 studies using GRACE data showed evidence of a TWS
280 increase for the Lena basin but did not quantify the magni-
281 tude of TWS increase [*Landerer et al.*, 2010; *Troy et al.*,
282 2011; *Sahoo et al.*, 2011] and did not account for bias
283 effects or leakage from surrounding regions on the GRACE
284 water storage signal [*Muskett and Romanovsky*, 2009]. Here,
285 we quantify the TWS increase for the Lena and find a strong
286 agreement between independent storage trends derived from
287 GRACE and climatological data.

288 [17] Several studies have identified biases in P-ET from
289 re-analysis data [*Serreze et al.*, 2006; *Simmons et al.*, 2007].
290 Due to sparse ground observations and regional water bud-
291 get uncertainties, it is difficult to estimate the bias. Here, we
292 estimate this bias using GRACE data, assuming that the bias
293 is constant over the period of record and applying water
294 mass conservation. In reality, the bias may be time depen-
295 dent [*Serreze et al.*, 2006; *Landerer et al.*, 2010], but this is
296 beyond the scope of the paper. Here, our goal is to close the
297 regional water budget over 7 years.

298 [18] Previous analysis by *Sahoo et al.* [2011] reports water
299 budget closure for the Lena basin to within $\pm 25\%$ of the
300 mean annual precipitation, with the uncertainty attributed
301 mainly to P and storage terms from GRACE. The authors
302 used monthly GRACE TWS gridded data averaged with a
303 750 km gaussian smoothing, but did not correct for the bias
304 in the GRACE data caused by smoothing and leakage. Here,
305 we correct for GRACE errors and for the bias in P-ET to
306 close the regional water budget to within $\pm 9\%$ of the mean
307 annual precipitation, i.e., an error reduction by a factor 3.

308 [19] The observed TWS increase for the Lena subregion is
309 twice as large as in the rest of the basin and is associated
310 with an increase in subsurface water storage of 9 ± 7 km³/yr
311 (1.8 ± 1 cm/yr) and cumulative storage increase of $13.6 \pm$
312 3.8 cm from December 2002 to March 2010. We have no
313 measurement of the groundwater table within the active
314 layer in that region. We estimate that a potential 10 cm rise
315 of the groundwater table toward the surface corresponds to
316 an average groundwater storage increase of 2.4 cm in the
317 Lena subregion, assuming a specific yield of 0.24 typical of
318 tundra soils [*Johnson*, 1967]. A 56 cm rise in the ground-
319 water table from 2002 through 2010 would be required to
320 account for the subsurface water storage increase measured
321 by GRACE. An increase in the active layer thickness (ALT)
322 may also increase groundwater storage in this subregion.
323 *Zhang et al.* [2005] analyzed regional soil temperature

measurements and estimated a mean ALT of 1.9 m, and 324
ranging from 1.2 to 2.9 m for the Lena basin; they also 325
identified a 31 ± 9 cm increase in mean ALT from 1956– 326
1990. Since the 1990s, air temperatures over Siberia have 327
increased significantly so the ALT should have increased at 328
an even greater rate than for previous decades. The relatively 329
conservative 1956–1990 trend would produce an ALT 330
increase of 8 cm for the 7-year study period. An 8 cm 331
decrease in ground water level over the same period repre- 332
sents 1.9 cm of potential additional soil water storage aver- 333
aged over the region, but would account for only 14% of the 334
TWS change detected by GRACE. However, much of the 335
upper permafrost layer is generally ice rich [*Brown et al.*, 336
1997]. When the active layer thickens, meltwater from 337
ground ice near the permafrost table keeps the newly thawed 338
layer saturated and leaves little or no room for lowering the 339
groundwater table within the active layer, resulting in little 340
or no change in ground water storage. Therefore, we con- 341
clude that changes in ALT have relatively little impact on 342
the observed TWS change. 343

[20] Over the Lena subregion, the fractional area of dis- 344
continuous permafrost ranges from 30 to 40%, with non- 345
permafrost areas covering from 15,000 to 100,500 km². In 346
non-permafrost areas, surface water can easily infiltrate into 347
groundwater at a rate of 10 to 70 cm/yr. *Ye et al.* [2004] find 348
that the ratio of maximum to minimum monthly discharge has 349
decreased from 1937 through 2000 in the upper Lena river 350
basin, concurrent with the Lena subregion. They also find that 351
the recession coefficient, the ratio of monthly discharge in 352
April to monthly discharge in December, during cold seasons 353
increased over the same period. These results imply that more 354
surface water is infiltrating as groundwater and increasing base 355
flows; they also speculate that regional permafrost degradation 356
plays an important role in these changes. 357

[21] Subsurface water storage that remains within the 358
active layer and is accessible to vegetation will strongly 359
impact terrestrial water, energy and carbon cycle processes 360
under a warming climate by providing additional moisture 361
for ET (latent energy flux) and plant growth. These changes 362
are consistent with positive vegetation growth and ET trends 363
for the Lena basin as derived from the global satellite record 364
[*Zhang et al.*, 2008]. However, the net effect of these changes 365
on regional soil carbon stocks will depend upon sub-grid 366
scale variability in surface soil moisture conditions, which 367
are strongly interactive with local terrain and permafrost. 368

[22] Besides representing a significant change in terrestrial 369
hydrology, the overall positive trend in TWS is consistent 370
with increasing precipitation trends and intensification of the 371
Arctic freshwater cycle with climate warming [*White et al.*, 372
2007; *Rawlins et al.*, 2010]. 373

374 5. Conclusion

[23] This study quantifies the increase in TWS in the Lena 375
river basin during a 7-year period using a rigorous analysis 376
of GRACE data. We find that TWS increases twice as rap- 377
idly as in the rest of the basin in an area of discontinuous 378
permafrost near the center of the basin. We attribute most of 379
this observed change in TWS to an increase in subsurface 380
water storage. The estimated TWS increase in the Lena 381
subregion implies an average increase in the groundwater 382
table of 56 ± 9 cm or groundwater recharging through areas 383
not underlain by permafrost, while changes in active layer 384

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

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