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Satellite gravimetry-based analysis of terrestrial water storage and its relationship with run-off from the Lena River in eastern Siberia

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ABSTRACT
We used 146 months of data from the Gravity Recovery and Climate Experiment (GRACE) spanning the period from April 2002 to August 2015 to analyse terrestrial water storage (TWS) in the Lena River basin. We examined the lag correlation between TWS values and the annual run-off from the Lena River and found a strong linear relationship between a given year's river run-off and the TWS during November of the previous year. This relationship persisted throughout the winter until the following May. We also found a negative trend in TWS in the downstream portion of the Lena River basin, which might be explained by increasing evapotranspiration associated with warming summer air temperatures. A better understanding of the Arctic freshwater cycle will require additional GRACE data and river run-off data.

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1. Introduction

The Arctic freshwater budget is a critical component of understanding climate, water cycling, and ocean circulation in the Arctic. The greatest contribution to the Arctic Ocean's freshwater input (approximately 38%) is terrestrial river inflow (Serreze et al. 2006). Over the past century, there has been an increase in freshwater river run-off from the six largest Eurasian rivers into the Arctic Ocean (Peterson et al. 2002).

The Lena River basin is the second largest source of freshwater inflow from rivers into the Arctic Ocean. Hydrological studies in cold regions have shown that terrestrial water storage (TWS) strongly affects the amount of river flow from a basin (Quinton, Hayashi, and Pietroniro 2003; Papa, Prigent, and Rossow 2008; Hood and Hayashi 2015). Therefore, it is important to evaluate the variability of the TWS. Velicogna et al. (2012) reported that Gravity Recovery and Climate Experiment (GRACE) data showed that TWS increased throughout the Lena River basin from 2002 to 2010, primarily because of rising groundwater levels in the discontinuous permafrost zone. In contrast, Vey et al. (2013)

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did not detect any significant trends in TWS in the Lena River basin after extending their study to 2011.

In the Lena River basin, most of the subsurface is covered by continuous permafrost. As it freezes, the soil preserves the imprints of climatic conditions throughout the winter (Suzuki et al. 2006; Matsumura and Yamazaki 2012; Suzuki 2013; Oshima, Tachibana, and Hiyama 2015). Despite these previous studies, it remains unclear how the TWS in a given year affects the following year's river run-off in the large, permafrost-dominated Lena River basin.

In this study, we extended the analysis of TWS anomalies in the Lena River basin to August 2015. Next, using a multi-model ensemble of reanalysed data from the Global Land Data Assimilation System (GLDAS), we characterized the TWS system with respect to various forcing variables, river run-off, and factors that cause variations in TWS. Finally, we investigated the causes of regional TWS trends in the Lena River basin.

2. Data and methods

2.1 *Study site*

Figure 1(*a*) shows a map of the Lena River basin in eastern Siberia in the Russian Federation. The one-degree basin map was provided by Hatta et al. (2009). The Lena River basin has an area of approximately 2,430,000 km^2. The Kusur hydrological station is located at 70.70°N, 127.65°E, near the mouth of the river. Most of the Lena River basin is covered by continuous permafrost and deciduous larch vegetation. However, the downstream and mountainous regions have tundra vegetation. In this study, we used a selected region in the basin to examine regional trends in TWS; the region is indicated by a blue box in Figure 1(*a*). Region 1 (68.5–71°N, 120–130°E) is an area that has exhibited a markedly decreasing trend in TWS. According to our analysis, the maximum error was approximately 1 mm year^{-1}. Therefore, the trend in Figure 1(*b*) was detectable.

2.2 *GRACE and forcing data*

We used GRACE data (Level 2, Release 5) from GeoForschungZentrum Potsdam (GFZ), Germany, consisting of 146 monthly data sets collected between April 2002 and August 2015 and spanning 13 Northern Hemisphere winters. GRACE data were unavailable for the following 14 months: June 2002, July 2002, June 2003, January 2011, June 2011, May 2012, March 2013, August 2013, September 2013, February 2014, July 2014, December 2014, May 2015, and June 2015. Each solution in these data sets included the coefficients of spherical harmonics (Stokes coefficient) at the maximum degree and an order of 90.

Here, the degree-1 and zonal degree-2 coefficients, which represent the geocentric motion and dynamic oblateness of the Earth, respectively, were replaced with coefficients measured by satellite laser ranging (SLR) because these components are not well constrained by GRACE (Cheng and Tapley 2004; Cheng, Ries, and Tapley 2012). GRACE data are known to be affected by short-wavelength noise that arises from aliasing errors and therefore must be suppressed using filtering techniques. In this study, the DDK-3 decorrelation filter proposed by Kusche et al. (2009) was applied to the GRACE data.

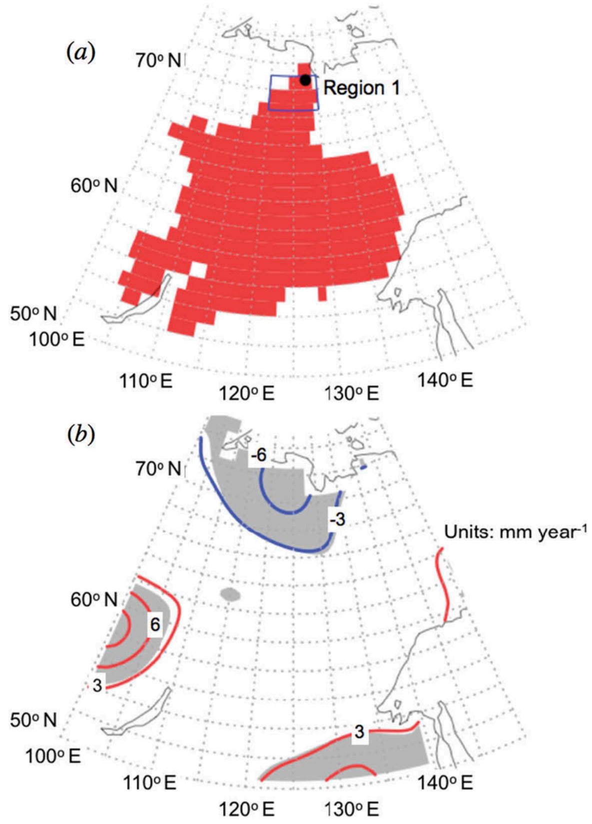

Figure 1. (*a*) Map of the Lena River basin. The blue box denotes Region 1 and the black circle indicates the location of the Kusur station. (*b*) The trend in TWS in the Lena River basin from April 2002 to March 2014. The red and blue lines indicate increasing and decreasing TWS trends (mm year^{-1}), respectively, as detected by GRACE. The area shaded in grey denotes a statistically significant area (at the 95% confidence level) in the TWS anomaly trend.

Subsequently, we converted the GRACE data into surface mass variations, using the methods presented by Wahr, Molenaar, and Bryan (1998). A degree-1 load Love number (k_1) of 0.021 was used to convert the GRACE reference (centre of mass) frame into the centre of figure frame to make the data consistent with GLDAS (Swenson, Chambers, and Wahr 2008). Atmospheric and oceanic mass variations were removed during processing of the original GRACE data. We corrected for the effects of glacial isostatic adjustment (GIA), using the model proposed by Geruo, Wahr, and Zhong (2013), which contributes less than 2% of the GRACE signal for the target region (Velicogna et al. 2012). Accordingly, the surface mass variations obtained reflected the TWS, including surface and subsurface water. When computing TWS from the GRACE data, the long-term mean of the Stokes coefficient was removed from each monthly solution. Thus, the TWS value that we obtained was an anomalous value from the static field. Hereafter, we refer to the TWS anomaly as the TWS.

In addition to the GRACE data, we also used GLDAS version 1 products (Rodell et al. 2004). Matsuo and Heki (2012) have reported that although the spatial patterns of the two data sets are roughly consistent, there are small differences in magnitude between the TWS observed by GRACE and estimated by GLDAS over the target region. Thus, we used the GLDAS products to corroborate our interpretation of the TWS variations. In this study, to examine the uncertainty in the GLDAS products, we used a multi-model ensemble of GLDAS products that consisted of four different land-surface models. The four land-surface models were the Noah Land Surface Model (Koren et al. 1999), the Community Land Model (CLM) (Dai et al. 2003), the Valuable Infiltration Capacity (VIC) Model (Liang et al. 1994), and the MOSAIC Land Surface Model (Koster and Suarez 1996). Each product has a monthly time step and a resolution of 1.0° × 1.0° degrees. The TWS derived from the multi-model GLDAS ensemble was defined as the GLDAS-based TWS. Its ensemble spread (standard deviation) can be considered to be a measure of the uncertainty of the land-surface models in GLDAS. A Gaussian filter with a radius of 240 km, which corresponds to the smoothing characteristics of the DDK-3 filter, was applied to the GLDAS data to adjust it to the same spatial resolution as the GRACE data.

We used R-ArcticNET data from the Arctic-RIMS database of the University of New Hampshire (Shiklomanov et al. 2012). This database included daily discharge data from the 1930s to 2009. We used monthly averaged data from the Kusur station at the mouth of the Lena River basin.

2.3 *Theory*

To evaluate the monthly variation in the TWS anomaly in the Lena River basin, we used the water balance equation, which is expressed as follows:

$$\Delta\mathrm{TWS} = P - E - R = (\Delta\mathrm{SWE}) + (\Delta\mathrm{SM}) + (\Delta\mathrm{CW}) + (\Delta\mathrm{GW}) + (\Delta\mathrm{SW}), \tag{1}$$

where P is the monthly precipitation (mm month^{-1}), E is the monthly evapotranspiration (mm month^{-1}), R is the monthly river run-off from the basin (mm month^{-1}), ΔSWE is the change in snow water equivalent (mm month^{-1}), ΔSM is the change in vertical accumulated soil moisture within the total soil layer (mm month^{-1}), ΔCW is the change in the total amount of water within the canopy (mm month^{-1}), ΔGW is the change in groundwater or ice within the permafrost (mm month^{-1}), and ΔSW is the change in surface waterbodies (such as lakes and wetlands; mm month^{-1}). The TWS determined by GRACE includes all the components in equation (1). In contrast, the TWS determined from GLDAS includes only ΔSWE, ΔSM, and ΔCW; because ΔCW is a minor factor, the TWS determined from GLDAS depends primarily on ΔSWE and ΔSM. Hereafter, we refer to the TWS values determined from GRACE and GLDAS as $\mathrm{TWS_{GRACE}}$ and $\mathrm{TWS_{GLDAS}}$, respectively.

3. Results

3.1 *Temporal and spatial variations*

Figure 2(*a*) shows the temporal variations in the basin-averaged monthly TWS anomalies determined by GRACE and GLDAS. The GRACE- and GLDAS-based TWS results were highly correlated (r = 0.71, p < 0.0001). The correlation coefficient r indicates the strength of the linear relationship between $\mathrm{TWS_{GRACE}}$ and $\mathrm{TWS_{GLDAS}}$; the coefficient of

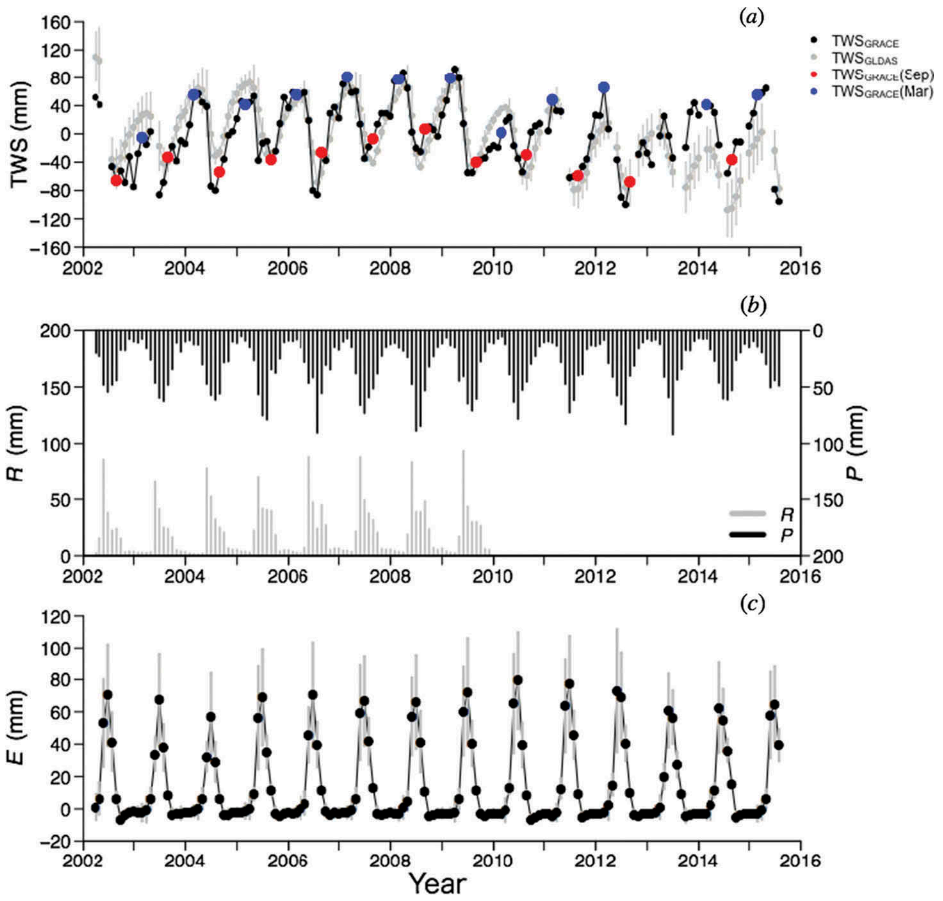

Figure 2. (*a*) Temporal variations in TWS in the Lena River basin. Black and grey circles denote TWS_{GRACE} and TWS_{GLDAS}, respectively, and red and blue circles denote the GRACE-based TWS in September (TWS_{GRACE}(Sep)) and March (TWS_{GRACE}(Mar)), respectively. Vertical grey bars indicate the standard deviation of the multi-model GLDAS ensemble. (*b*) Temporal variations in the monthly Lena River run-off (*R*) at Kusur station and the basin-averaged monthly precipitation (*P*). (*c*) Temporal variations in the monthly evapotranspiration (*E*), shown with the standard deviation of the multi-model GLDAS ensemble.

determination R^2 (here, $R^2 = 0.50$) indicates the degree to which the variation could be explained by a linear model. Based on the high correlation between the two TWS data sets, we were able to calculate a TWS change of approximately 50% at the basin scale using GLDAS, thus allowing us to determine the primary factor controlling the changes in TWS_{GRACE}. The similarity between the two data sets implies that, similar to TWS_{GLDAS}, TWS_{GRACE} also largely depends on SWE and SM.

We tested how the surface and subsurface water storage during the previous autumn affected the winter TWS. To accomplish this, we defined the autumn water storage during September of the preceding year as TWS_{GRACE}(Sep) and the winter water storage in March of a given year as TWS_{GRACE}(Mar). Figure 2(*a*) shows the temporal variations in TWS_{GRACE}(Sep) and TWS_{GRACE}(Mar). TWS_{GRACE}(Sep) values exhibited similar behaviour to TWS_{GRACE}(Mar) values of the following year. The correlation coefficient *r* was 0.641, with a 97% degree of confidence. Thus, we found that surface and subsurface water storage during the autumn, as indicated by $\mathrm{TWS}_{\mathrm{GRACE}}$(Sep), explained approximately 41% ($R^2 = 0.41$) of the variability in $\mathrm{TWS}_{\mathrm{GRACE}}$(Mar) of the following year. The influence of autumn TWS from the preceding year was discernible despite the inclusion of the snow water equivalent over the land. Thus, we suggest that autumn conditions persisted into the winter in a frozen state below the snowpack.

Figure 2(*b*) shows the temporal variations in the monthly basin-averaged precipitation and river run-off from the Kusur station. The maximum monthly precipitation in July corresponded to the minimum TWS, as shown in Figure 2(*a*). The maximum river run-off occurred in June, just one month ahead of the minimum observed TWS values. The mean river run-off during the period of snowmelt (April to June) was approximately 40% of the annual river run-off, and the peak snowmelt run-off was the highest during this period. As shown in Figure 2(*b*), there was no correlation between the precipitation and river run-off.

Figure 1(*b*) shows the linear trend of $\mathrm{TWS}_{\mathrm{GRACE}}$ in the Lena River basin. The grey-shaded area denotes a statistically significant area (at the 95% confidence level) in the trend of the TWS anomalies. Our results indicate significant negative trends downstream of the Lena River basin and at the coast along the Arctic Ocean.

Despite the negative trend in the downstream part of the Lena River basin, the basin-averaged $\mathrm{TWS}_{\mathrm{GRACE}}$ in Figure 2(*a*) did not exhibit any clear trend, as reported previously (Vey et al. 2013), because of the decrease in TWS after 2009. To explain this trend, we examined the monthly basin-averaged evapotranspiration (Figure 2(*c*)). The evapotranspiration from June to August (JJA) in 2009 was over 12 mm greater than the 14 year average. Similarly, evapotranspiration in the subsequent three years was over 20 mm greater than the 14 year average. Consistently with these higher evapotranspiration levels, GRACE(Sep) decreased steadily from 2010 to 2012. This suggests that increased summer evapotranspiration from 2009 to 2012 caused a decrease in TWS in the Lena River basin beginning in 2010. The TWS did not exhibit an overall trend from 2002 to 2015, as shown in Figure 2(*a*).

3.2 *Relation to Lena River run-off*

Following previous work, our analysis focused on the hypothesis that the conditions during autumn and winter would affect river run-off in the following year (Suzuki et al. 2006). For each month, we tested the correlation between monthly TWS values from July of the previous year to June of the current year and the annual river run-off by using data from 2002 to 2009 (as shown in the schematic diagram in Figure 3(*a*)). Over these 8 years of data (2002–2009), we examined the monthly correlation coefficient (r) by using the relationship between the TWS for each month from July to December and the annual river run-off in the subsequent year, as well as between the TWS for each month from January to June and the annual river run-off in the same year.

Figure 3(*b*) shows the seasonal variations in the monthly r from July of the previous year to June of the current year. The r increases during September and was statistically significant from November of the previous year to May of the current year. The maximum r corresponded to the TWS from January to February.

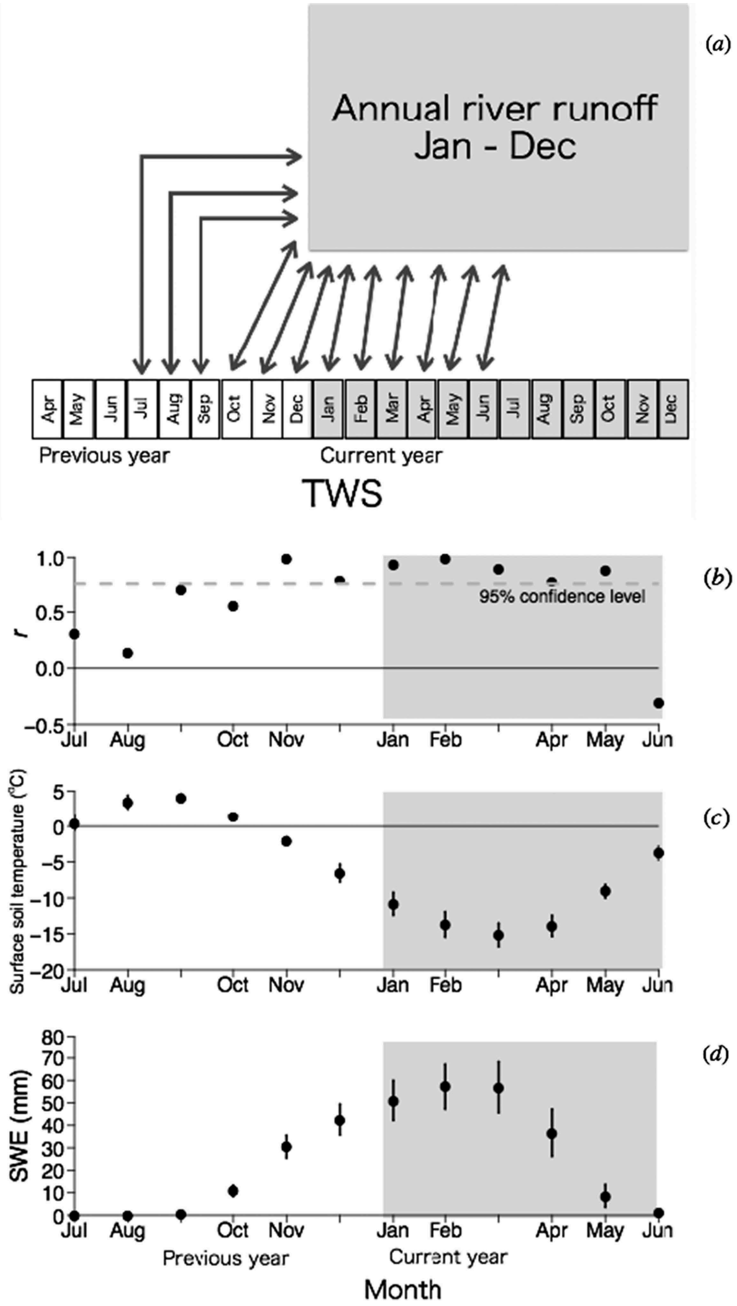

Figure 3. (*a*) Schematic diagram of the correlation between monthly TWS and annual Lena River run-off. (*b*) Seasonal variations in the monthly correlation coefficients, *r*, for different time-lagged TWS anomalies. Dashed grey lines indicate the 95% confidence level. (*c*) Temporal variations in climatological surface soil temperatures (from 0 to 0.1 m in depth) from 2002 to 2015, according to the GLDAS Noah model. (*d*) Temporal variations in climatological SWE from 2002 to 2015, according to the GLDAS Noah model. Vertical black bars denote the standard deviation of the inter-annual variations from 2002 to 2015.

Figure 3(*c*) and (d) shows the seasonal variations in the average surface soil temperature at a depth of 0–0.1 m and the SWE from 2002 to 2015; these data were from the GLDAS Noah model, which outputs the surface soil temperature at this depth. Immediately after *r* began to become statistically significant during November, the surface soil temperature dropped below 0°C, and the soil was frozen over the entire river basin. Subsequently, *r* remained statistically significant until May of the following year, when the SWE term disappeared. This period encompasses the time during the autumn when the soil surface begins to freeze until the time during the following spring when the snow cover disappears.

These results suggest that conditions during the previous autumn and winter affect river run-off and that the time lag can be attributed to snowmelt infiltration into the frozen ground, as noted by Suzuki et al. (2006). This means that autumn TWS serves as a climatic record of the Lena River run-off in a given year.

4. Discussion

4.1 *Regional changes in TWS*

Figure 1(*b*) shows a strong negative trend in $\mathrm{TWS}_{\mathrm{GRACE}}$ in the areas downstream of the Lena River basin and near the coast along the Arctic Ocean. To explain this trend, we selected a location in Region 1 where $\mathrm{TWS}_{\mathrm{GRACE}}$ decreased (–6 mm year^{-1}), as shown in Figure 1(*b*). We determined the mean annual $\mathrm{TWS}_{\mathrm{GRACE}}$ (Figure 4(*a*)) and then examined various factors that might affect the annual $\mathrm{TWS}_{\mathrm{GRACE}}$ trend in the region; Figure 4(*b*) and (*c*) shows the evapotranspiration (E) and net precipitation (P-E), respectively, from 2003 to 2014. E increased steadily from 2003 to 2014 with a slope of approximately 4 mm year^{-1}, which was significant at the 96% confidence level. This increase in E explains most of the decrease in $\mathrm{TWS}_{\mathrm{GRACE}}$ shown in Figure 4 (*a*). In addition, the coefficient of determination (R^2) between E and $\mathrm{TWS}_{\mathrm{GRACE}}$ was approximately 0.37, which indicates that E can explain 37% of the variations in $\mathrm{TWS}_{\mathrm{GRACE}}$. The positive trend in E meant that there was also a negative trend in net precipitation (P-E; R^2 = 0.46). Although precipitation (P) decreased slightly from 2003 to 2014, the trend in P was not statistically significant. Thus, evapotranspiration was the primary factor controlling the net precipitation. In addition, the mean summer air temperatures in the region during JJA from GLDAS products increased by approximately 0.36°C year^{-1} (Figure 4(*d*)).

We next considered the factors that might influence the increase in evapotranspiration in Region 1. Figure 5(*a*) plots evapotranspiration (E) against JJA air temperatures in the region. The clear relationship between these variables suggested that summer air temperatures affect evapotranspiration in the downstream reaches of the Lena River. Most evapotranspiration occurs during JJA and high air temperatures increase the saturation water vapour pressure and thus increase the water vapour deficit. Figure 5 (*b*) shows a negative linear relationship between the annual mean $\mathrm{TWS}_{\mathrm{GRACE}}$ and JJA air temperatures in the region. Therefore, our results suggest that recent summer warming reduced TWS in the high Arctic near the Lena River basin.

We conclude that the increase in E in the downstream reaches of the Lena River basin is the primary cause of the decrease in TWS from 2002 to 2015. This positive trend in E is

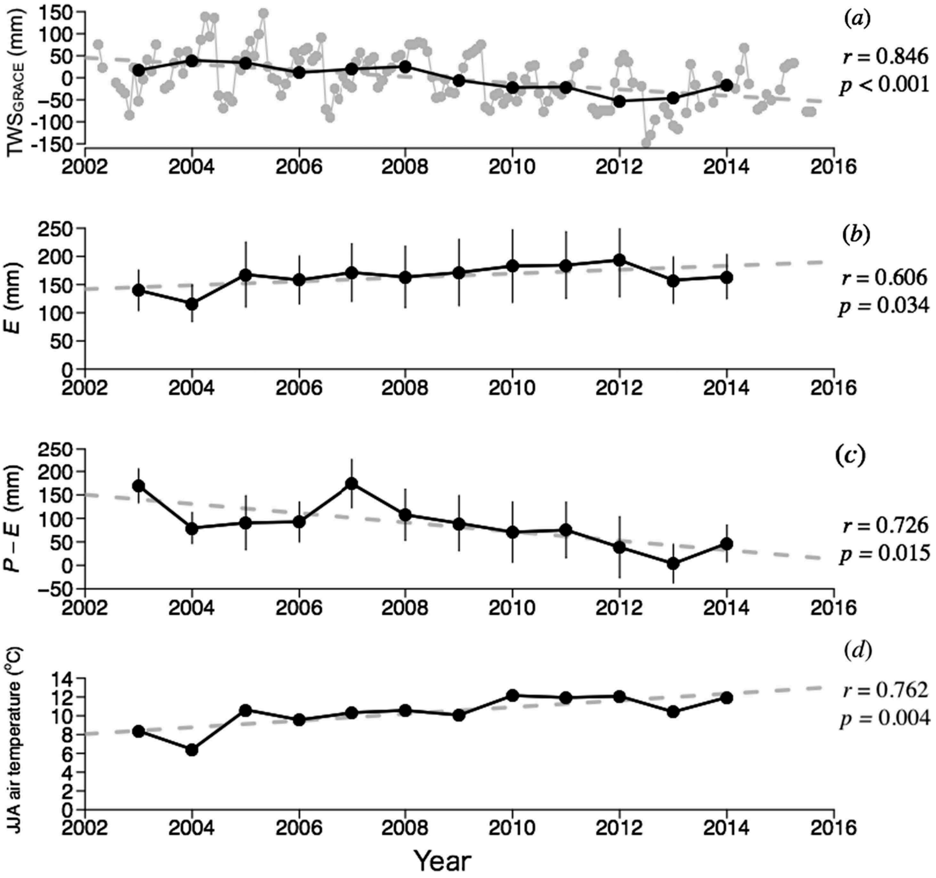

Figure 4. Temporal variations in TWS_{GRACE}, evapotranspiration (E), net precipitation (*P-E*), and the mean summer air temperature from June to August (JJA) in Region 1: (*a*) TWS_{GRACE}, (*b*) *E*, (*c*) *P-E*, and (*d*) JJA air temperature. Black and grey circles denote the annual and monthly values, respectively, and vertical bars indicate the standard deviation of the multi-model GLDAS ensemble. Dashed grey lines indicate linear regression lines for each variable, and *r* and *p* indicate the correlation coefficient and *p*-value, respectively, of each linear regression line.

associated with an increase in summer air temperatures, suggesting that future warming might further decrease TWS at high latitudes in the Lena River basin.

4.2 *The effect of permafrost thaw*

We finally considered the effect of permafrost thaw on TWS and on river run-off. Brutsaert and Hiyama (2012) have proposed a method to relate low river flows during the open water season with the rate of change of the active layer depth resulting from permafrost thaw in the upstream reaches of the Lena River basin. They have found that since the 1990s, the active layer depth has grown at an average rate of 2 cm year^{-1}. However, the discharge of water from thawed permafrost might be minor; McClelland (2004) has shown that long-term variations in river discharge are not significant in areas with continuous permafrost such as the Lena River basin. On the other hand, we note

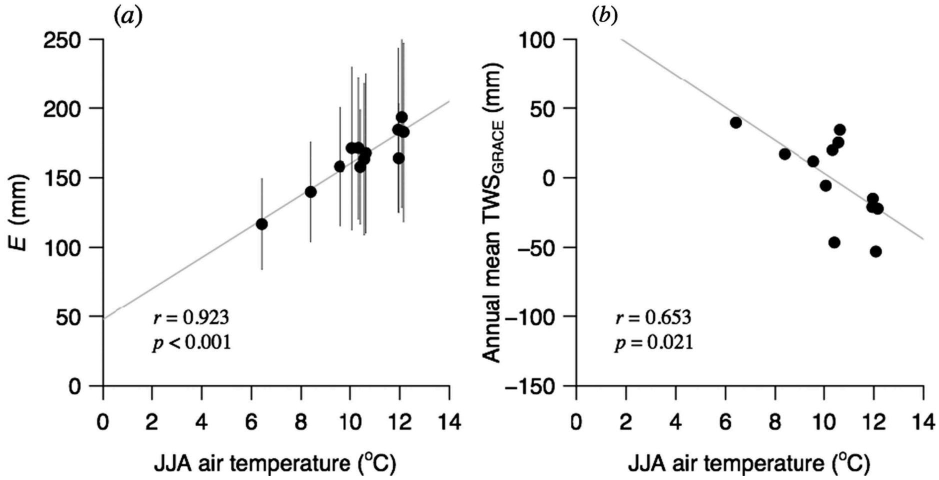

Figure 5. (*a*) Plot of evapotranspiration (*E*) versus the mean summer air temperature in Region 1 from June to August (JJA) from GLDAS products. Vertical black bars denote the standard deviation of the multi-model GLDAS ensemble. (*b*) Plot of annual mean $\text{TWS}_{\text{GRACE}}$ versus the mean summer air temperature in Region 1 from June to August (JJA) from GLDAS products. Grey lines are linear regression lines, and *r* and *p* indicate the correlation coefficient and *p*-value, respectively, of each linear regression line.

that a thicker active layer can hold much more water than a frozen layer. Vey et al. (2013) have analysed changes in TWS within the active layer (from a depth of 0.1 m to 1.1 m) in Yakutsk, using *in situ* data collected by Iijima et al. (2010); they have found that TWS increased by approximately 5 mm between 2002 and 2010 and that the TWS within the active layer increased by approximately 0.6 mm year^{-1}. Thus, in our analysis, we considered the effects of permafrost thaw on regional trends in TWS to be small. Despite the lack of permafrost in the GLDAS-based TWS, we suggest that the data will be helpful in interpreting variations in the GRACE-derived TWS.

5. Conclusions

We present a record of TWS in the Lena River basin from April 2002 to August 2015, extending the results of previous studies. Using a multi-model ensemble of reanalysed data from GLDAS, we found that the TWS levels during autumn had an effect that persisted through the winter until the following year. Comparing monthly TWS values and the annual run-off of the Lena River, we found a clear linear correlation from November of one year to May of the following year.

There was a negative trend in TWS in the downstream reaches of the Lena River basin, which primarily depended on evapotranspiration. The coefficient of determination indicates that 37% of the variation in regional TWS can be explained by a linear function of the variation in evapotranspiration. In turn, summer air temperatures control evapotranspiration because most evapotranspiration occurs during JJA. Further warming during the summer at high latitudes in the Lena River basin might enhance the already substantial reduction in TWS in the area.

Given the availability of Lena River run-off data, our analysis of the relationship between river run-off and TWS anomalies was limited to the period from 2002 to 2009. Further improving the understanding of the Arctic freshwater cycle will require additional data from GRACE and regarding river run-off.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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