REVIEW

Inter-annual water mass variations from GRACE in central Siberia

Sibylle Vey · Holger Steffen · Jürgen Müller · Julia Boike

Abstract Our study analyses satellite and land-based observations of the Yakutsk region centred at the Lena watershed, an area characterised mainly by continuous permafrost. Using monthly solutions of the Gravity Recovery And Climate Experiment satellite mission, we detect a mass increase over central Siberia from 2002 to 2007 which reverses into a mass decrease between 2007 and 2011. No significant mass trend is visible for the whole observation period. To further quantify this behaviour, different mass signal components are studied in detail: (1) inter-annual variation in the atmospheric mass, (2) a possible effect of glacial isostatic adjustment (GIA), and (3) hydrological mass variations. In standard processing the atmospheric mass signal is reduced based on the data from numerical weather prediction models. We use surface pressure observations in order to validate this atmospheric reduction. On inter-annual time scale the difference between the atmospheric mass signal from model prediction and from surface pressure observation is <4 mm in equivalent water height. The effect of GIA on the mass signal over Siberia is calculated using a global ice model and a spherically symmetric, compressible, Maxwell-viscoelastic earth model. The calculation shows that for the investigated area any effect of GIA can be ruled out. Hence, the main part of the signal can be attributed to hydrological mass varia-

tions. We briefly discuss potential hydrological effects such as changes in precipitation, river discharge, surface and subsurface water storage.

1 Introduction

Siberia is one of the regions which is most affected by recent climate warming. The atmospheric warming trend in Siberia is larger than the global average (Groisman et al. 2006; Chudinova et al. 2006; McBean et al. 2005). Understanding the impact of climate warming on the permafrost system is important for assessing possible consequences on hydrology and ecosystems. Several studies report a remarkable increase in the Arctic river discharge (e.g. Yang et al. 2002; Berezovskaya et al. 2004; Shiklomanov et al. 2007; Rennermalm et al. 2010). These changes in the freshwater discharge into the Polar Ocean affect ocean circulation and global sea level rise. The discussion on causes of increased Eurasian river discharge, however, is still ongoing. The increase in discharge cannot be related to only one source (Rawlins et al. 2009).

The Gravity Recovery And Climate Experiment (GRACE) satellite mission has been proven as a valuable tool to observe various hydrological mass variations, e.g. in the Amazon basin or Okavango Delta (Chen et al. 2009; Andersen et al. 2010), groundwater depletion in Northwest India (Rodell et al. 2009) or in the Murray Darling basin (Leblanc et al. 2009), inland glacier mass losses (Matsuo and Heki 2010) and El Nino Southern Oscillation (ENSO)-related water storage variations (e.g., Morishita and Heki 2008; Becker et al. 2010). With more than 10 years in orbit, the GRACE

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mission now also allows the detection of smaller inter-annual mass changes. In this regard, recent results from GRACE show a mass increase in Siberian permafrost regions, such as in the Central Siberian Plateau and in the Kolyma River watershed (Muskett and Romanovsky 2009; Ogawa 2010; Seo et al. 2010; Chao et al. 2011; Landerer et al. 2010), whereas in Alaska, an increase in the Alaska coastal plain and a decrease in the Yukon watershed are observed (Muskett and Romanovsky 2011). Different sources for the mass changes are currently discussed. Frappart et al. (2010) presented a method to isolate the water storage below the root zone for basins with extensive floodplains, such as the Lower Ob watershed. In their approach they used GRACE data and combined them with remote sensing data and soil water storage from hydrological models. However, ground water and soil moisture from hydrological models include large uncertainties in the regions covered by permafrost (Schmidt et al. 2008).

Different interpretations are related to the fact that GRACE detects the integral mass variations of ocean, atmosphere, land and hydrology. Fortunately, oceanic and atmospheric contributions as well as tidal effects can be reduced with the help of dedicated models and calculations. This is usually done in the so-called standard processing of different analysis centres (Flechtner 2007).

After this process, gravity variations remain that are mainly related to signals from hydrology and solid Earth. Seo et al. (2010) and Chao et al. (2011), for example, speculate that the trend over Siberia is associated with glacial isostatic adjustment (GIA). However, most papers studying mass variations in Siberia consider different hydrological reasons for the observed positive mass trend. Muskett and Romanovsky (2009) assume an increase in groundwater storage in the Lena region. They hypothesise that the storage variations are related to a decrease in the lateral extent of the continuous permafrost zone and to talik development. Taliks are areas characterised by unfrozen material in the permafrost, e.g. underneath lakes. Ogawa (2010) discusses the effects of increased precipitation and the expansion of soil water capacity.

Steffen et al. (2012) use the Global Land Data Assimilation System (GLDAS, Rodell et al. 2004) for a correction of the hydrological component of the GRACE signal. GLDAS does not parameterises permafrost conditions such as continuously frozen ground or thaw and freeze processes at the surface (Rodell et al. 2004). The hydrological component was subtracted by Steffen et al. (2012) from the GRACE signal by applying the GLDAS model. This resulted in positive mass changes of about 0.8 μGal/year in the Central Siberian Plateau. The authors suppose that the remaining signals may point to permafrost changes in this region. In another approach, Frappart et al. (2011) estimate snow depth for the Arctic from the combination of GRACE data and a hydrological model. For the Lena watershed, they find a poor correlation of snow depth from GRACE and snow depth climatologies from different data sets and models.

In this study, we analyse GRACE mass variation over the Lena watershed in central Siberia, and in particular, on the region of Yakutsk with an area of about 100,000 km^2. We investigate different phenomena that have not yet or only partly been addressed in former works, and that may result in the signals determined with GRACE: (1) after standard processing by the different analysis centres, residual signals from insufficient a priori reduction models may be included in the derived gravity variations. The separation of different signal contributions is extensively studied on daily to monthly time scales (Han et al. 2004; Velicogna et al. 2001; Zenner et al. 2010). We focus on inter-annual time scales and investigate the effect of uncertainties in the atmospheric model on temporal gravity variations between 2003 and 2011. (2) We review the ice coverage over Siberia and study the GIA effect in this region through forward modelling with a global ice model and a spherically symmetric (1D), compressible, Maxwell-viscoelastic earth model. (3) Global hydrological models do not consider the special permafrost conditions like, for example, surface freeze thaw processes and continuous frozen ground. Thus, models of ground water and soil moisture include large uncertainties in the regions covered by permafrost (Schmidt et al. 2008). Werth and Güntner (2010) showed that GRACE data can help to constrain hydrological models and to capture the processes of ground water storage. They studied the calibration of the WaterGAP Global Hydrology Model (WGHM) using a multi-objective approach by combining GRACE and river discharge data. As a result, the model simulations improved and the error in the monthly discharge and water storage change was reduced significantly. In the data sparse permafrost region the integration of GRACE data may help to constrain the hydrological modelling.

In order to better understand the observed mass variations in the permafrost regions, we focus on the separation of the different signal components (atmosphere, solid Earth and hydrology). In addition, possible reasons for hydrological mass variations will be discussed. The following section describes our study area, followed by an overview of the GRACE processing and the GIA modelling in Sect. 3. We present and discuss our results in Sect. 4. Finally, conclusions are given in Sect. 5.

2 Study region

Our study area, the region of Yakutsk, in the following also referred to as central Siberia, is part of the Lena watershed (Fig. 3). Central Siberia is the only region worldwide with large areas of forest growing on continuous permafrost described as taiga (Osawa et al. 2009). The Lena River, one of the largest Eurasian watersheds (2,430,000 km^2), drains about 530 km^3 of discharge into the Arctic Ocean yearly.

The hydrological situation is dominated by the Vilyuy River, the largest tributary of the Lena besides the Aldan River. The Vilyuy River network originates in the Central Russian Upland in the region Krasnoyarsk and flows in an easterly direction with strong meandering (Chevychelov and Bosikov 2010). Annual discharge is dominated by snow melt in late April and early May, resulting in periodical flood events (Costard and Gautier 2008). The drainage in winter is relatively low because the rivers are frozen for 180–200 days/year (Chevychelov and Bosikov 2010).

The area experiences extreme continental climate conditions with long and cold winters and moderate summers. Annual mean temperature is about −9.5 °C, with maxima up to 27 °C in July and minima with temperatures down to −57 °C in February (Chevychelov and Bosikov 2010). The range of more than 80 °C/year is typically for extreme continental climate in the Yakutsk area. The long-term average of annual precipitation is about 228 mm. The area is snow-covered from late September or early October until the end of April or May. Typical for boreal forests is a higher precipitation in summer than in winter, but the climate is humid or semi-arid during the whole year (Chevychelov and Bosikov 2010). More than 90 % of the ground is underlain by continuous permafrost (Brown et al. 1998).

The area is situated in the Central Yakutian Basin and is surrounded by the Middle Siberian and East-Siberian Plateaus in the west and the east, and the Aldan Upland in the south. The elevation is between 90 m up to nearly 200 m above sea level. One typical shape of permafrost landscapes is the thermokarst relief, which is approximately 40 % of the study area (Brouchkov et al. 2004). The genesis of the thermokarst relief starts by a local thawing of frozen ground with a high percentage of ice (Czudek and Demek 1970). Thermokarst lakes are widely distributed. In some parts of Siberia the ground consists of about 70 % of ice (Brown et al. 1998). The permafrost reaches depths between 300 and 400 m, in west Yakutia up to 1,500 m (Chevychelov and Bosikov 2010).

3 Data and methods

3.1 Data sets

GRACE data are made available by several institutes and can be accessed via the International Centre for Global Earth Models (http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html). The University of Colorado real-time GRACE data analysis site (http://geoid.colorado.edu/grace/grace.php) provides a tool for the calculation of selected filtered gravity field solutions. We employ monthly GRACE data of the Release RL04 from January 2003 to December 2011 provided by the Helmholtz-Zentrum Potsdam,

Deutsches GeoForschungsZentrum (GFZ) and the University of Texas Austin, Center for Space Research (CSR). Atmospheric, oceanic and tidal effects are modelled and removed by the GRACE analysis centres (Flechtner 2007).

The atmospheric mass is reduced in the standard processing by the GRACE average atmosphere (GAA). The GAA gravity field is provided by the analysis centres. The GAA product is the monthly mean of all atmospheric mass variations given at a grid spacing of 0.5°. The calculation of the atmospheric mass contribution is based on operational analysis data from the European Center for Medium-range Weather Forecast (ECMWF) Integrated Forecast System (http://www.ecmwf.int/research/ifsdocs/index.html). The parameters for pressure, temperature and specific humidity are extracted from the model output for the synoptic times at 0:00, 6:00, 12:00 and 18:00 o'clock for 60 layers and integrated vertically. The atmospheric mass contribution is reduced in the GRACE monthly solutions provided by the analysis centres. Errors in the atmospheric model directly propagate in the GRACE solutions.

In the GIA modelling, we load a spherically symmetric (1D), compressible, Maxwell-viscoelastic earth model with the Late Pleistocene glacial history from global ice model RSES (Lambeck et al. 2010) using the modelling software ICEAGE (Kaufmann 2004). The modelling follows the pseudo-spectral approach outlined in Mitrovica et al. (1994) and Mitrovica and Milne (1998), using an iterative procedure in the spectral domain, and a spherical harmonic expansion truncated at 192. Input parameters are lithospheric thickness, mantle viscosity and the elastic structure, which is derived from PREM (Dziewonski and Anderson 1981). The Earth's core is assumed to be inviscid, and incorporated as lower boundary condition. The mantle viscosity is set to 7×10^{20} Pa s in the upper and 2×10^{22} Pa s in the lower mantle, which are good global averages (Wang et al. 2008). Three different lithospheric thicknesses of 80, 120 and 160 km are tested as the observed lithospheric thickness regionally varies in Siberia. Zorin et al. (1989) found by inverting gravity data with seismic constraints that the Baikal rift zone has an estimated lithospheric thickness of 40–50 km, which then increases to 200 km beneath the Siberian platform. Underneath the Trans-Baikal region it ranges from 75 to 175 km (Zorin et al. 1989). As we cannot simulate this depth variation with the used software, we apply the three constant thicknesses mentioned above. The best approximation in this regard is a lithospheric thickness of 160 km as most parts of Siberia are characterised by a high thickness. The Baikal rift zone is a rather narrow band in between much thicker parts. To somehow accommodate the effect of these weaker zones, we also investigate the thinner average thicknesses. For these three earth models, we iteratively solve the sea level equation (Farrell and Clark 1976) for a rotating Earth for time steps given by the ice model and determine time-dependent

Fig. 1 Snapshots of four times (ka BP) beginning with LGM (21.4 ka BP) of assumed ice sheet distribution in Siberia for modelling. Glaciated areas are marked in the *lower right plot*: (1) Taymyr Peninsula and Putorana Mountains, (2) western Stanovoy Range, (3) Verkhoyansk Range, and (4) existing ice sheets at LGM in Pekulney and Koryak mountains
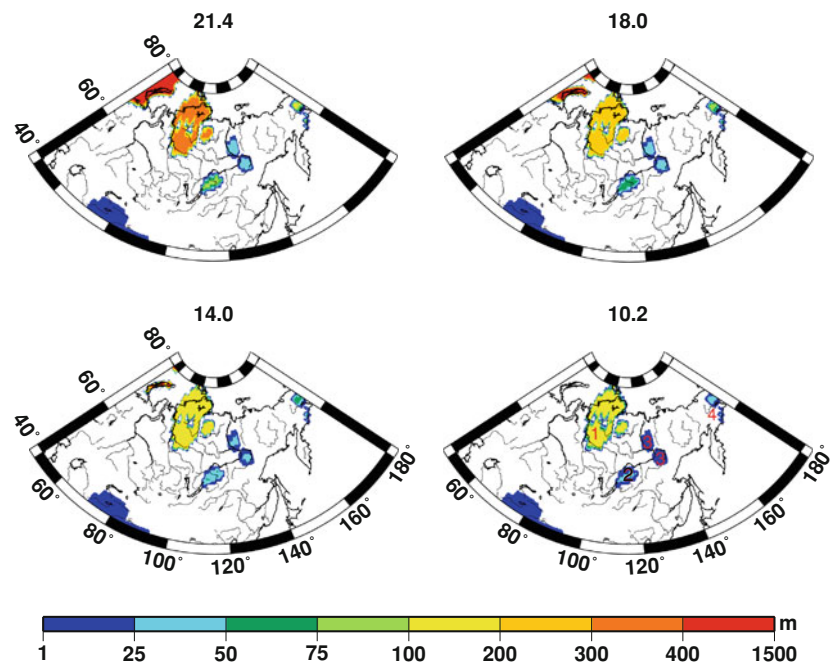
perturbations of the gravitational field, which can be compared to GRACE. For more information on the calculation method and the theory behind we refer to Kaufmann and Lambeck (2002) and Steffen and Kaufmann (2005).

The ice sheet distribution from RSES (Lambeck et al. 2010) during LGM is shown in Fig. 1. It shows glaciation in the Putorana Mountains, in the western Stanovoy Range, the Verkhoyansk Range, and Pekulney and Koryak mountains. The Barents-Kara as well as Tibet ice sheets are visible in the far North-west and South, respectively. Thus, we are able to investigate gravity effects from the restricted Siberian glaciers as well as from ice sheets in the far field, e.g. in Fennoscandia, North America, and Antarctica.

The mountain glaciers have been adopted for the RSES ice model from Denton and Hughes (1981) using their ice margins and ice volumes and assuming that their growth and melt history follow the global eustatic sea level (ESL) function (Kurt Lambeck, 2012, personal communication). Thus, the glacier model is approximate only with the intention to complement the ESL function. When a region is described as a complex of mountain glaciers (e.g. Verkhoyansk Range), the estimated total volume is taken and averaged over the area covered by the glaciers. Hence, restricted mountain glaciers may appear as ice sheets in Fig. 1 and a local GIA analysis is not recommended.

3.2 Data analysis

The method for GRACE data retrieval is extensively described in, e.g., Duan et al. (2009). Here, we do not concentrate on the retrieval of the signal and differences between analysis methods, but on the error budgeting and interpretation of the observed mass changes.

The used gravity fields are developed up to degree and order 120 for the GFZ solution and up to degree and order 60 for the CSR solution. In order to accurately consider the inter-annual variations of Earth's oblateness, the C_{20} terms are replaced with the C_{20} solution derived from Satellite Laser Ranging (Cheng and Tapley 2004). We apply a Gaussian filter with a radius of 300 km (Wahr et al. 1998) following Werth et al. (2009). They compared several filtering methods with different sets of parameters over large river basins to determine the most suited in each case with respect to the minimisation of errors and leakage effects on the GRACE data. They found that a Gaussian filter with a radius of 300 km is the most suited for the Lena basin.

Three different approaches were used to quantify the inter-annual signal. (1) A linear trend was fitted to the data of the whole observation period of 9 years. (2) A quadratic term was estimated to consider a possible acceleration/deceleration. (3) Two linear trends were fitted, one covering the period from 2003 to 2007 and the other from 2007 to 2011 in order to consider the large precipitation anomaly in 2007 (Rawlins et al. 2009).

For the estimation of the trends and the quadratic term we considered the seasonal variability by simultaneously estimating the amplitude and phase of an annual and semi-annual signal in a least-square adjustment. 50–60 % of the total variability is represented by the annual signal. The semi-annual signal is smaller and represents about 20 % of the total variability. Semi-annual signals in GRACE time series were also found by Schmidt et al. (2008) in high-latitude basins. They

carried out an empirical orthogonal functions (EOF) analysis for 18 large drainage basins including the Lena watershed. From the principal components of the dominant modes, they estimated amplitude, phase and frequency in a least-square adjustment. The seasonal variability can be explained by two storage peaks. The first peak with the largest amplitude is related to snow accumulation in the winter and the second, much smaller peak to surface water storage in the summer (Güntner et al. 2007).

Besides the annual and semi-annual signals, Schmidt et al. (2008) found small contributions of long-periodic signals in the range of 2.1–2.5 years on the total variability. They showed that these small signals are still significant and in good coherence with climate indices. In addition to these long-periodic signals and seasonal periodicities, we fitted tidal aliasing frequencies with the periods of 161 days and 3.7 years to the GRACE time series. The 3.7-yearly and the 161-daily signals result from an insufficient ocean tide correction (Ray et al. 2003). Their contribution on the total variability is at the level of 5–10 %. The estimation of the tidal aliasing signals and the 2.5 years periodicity has no effect on the trend estimates for the 9 years period and affects only little the quadratic terms and the trend estimates for the 4 and 5 years periods. For the grid cell-wise trend estimation with 1° spacing, a bias, a linear trend, an annual and semi-annual, a 2.5-yearly, a 3.7-yearly and a 161-daily amplitude were fitted to the gravity values.

Ramillien et al. (2005) present an iterative inverse method to separate the GRACE solutions into different hydrological components. This method is based on hydrological models and separates, in particular, snow water, soil wetness and ground water. This approach from Ramillien et al. (2005) was applied by several authors (e.g. Frappart et al. 2006; Seo et al. 2010). Schmidt et al. (2008) analysed the WGHM and the GLDAS. The state-of-the-art global hydrological models do not include a permafrost contribution (Rodell et al. 2004; Döll et al. 2003). This means that these models do not consider effects of the continuous frozen ground and coupled freeze thaw processes. Due to the deficiencies of the hydrological models in the permafrost regions, we do not apply them in our analysis and examine the total continental water storage.

4 Results

4.1 GRACE mass variations

Mass variations in the Lena watershed are presented for the Yakutsk region in Fig. 2. In the period from 2003 to 2011 the estimates of the linear trends fitted to the GFZ and CSR solutions are -2.2 ± 3.4 and 2.9 ± 3.2 mm/year. The trend estimates show an opposite sign but their values do not exceed
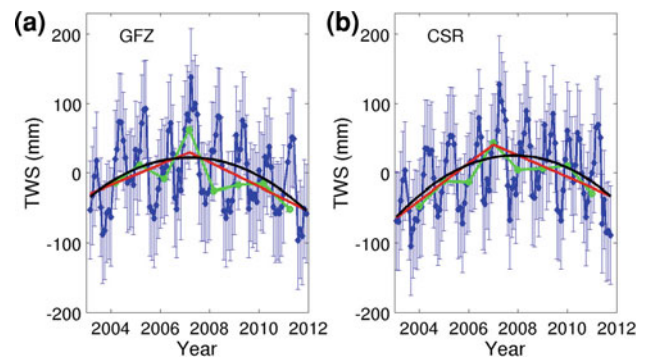

Fig. 2 Variations of TWS from GRACE for the Yakutsk region (GFZ and CSR solution, 300 km Gauss filter, *blue* monthly solution, *green* annual mean, *black* quadratic term fitted to the data). The mass increase from 2003 to 2007 reverses into a decrease from 2007 onward (*red lines*). For the whole observation period no significant trend was detected. The location of the Yakutsk region is marked in Fig. 3

the uncertainty range. For both the CSR and the GFZ solutions no significant trend was detected for the whole 9-year observation period.

However, the time series exhibit a non-linear inter-annual signal which approaches a quadratic term. This corresponds to the results from Ogawa et al. (2011) who used 6 years of GRACE data. Their analysis of data from GRACE and the GLDAS hydrological model showed that quadratic variations indicate inter-annual changes in terrestrial water storage (TWS). The maximum of the quadratic term appears for both GRACE solutions in 2007, for GFZ at the beginning and for CSR at the end of the year.

During the time period from 2003 to 2007, a significant increase in the TWS can be observed. The terrestrial water change (TWC), estimated by fitting a linear trend to the data, will be given in the following in mm/year equivalent water height (EWH). The TWC derived from the GFZ solution is with 11.5 ± 6.5 mm/year a little smaller than the TWC of 13.8 ± 6.8 mm/year estimated from the CSR solution. After 2007 the TWC is reversed and shows a slightly stronger decrease of -17.6 ± 4.0 mm/year for the GFZ solution compared to -14.8 ± 4.7 mm/year for the CSR solution.

The trend estimates for the 9-years period are independent of the time span. The difference between the trend estimates for a period of 8 and 9 years is <0.7 mm/year which is within the uncertainty range. However, the trends do depend on the time interval when analysing the 4- and 5-year periods. The trend estimates differ by 2–3 mm/year between the time intervals from 2003 to 2007 and 2003 to 2008, as well as between the intervals from 2007 to 2011 and 2008 to 2011. We have chosen the periods from 2003 to 2007 and from 2007 to 2011 in regard to the large precipitation anomaly in 2007 (Rawlins et al. 2009). The spatial distribution of the mass trends for the Lena watershed is presented in Fig. 3 for the periods from 2003 until 2007 and from
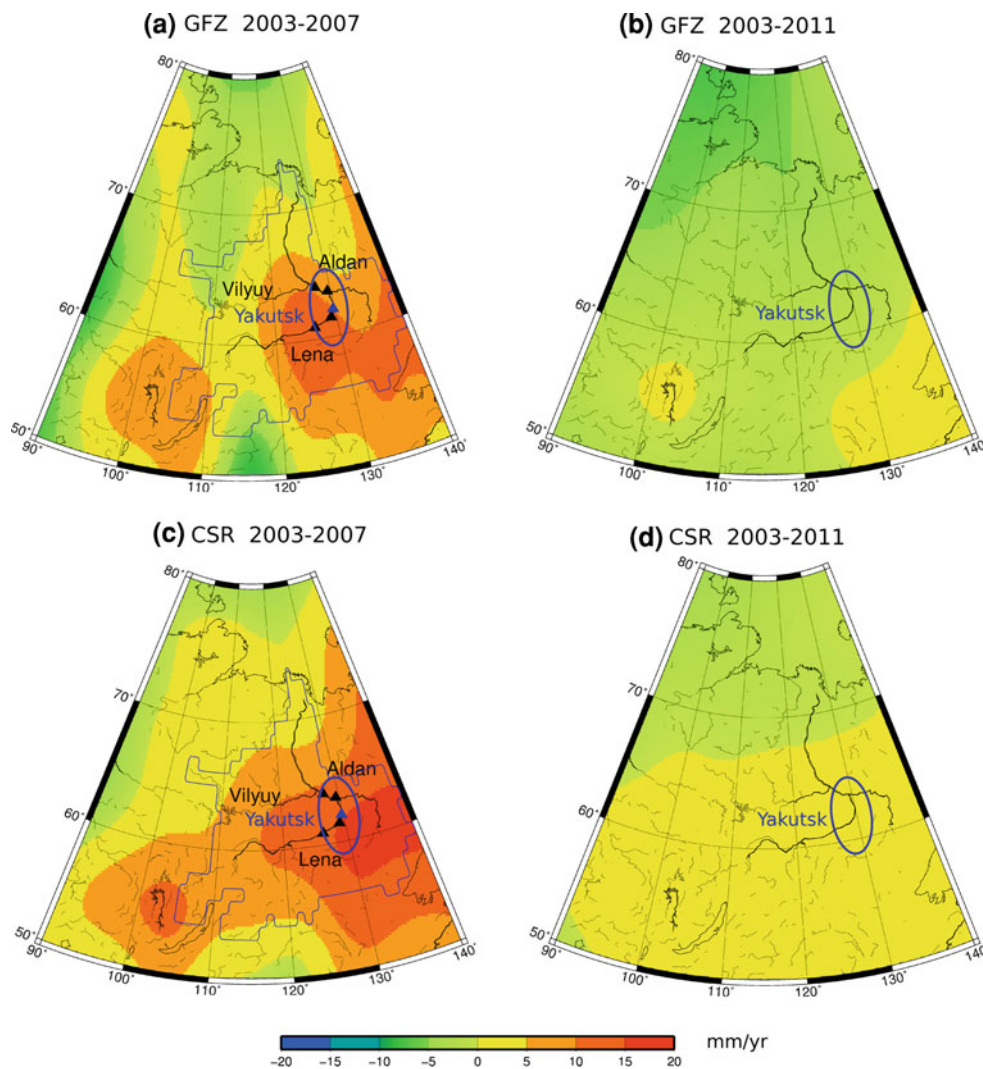
Fig. 3 Trend in water mass for the Lena watershed based on the GFZ and CSR GRACE solutions with a 300 km Gauss filter for different time periods. **a** and **c** 2003–2007, two prominent maxima in the TWC of 10–15 mm/year are visible. **b** and **d** 2003–2011, the maximum values in TWC are reduced to 2–4 mm/year. The *black triangles* mark the location of the meteorological stations listed in Table 1. At Yakutsk (*blue triangle*) discharge and soil moisture observations are additionally used. The *blue line* represents the border of the Lena watershed. The *blue ellipse* marks the area of the study region

2003 until 2011. In the map with the trend estimates for the GFZ solution from 2003 to 2007 (Fig. 3a), two prominent maxima of more than 10 mm/year are visible. One maximum is situated north of the Lake Baikal and the other in the Yakutsk region. In the CSR solution (Fig. 3c) these maxima are with more than 15 mm/year even more pronounced. In the time period 2003–2011, the maximum north of Lake Baikal is reduced and the maximum in the Yakutsk region nearly disappeared for the GFZ solution (Fig. 3b) and strongly reduced for the CSR solution (Fig. 3d). The increase in water mass until 2007 confirms other previously published results (Muskett and Romanovsky 2009; Seo et al. 2010; Steffen et al. 2012; Ogawa 2010; Chao et al. 2011; Landerer et al. 2010).

4.2 Inter-annual atmospheric mass variations

We investigate the sensitivity of the GRACE gravity solutions to uncertainties in atmospheric models for inter-annual time scales. The atmospheric correction used in the GRACE analysis is based on the data from the ECMWF. Errors in surface pressure of the operational analysis as provided by the ECMWF range from 0.5 to 0.7 hPa in Siberia (ECMWF 2009). The effect of these errors on the TWS is 3 mm (Zenner et al. 2010). However, those internal error estimates from ECMWF may not be realistic. A more obvious error estimation can be derived from comparisons with another numerical weather model or observations. Comparisons between the application of the model from the

Table 1 Station information including station ID, longitude, latitude and height (H) above mean sea level

Name	ID	Lat (°)	Long (°)	H (m)
Yakutsk	218230	62.100	129.767	99
Batamay	246560	63.517	129.483	79
Isit	249510	60.817	125.317	118
Pokrovskaya	248560	61.483	129.150	115
Sangary	246520	63.967	127.467	96

National Centre for Environmental Prediction (NCEP) and the ECMWF show differences in TWS of >30 mm for Siberia (Flechtner 2007).

We compare the atmospheric correction as applied in the GRACE standard processing with surface pressure observations from five meteorological stations in the region of Yakutsk (Table 1). The atmospheric correction implemented in the GRACE standard processing considers the vertical structure of the atmosphere. The accuracy of the vertically integrated atmospheric pressure is mainly dependent on uncertainties in the surface pressure (Zenner et al. 2010). Variations in the specific humidity, temperature and geopotential height have an insignificant effect on the vertically integrated atmospheric pressure. The geopotential height describes the height of a pressure surface above mean sea level. Meteorological observations are taken at several predefined pressure levels. Considering the study of Zenner et al. (2010), using surface pressure instead of vertical atmospheric layers does not result in changes of the GRACE reduction.

Figure 4 shows the comparison of the atmospheric correction as applied in GRACE standard processing with the mass variation derived from surface pressure observations in the region of Yakutsk. The solid line represents the atmospheric correction applied by GFZ (GAA product, Flechtner 2007). The GAA product (see also Sect. 3.1) represents the atmospheric mass signal that is subtracted in the standard processing to obtain continental water mass variations. The mass variation derived from surface pressure observations as mean over all five stations is given as dashed line. For the monthly resolution, both time series show a strong seasonal signal. However, differences in the TWS up to 50 mm occur in the seasonal signal. One reason might be related to uncertainties in the ECMWF data. The ECMWF model is only loosely constrained by observations in Siberia where only a very sparse coverage with measurements is available. Additionally, numerical weather prediction models have the tendency to significantly under-predict the true fluctuations (Vey et al. 2010). On inter-annual time scales, both the atmospheric correction and the mass variation from surface pressure observations agree very well. The differences in the TWS are smaller than 4 mm. This corresponds to <10 % of the total observed inter-annual mass variations
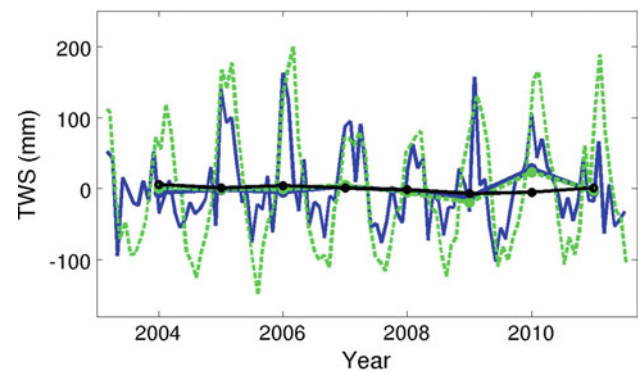
Fig. 4 Comparison of the variations in atmospheric mass in TWS derived from the GAA product (*solid line*) and computed from surface pressure observations P (*dashed line*). *Dots* represent the annual mean values and the *black line* shows the difference between GAA and P

(Fig. 2). It implies that uncertainties in the atmospheric model have only a minor effect on the GRACE standard processing on inter-annual time scales in the Yakutsk region.

4.3 Glacial isostatic adjustment

A potential gravity signal in Siberia that is recently under discussion (see Seo et al. 2010; Chao et al. 2011) is related to GIA. It is assumed that during the last ice age parts of or whole Siberia have been glaciated by ice sheets, ice caps and/or large mountain glaciers which forced the Earth's crust to sink into the mantle due to their enormous weight. After deglaciation the Earth is still rebounding into its initial position which can be detected by, e.g., gravity measurements. This process is well known in North America and Fennoscandia and has been successfully detected using GRACE (Steffen and Wu 2011; Steffen et al. 2008, 2009). However, it is well known that Siberia and especially its centre were ice-free during the last glacial maximum (LGM) (see, e.g. Svendsen et al. 2004; Lambeck et al. 2006; Velichko et al. 2011), the time when ice sheets in other parts of the world reached their largest volume. Only restricted glaciers in valleys have been found, but no prominent ice sheets as known from Fennoscandia or North America. The reason that no large-scale glaciation in Siberia is observed during LGM is due to changes in moisture transport across the Eurasian continent from the west (Stauch and Lehmkuhl 2011). Velichko et al. (2011), based on an analysis of quartz sand grains from sediments, noted that the West Siberian Plain was a late glacial desert (cold desert) due to the reduced evaporation and decrease in precipitation. Moreover, due to the ocean regression open flatlands extended 300–400 km and more northward (Velichko et al. 2011). Only in northern Siberia, glaciation during LGM reached to the North Taymyr ice-marginal zone, near the peninsulas west coast (Möller et al. 2011). This glaciation is connected to

Fig. 5 Gravity rate of change given in TWC (mm/year) in Siberia from three different Earth models having a lithospheric thickness of **a** 80 km, **b** 120 km, and **c** 160 km , as well as **d** the result according to Paulson et al. (2007) applying 300 km Gauss filtering
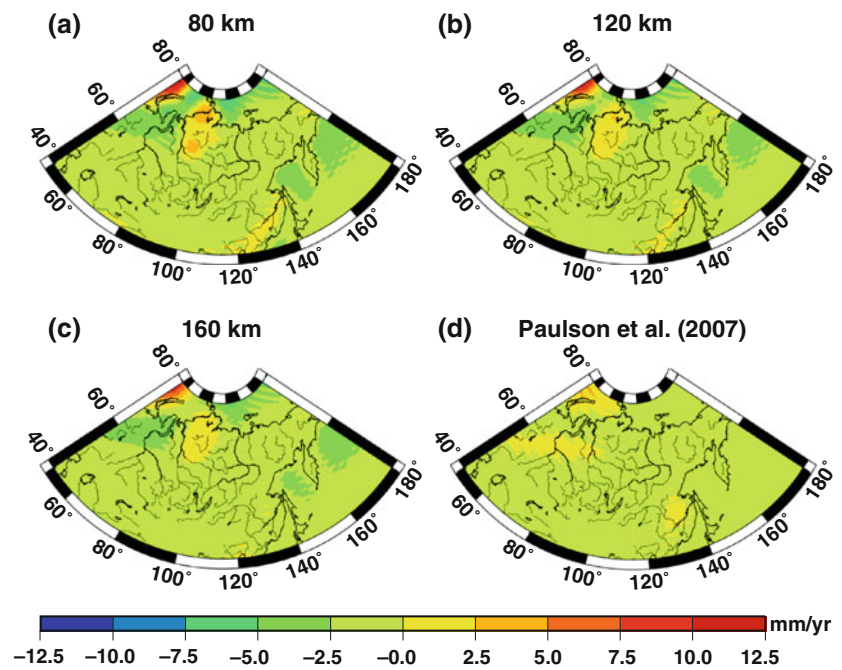
the Barents-Kara Ice Sheet (Alexanderson et al. 2001, 2002) and has been explained as a very short-lived event of surging from the higher parts of the ice sheet at its Barents-Kara Sea interfluve north of Novaya Zemlya (Alexanderson et al. 2002; Svendsen et al. 2004). In the Putorana Mountains south of the Taymyr Peninsula, Svendsen et al. (2004) point to the presence of restricted valley glaciers during the LGM. Large-scale glaciations at this location are older which is implied by deposition of aeolian sediments and formation of ice wedges at several investigated sites (Svendsen et al. 2004). The same holds for central Siberia. Here, Stauch and Gualtieri (2008) showed that the last glaciation in the Verkhoyansk Range east of the Lena River ended around 50 ka BP. They also investigated several areas in North-eastern Russia regarding late Quaternary glaciations and noted that, in general, glacial advances were more extensive earlier rather than later, in the last glacial cycle. During LGM, only evidence for restricted glaciation is found in the Pekulney and Koryak mountains in the far North-east and in Kamchatka (Zech et al. 1997, 2011; Gualtieri et al. 2000; Brigham-Grette et al. 2003; Stauch et al. 2007), which is far away from our investigation area. The extent of these glaciers was 25 km and less (Stauch and Gualtieri 2008).

In view of the summary above, any GIA effect from Siberian ice sheets during the LGM can be ruled out for our area of interest. The ice sheets or glaciers have been too small or too far away from the Lena watershed in central Siberia. To further demonstrate this and to quantitatively disprove wrong assumptions in relevant geodesy papers (Seo et al. 2010; Chao et al. 2011), we load, as outlined in Sect. 3, a spherically

symmetric (1D), compressible, Maxwell-viscoelastic earth model with the Late Pleistocene glacial history from global ice model RSES (Lambeck et al. 2010) using the modelling software ICEAGE (Kaufmann 2004). In addition, we show a result by Paulson et al. (2007) calculated with the ICE-5G ice model (Peltier 2004) that is provided for GRACE users on the Tellus website (http://gracetellus.jpl.nasa.gov/ data/). We note that ICE-5G does not contain any ice sheets in Siberia, thus this result can only indicate the far field contribution.

Figure 5a–c shows the calculated gravity rate of change for the three different earth models and the applied glacial history from RSES. It becomes evident that there is no GIA signal observable with GRACE in most parts of central and east Siberia independent of lithospheric thickness. This especially holds for the Yakutsk area. Apparently larger signals are found in the Putorana Mountains and the Taymyr Peninsula. Here, lithospheric thickness has an effect on the TWC signal of 1–2 mm/year. Values of 7.5 mm/year and higher in the North-west are related to the Barents Sea ice sheet. The negative trend south of it with values of −2.5 mm/year and less indicates the forebulge areas of the Fennoscandian and Barents Sea ice sheets. Similarly, the result by Paulson et al. (2007) (Fig. 5d), which is based on the ICE-5G ice model that does not contain any glaciation in Siberia, does also not yield significant GIA effects in central Siberia. Hence, we clearly show with both the modelling including known glaciers in central Siberia as well as with the result using the approach of Paulson et al. (2007) that GIA can be ruled out as a summand of the observed GRACE signal in our study area.
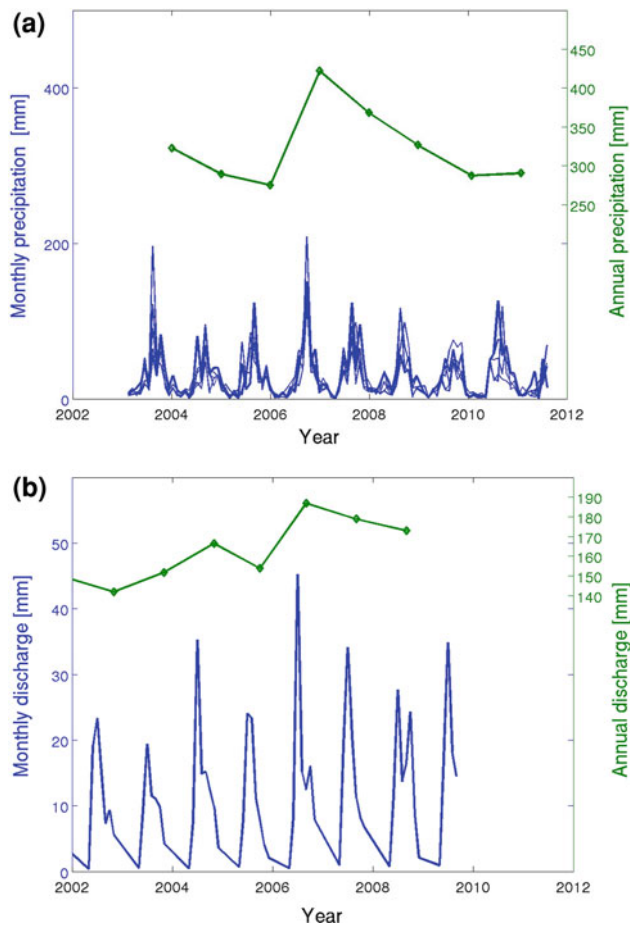
Fig. 6 Annual (*green*) and monthly (*blue*) variation in **a** precipitation measurements of five meteorological stations in central Siberia, **b** discharge observations of the Lena River at the Tabaga site. For station locations see Fig. 3

4.4 Hydrological variations

As shown above, only a small signal remains from the reduction of the atmospheric mass and also the GIA effect can be ruled out for the region of Yakutsk. Hence, the mass variations observed by GRACE in central Siberia can mainly be attributed to changes in hydrology. This section briefly discusses potential sources for hydrological mass variations.

Variations in water storage dS as observed by GRACE results from the differences of precipitation P, discharge R and evapotranspiration E. Figure 6a shows the variations of precipitation over the last decade for five meteorological stations in central Siberia (Table 1). The mean annual precipitation shows a strong positive anomaly in 2007. This is related to large snowfall events in the late winter of 2006/2007 followed by positive rainfall anomalies in summer 2007. The positive precipitation anomalies in 2007 are caused by unusual atmospheric patterns (Rawlins et al. 2009).

The discharge from gauge measurements of the Lena River at Tabaga, located close to Yakutsk, is shown in Fig. 6b (http://rims.unh.edu). From 2003 to 2007, the annual discharge at Tabaga increased by −11 mm/year. Berezovskaya et al. (2005) estimated the same discharge trend for the period from 1936 to 2001 in the Lena River basin. Seo et al. (2010), Landerer et al. (2010), Ogawa (2010) and Velicogna et al. (2012) analyse the water budget in the Lena watershed using data of P, R and E from different sources. All four studies show a good agreement between the water storage variations from GRACE and integrated meteorological data. The TWS as well as discharge over large areas of the Eurasian pan-Arctic region has increased during 2003–2010. The authors conclude that both the increase in TWS and the discharge are driven by increased atmospheric moisture fluxes accompanied by more precipitation rather than by melting of excess ground ice in permafrost regions.

One interesting feature is that besides the Lena Basin all other Eurasian watersheds in the Arctic experience a mass loss (Frappart et al. 2011). From 2007 onward, a mass loss is now also observed in the Yakutsk region of the Lena Basin. For the time period from April 2002 to September 2010, Velicogna et al. (2012) estimated a mass increase for the whole Lena basin using the CSR solution. We also see an increase in the mass variations of the CSR solution for the time period from 2003 until 2010 for the Yakutsk region (Fig. 2). However, when adding one more year of data the mass decreases strongly and the trend is not significant anymore. The increase and decrease of the investigated time series are inter-annual signals which cannot give an indication on long-term changes. For the detection of possible changes in the permafrost water storage as response to global warming longer time series are necessary.

Another possible source for changes in water storage is an increase in soil moisture in the active layer. The active layer is the upper part of the permafrost which freezes in winter and thaws in summer. It is important for tree growth in the dry environment since water is stored above the frozen layer. The soil moisture in the active layer increased over the last decade (Iijima et al. 2010). For two sites at Yakutsk, soil moisture observations were integrated for the top layer between 0.1 and 1.1 m. The upper 10 cm of the ground were not included in the analysis as this top layer may be influenced by surface flow. Down to a depth of 1.1 m the soil is not frozen during the summer months. As the measurements consider only liquid water, we restrict our analysis to the unfrozen layer. The inter-annual variations were derived from the mean soil moisture observations during the months from July to September. The two analysed sites are characterised by different soil type, topography and vegetation. Both sites show an increase in soil moisture which corresponds to an increase in TWC of 4 mm/year (Fig. 7). For a quantitative estimation of the soil water storage in the supra-permafrost groundwater, more
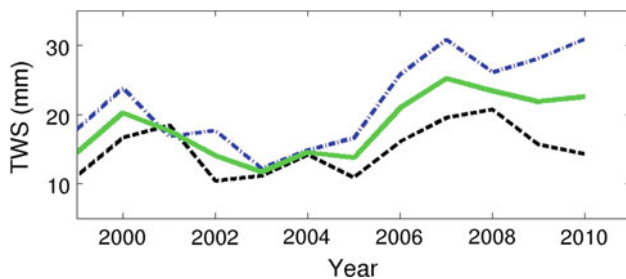
Fig. 7 Integrated soil moisture storage for two sites at Yakutsk (*dashed lines*) for the layer from 0.1 to 1.1 m depth (Iijima et al. 2010). The *solid line* representing the station mean has its maximum in 2007

sites are necessary. However, this example gives an impression of possible water storage changes in the active layer.

Besides variations in subsurface water storage (active layer) changes in the surface water storage can have a noticeable impact on the total water mass variation. Surface water storage variations include changes in the inundation extent and the water-level height. Frappart et al. (2010) combined altimetry data with a multi-satellite inundation data set over the Lower Ob Basin. They showed large inter-annual variations in the surface water storage ranging from 40 to 140 km^3 (4–14 cm in EWH) over the time period from 1993 to 2004. For the Lena Basin inter-annual variations in spring inundations show a lower variability than for the Ob Basin (Papa et al. 2008). The inundation extent is largest for the months of June and July. In these months the water inundates an area of 40,000 km^2 corresponding to about 2 % of the Lena Basin surface. The inundation extent in the Lena Basin shows an inter-annual variability of about 30 % (Papa et al. 2008).

Besides inundations, the development of thermokarst lakes is one phenomena which influences the surface water storage. In particular in the Lena watershed, thermokarst lakes are an important component of the permafrost landscape and can cover up to 40 % of the land surface (Brouchkov et al. 2004). Thermokarst lakes are created by partial thawing of the permafrost followed by a compaction of the soil and ground subsidence. Precipitation accumulates in the thermokarst basins and forms lakes. This reduces run-off and increases the surface water storage. The thermokarst lakes can reach diameters from several hundreds of metres to tens of kilometres. Kravtsova and Bystrova (2009) studied variations in thermokarst lake size using multi-temporal Landsat images. For central Yakutia they mapped the development of new lakes through the filling of thermokarst depressions with water and showed a doubling of the lake areas between 1970 and 2000.

Other possible effects for surface water storage changes could result from variations in the level of existing natural lakes or artificial reservoirs. Lee et al. (2011) studied the lake-level variations in permafrost regions using altimetry data. They showed well the positive response of the water

level to the precipitation amount for two lakes in Canada and on the Tibetan Plateau. The land surface of central Siberia is covered by thousands of lakes. The effects of lake-level change and filling of new thermokarst basins with water have a considerable effect on the surface water storage. The exact quantification of changes in surface water storage is subject to further research.

5 Conclusions

For the Yakutsk region, GRACE observations show a strong non-linear inter-annual signal which can be approached by an quadratic term. For the period from 2003 to 2007, the Yakutsk region experiences a mass increase of 11.5±6.5 mm/year and from 2007 to 2011 a mass decrease of −17.6 ± 4.0 mm/year (GFZ solution). For the whole observation period (2003–2011) no significant mass trend is visible.

Our literature research on the ice history over Siberia reveals no large-scale ice sheets during the LGM. Additionally, no GIA effect on the mass signal can be found in central Siberia when applying the two ice models RSES and ICE-5G and carrying out the GIA modelling for different lithospheric thicknesses.

Possible mass contributions from inter-annual variation in the atmospheric mass which might not be considered by the atmospheric model applied in the standard processing can also be ruled out. As atmospheric and GIA effects can be excluded for the observed mass changes, we can completely attribute the mass changes to hydrological variations.

The inter-annual water storage variations are mainly related to strong precipitation events which occurred in the winter 2006/2007. The increased precipitation seems to lead to an increase in soil moisture. The quantification of the surface water storage in lakes and changes in subsurface water storage such as soil moisture variations and talik formation need to be further studied.

Longer GRACE time series are necessary to answer if the mass decrease from 2007 onward continues, as well as if it is an indication for long-term changes in the permafrost water storage or if the decrease is rather part of an inter-annual signal.

and Atmospheric Administration (NOAA) for making meteorological observations via its website (ftp://ncdc.noaa.gov) available to us.

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