**Analysis of mass variation in the Lena river basin using GRACE.**

David Haasnoot 4897900 AESM50C

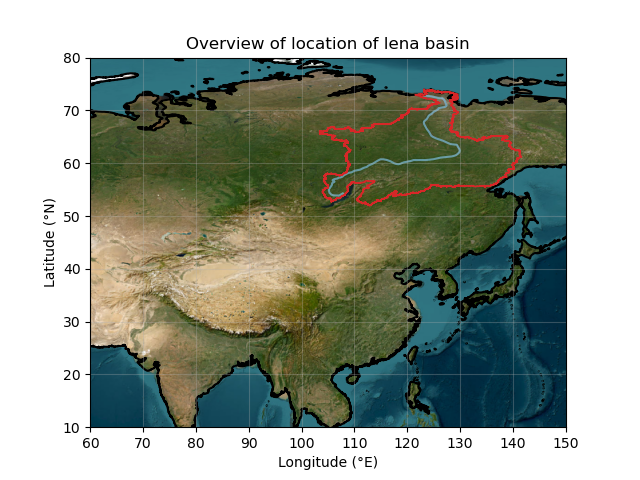
**Keywords:** GRACE, mass variations, river basin

**Introduction**

Artic rivers in Eurasia and North America discharge freshwater directly into Polar ocean. This ocean plays a large role in global patterns such as large scale ocean circulations and global sea level rise. The amounts of freshwater moving into the polar ocean can have large effect on this. Climate change is causing warming in Siberia (Groisman et al, 2012). The expected changes in temperature and the global effect it can have makes Siberia an interesting region to study. One main issue with studying the Artic area is the remoteness of the area making in situ measurements difficult and sparse. The Gravity Recovery And Climate (GRACE) satellite mission allows analysis of mass variations globally since 2002. Mass variations in rural regions can be linked to the variations water masses in the hydrological cycle of such systems.

Previous studies (Velicogna, 2012; Vey, 2012; Landerer, 2010) looked at the time series from 2002 up until 2009-2012 in the Lena basin. These older publications were limited to the data available at that time. Velicogna (2012) concludes a rapid increase between 2003 and 2010 and attributes this to an increase in the water storage in the subsurface. Vey (2012) concludes that there is an increase between 2003-2007, but a decrease in 2007 and 2011. This increase is also seen on the plot Velicogna (2012) presents, however Velicogna’ focus remains on the linear trend. Vey (2012) attributes the increases till 2007 to precipitation events and concludes it is unknown whether the increase is seasonal or due to a long term change. Landerer (2010) studies the region more widely and suggests that there is permafrost thaw causing a reduction in mass. All studies agree that separating long term trend and seasonality in these relatively short time series is difficult.

The aim of this study is to analyse the dataset from 2003 to current and see whether a longer data set reveals more insight into changes in water storage in the Lena Basin.



*Figure 1: Location of the Lena Basin*

**Data**

Grace data is available from various sources. Monthly averaged Level 2 data can be obtained from the model ITSG-Grace2018 produced by the university of Graz (Mayer-Gürr, 2018). Alternatively a smoothed version obtained from UTCSR (2018) also should yields results but smoothed. Both used to degree 60. To compare to an already existing level 3 data, ‘The Graceplotter.com’ (2023) was used to obtain a timeseries for the Lena basin, again using the CSR data from UTCSR (2018) which uses coefficients up to degree 96.

**Theory**

The level 2 stokes coefficients measured by grace can be used from degree 2 to 96. , and are replaced by those calculated by Landerer (2023), whilst and by those calculated by Loomis et al (2020). To deal with the Glacial Isostatic Adjustment in the area, the stokes coefficients were adjusted with a linear trend to deal with this shift (Argus, 2014; Peltier, 2015). The stokes coefficients () are scaled in order to obtain with the formula . Where is the love number of the order and The mass anomalies are converted to equivalent water height for a given longitude and latitude using: This is computed for grid cells of 1x1 degree with degree longitude and latitude, corresponding to the extent of the Lena Basin. Once the whole grid is computed as shown in figure 2 the basin can then be masked out as shown in figure 3. The shape of the basin is based on a Digital Elevation Map of the area (Digital Journal of Global Change Data Repository, 2016). Coastline in the figures are supplied by Natural Earth Data (2023).

A map of the earth

Description automatically generated

*Figure 2: Computed grid of mass anomalies*

A map of the earth

Description automatically generated

*Figure 3: Mask for Lena river basin*

The mean of the masked area can then be taken as the mass anomaly over a given timestep. This produces a series for the basin over time. With this timeseries a set of timeseries analysis steps can be taken to analyse a trend in the mass anomalies.

**Results**

The data from ITSG-Grace2018 (Mayer-Gürr, 2018) for the region contains more noise and thus the smoothed version from UTCSR (2018) was preferred. Although quite close, the coefficients filtered with a DDK4 algorithm produce lightly smoother results. This is effect is especially visible when considering the individual timestep maps. Data obtained from ‘The Graceplotter.com’ (2023) was also used as comparison to verify the nature of the computations as shown in figure 4.

A graph of a number of numbers

Description automatically generated with medium confidence

*Figure 4: Processed stokes coefficients compared to time series provided by ‘The Graceplotter.com’, 2023.*

As the smoothed coefficients seem to include less noise the UTCSR timeseries will be used to analyse the trend. A simple linear trend line as used by Velicogna (2012) shows no clear relationship with a slope of 0.28mm/year with a Root Mean Square Error (RMSE) of 3.71cm.

A graph of a graph with blue dots

Description automatically generated

*Figure 5: Showing a simple linear trend.*

Similar to Vey (2012) the time series can be split into different segments. Vey (2012) considered sections of 5 years. This can be continued up to 2017, splitting the time series into three sections. These combined sections yield a RMSE of 3.15cm which is only just better than the single linear trend. The resulting trends suggests a like cubic relationship which is plotted in the same graph in figure 6. These three linear trends have a slope of 1.9, -1.3 and 0.5 cm/year for the years 2002-2007, 2007-2012 and 2012-2017 respectively. This shows that Vey (2012) was correct given the data available in 2012, however the more recent data shows that this relation is more complex than a combination of linear trends. A cubic relation as shown in figure 6 shows a good fit for the data set between 2002-2017 which follows the annual mean well, however has an RMSE of 3.21cm.

The annual variation in signal can be approximated using the function:

where A through E are coefficients to be found, is the midpoint of the timeseries and with T being 12 months. This fit can be seen in figure 7 which has an RMSE of 2.82cm, the lowest until now as it is able to capture the annual seasonal variation.

A graph of a graph with blue dots and red lines

Description automatically generated with medium confidence*Figure 6: Showing three linear and a cubic trendline with monthly anomalies and annual mean plotted.*

Although it has a quadratic term, the reduction around 2010 is not captured well which the cubic does cover.

A graph of a number of numbers and a number of points

Description automatically generated with medium confidence

*Figure 7: Quadratic function with annual signal*

Thus a adding a cubic term models the timeseries better with an RMSE of 2.41cm. Still the yearly amplitude is not covered well, thus a change can be tested by splitting the dataset in 3, similar to the linear trends in figure 6.

A graph of a graph with blue dots and black lines

Description automatically generated

*Figure 8: Cubic function with annual signal*

This results in an RMSE of 1.82cm which can be seen figure 9.

A graph of a graph

Description automatically generated with medium confidence

*Figure 9: Annual trend fit to 3 sections of timeseries separately*

A 3-σ criterion can be applied to check whether the obtained coefficients are significant, which can be seen in table 1. The intercepts are insignificant the periods 2002-2007 and 2012-2017, highlighted orange.

*Table 1: coefficients with uncertainties.*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Years** | **A**  **[cm]** | **B [cm/**  **month]** | **C [cm/**  **month^2]** | **D**  **[cm]** | **E**  **[cm]** | **F**  **[cm]** | **Tfm\***  **[d]** |
| 02-07 | -0.03 | -0.16 | -0.0027 | 2.04 | -2.38 | 3.14 | 50 |
| σ | 3.89 | 0.14 | 0.0011 | 0.36 | 0.37 | 0.37 | 15 |
| 07-12 | 0.32 | -0.07 | 0.001 | 2.09 | -3.16 | 3.79 | 57 |
| σ | 0.36 | 0.02 | 0.0009 | 0.34 | 0.35 | 0.35 | 14 |
| 12-17 | -4.65 | 0.14 | -0.0013 | 3.21 | 1.5 | 3.54 | 25 |
| σ | 2.54 | 0.1 | 0.0009 | 0.37 | 0.39 | 0.38 | 16 |

*\*Time to function maximum (in days)*

To compare the trends a Signal to Noise Ratio (SNR) can be used according to the following relation:

Which yields the values in table 2 below.

*Table 2: signal to noise ratio(SNR) for comparison trends for two time periods*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Years** | **A [-]** | **B [-]** | **C [-]** | **D [-]** | **E [-]** | **F[-]** | **Tfm[-]** |
| 02-07 -- 07-12 | 0.84 | 1.56 | 2.52 | 1.46 | 0.73 | 1.64 | 0.03 |
| 07-12 -- 12-17 | 1.94 | 2.22 | 1.84 | 2.22 | 8.85 | 0.47 | 2 |

These values are quite small, highlighting the high amount of noise and lack of a good fit for all. The change in quadratic term C from the first to the second period is relatively high showing the change in trend which can be seen in figure 9. All values apart from the phase F show a SNR of around 2, suggesting this could be significant. The value of E

This procedure can be repeated for the timeseries obtained from ‘The Graceplotter.com’(2023) as seen in table 3 and figure 10 yielding the same RMSE of 1.82cm.

*Table 3: SNR for data from ‘The Graceplotter.com’(2023)*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Years** | **A [-]** | **B [-]** | **C [-]** | **D [-]** | **E [-]** | **F[-]** | **Tfm[-]** |
| 02-07 -- 07-12 | 0.84 | 1.56 | 2.52 | 1.46 | 0.73 | 1.64 | 0.03 |
| 07-12 -- 12-17 | 0.95 | 0.98 | 2.19 | 7.93 | 5.90 | 1.90 | 4.67 |
| 12-17 -- 18-22 | 2.77 | 3.19 | 3.76 | 7.69 | 6.71 | 2.33 | 4.22 |

A graph of a line graph

Description automatically generated

*Figure 10: Annual trend fit to 3 sections of timeseries separately for data from ‘Thegraceplotter.com’,2023.*

Using the data from Grace Follow On (GFO) from 2018 – 2022 shows a change in trend for the signal to noise ratio computed between 2012-2017 compared to 2018-2022. These coefficients have a signal value 2 to 3 times greater than the noise and thus are significant.

**Conclusion**

From the analysis of more recent data we can conclude that there are ongoing changes to terrestrial water storage (TWS) in the Lena basin. Although there is a linear upward trend which Velicogna (2012) suggests, this is too much of a simplification. Vey’ (2012) suggestion of an upward trend between 2002-2007 and downward between 2007-2012 can be confirmed. This suggestion can be applied to the rest of the time series with positive results as it yields a trend which has the lowest RMSE. The results Landerer (2010) can’t be reproduced. Although the noise makes drawing conclusions difficult, the trend line is significant for the separate periods. Visually we clearly see a trend and the simple cubic trend line shows a strong basis for splitting the time series in sections of 5 years. The resulting trendlines suffer from relatively high noise and thus we can’t conclusively say that there is a change in the trend. The timeseries from ‘Thegraceplotter.com’,2023 does show that the recent data from the Grace Follow On mission has a different trend from the years 2012-2017 of the grace mission. Given a significant trend for the years

**Discussion**

Reducing the noise in the data would make fitting a trend line easier. This could be achieved by better filtering or applying data assimilation techniques to better estimate the time series. Alternatively, the more effort could be put in finding a more fitting trend line. The current function captures part of the signal well but a RMSE below 1.82cm should be attainable. Addressing these two factors would create a stronger case for the change in trends over time.

TODO: more effort in removing seasonal trend

**AI Statement**

No AI tools were used in the writing of this report nor in the production of the code on which the report is based.

**Literature list**

**Data**

Argus, D.F., Peltier, W.R., Drummond, R. and Moore, A.W.(2014) *The Antarctica component of postglacial rebound model ICE-6G\_C (VM5a) based upon GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories*. Geophys. J. Int., 198(1), 537-563, doi:10.1093/gji/ggu140.

Digital Journal of Global Change Data Repository (2016), *Boundary Data of the Lena River Basin* <https://doi.org/10.3974/geodb.2016.05.18.V1>

Landerer, F. (2023),Jet Propulsion Laboratory (JPL) *Monthly estimates of degree-1 (geocenter) gravity coefficients, generated from GRACE (04-2002 - 06/2017) and GRACE-FO (06/2018 onward) RL0601 solutions*. <https://archive.podaac.earthdata.nasa.gov/podaac-ops-cumulus-docs/grace/open/docs/TN-13_GEOC_CSR_RL0601.txt>

Loomis et al., 2020, Geophys. Res. Lett., *SLR-derived C20 and C30 values for replacing GRACE/GRACE-FO GSM* https://doi.org/10.1029/2019GL085488

Mayer-Gürr, Torsten; Behzadpur, Saniya; Ellmer, Matthias; Kvas, Andreas; Klinger, Beate; Strasser, Sebastian; Zehentner, Norbert (2018): ITSG-Grace2018 - Monthly, Daily and Static Gravity Field Solutions from GRACE. GFZ Data Services. <https://doi.org/10.5880/ICGEM.2018.003>

McClelland, J.W., S.E. Tank, R.G.M. Spencer, A.I. Shiklomanov, S. Zolkos, and R.M. Holmes. (2023). *Arctic Great Rivers Observatory. Discharge Dataset*, Version 20230810. <https://arcticgreatrivers.org/discharge/#Lena_Kyusyur>

Natural Earth Data (2023). ‘*Rivers, Lake Centerlines’*,Retrieved October 24, 2023, from Naturalearthdata.com website: <https://www.naturalearthdata.com/downloads/110m-physical-vectors/110m-rivers-lake-centerlines/>

Peltier, W.R., Argus, D.F. and Drummond, R. (2015) *Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G\_C (VM5a) model.* J. Geophys. Res. Solid Earth, 120, 450-487, doi:10.1002/2014JB011176.

‘The Graceplotter’ - Visualization tools – GRACE / SLR. (2023). Retrieved October 26, 2023, from Thegraceplotter.com website: <https://thegraceplotter.com/>

University Of Texas Center For Space Research (UTCSR) (2018) *Grace static field geopotential coefficients CSR release 6.0.* <https://doi.org/10.5067/GRGSM-20C06>

**Literature**

Groisman, P. Y., Blyakharchuk, T., Chernokulsky, А. V., Arzhanov, M. M., Luca Belelli Marchesini, Богданова, Е. Г., … Vygodskaya, N. N. (2012). Climate Changes in Siberia. Springer Environmental Science and Engineering, 57–109. <https://doi.org/10.1007/978-94-007-4569-8_3>

Landerer, F. W., Dickey, J. O., and Güntner, A. (2010), *Terrestrial water budget of the Eurasian pan-Arctic from GRACE satellite measurements during 2003–2009*, J. Geophys. Res., 115, D23115, <https://doi.org/10.1029/2010JD014584>

Velicogna, I., Tong, J., Zhang, T., & Kimball, J. S. (2012). *Increasing subsurface water storage in discontinuous permafrost areas of the Lena River basin, Eurasia, detected from GRACE*. Geophysical Research Letters, 39(9), L09403. <https://doi.org/10.1029/2012gl051623>

‌Vey, S., Steffen, H., Jürgen Müller, & Boike, J. (2012)*. Inter-annual water mass variations from GRACE in central Siberia*. Journal of Geodesy, 87(3), 287–299. https://doi.org/10.1007/s00190-012-0597-9

Suzuki, K., Matsuo, K., & Hiyama, T. (2016). *Satellite gravimetry-based analysis of terrestrial water storage and its relationship with run-off from the Lena River in eastern Siberia*. International Journal of Remote Sensing, 37(10), 2198–2210. <https://doi.org/10.1080/01431161.2016.1165890>

**Appendix**

Main python notebook is included as PDF attachment. Whole repository can be accessed on GitHub () . This is including pre-computed NetCDF files containing solutions for the area, which can save in computation times when reproducing the code.