This file contains five parts:

- Response to the 1st reviewer
- Response to the 2nd reviewer
- Response to the 3rd reviewer
- Response to the 4th reviewer
- Track changes of the manuscript

Response to the 1st reviewer:

Below, 'Q' is the question/comment, 'R' is our response, and 'C' is the revision in the manuscript.

R0:

The reviewer raised two major concerns. The first one is that a sinusoidal function is unsuitable for glacier and snow mass change. We add a semiannual variation to improve the simulation. We show that the new model is physically reasonable and accurate enough, and the conclusion still holds. The second one is why there is a big difference in amplitude between the EOF_1 results of GLDAS and GRACE. We explain that it is an inevitable result due to the exclusion of unavailable surface water and groundwater in the GLDAS product.

Q1:

The manuscript aims to estimate snow/glacier melt in the Brahmaputra river basin. Considered that different water storage components (snow/glacier vs. soil moisture etc) tend to have different spatiotemporal signatures, the authors apply EOF analysis on the GRACE data to extract these signatures. The underlying hypothesis is that the two dominant EOFs separate snow/glacier mass balance from the other hydrological components. The manuscript also explores the correspondence between energy input (temperature) and the estimated snow/glacier mass balance. The study fits the scope of the journal. The robustness of the analysis mainly depends on the validation of the underlying hypothesis, which needs to be strengthened.

The authors validate their underlying hypothesis by analyzing (a) the correspondence between mode-1 and modeled soil moisture estimates, (b) how a phase difference of certain magnitude between two modes leads to their orthogonality, and (c) the corre- spondence between mode-2 and the ICESat results. In my opinion, the logic of (b) is questionable and not necessary. The result from (b) is solely determined by the orthogonality of the sinusoidal functions (as one of the modes are fixed as a cosine function in the analysis), and it does not address the physical meanings of these functions.

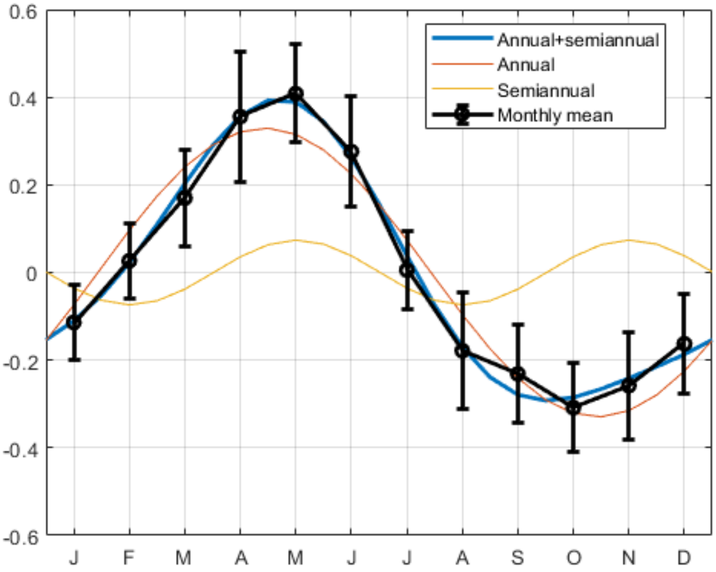
R1:

We feel the hypothesis (b) is very important for two reasons. First, it is the prerequisite for signal separation. Another reviewer suggested us to use the same technique in the west Tibet where the winter westerly is stronger and the summer monsoon is weaker. It cannot be implemented because both hydrological and glacial signals peak in winter, so the orthogonality disappears there. Second, the simulation enlightens the possible leakage between different signals and it is necessary for the uncertainty estimation.

We will update the simulation with an extra semiannual variation and address its physical meaning.

In the previous version, we only use a 1-year-cyle sinusoidal function (the orange curve, refer to Fig. 1) to simulate the temporal pattern of glacier melting. The simulation could be improved by another 0.5-year-cycle sinusoidal function (the yellow), as shown below. Periodic functions with periods shorter than 0.5-year can further improve the fitting to the monthly GRACE PC_2 series (the black curve with error bars), but we can tell that there is little room left for the improvement. A consequent question is how to determine the amplitude and the phase of the semiannual variation, and the answer is the information from GRACE PC_2.

Using GRACE PC2 series to find the monthly changing pattern is self-verifying, but we have no information more accurate than this. Below we will discuss the rationality of the new semiannual variation.



[Fig. 1. Seasonal variation of the PC2]

Here, we express the amplitude of annual and semiannual variations as A1 and A2, respectively. Their corresponding phase is P1 and P2, respectively. In fact, the relationship between As and between Ps can be determined by the varying form of their constituent signal.

As for the glacial mass signal, we have such information: its increase and decrease processes are asymmetric; it is slowly increased in winter, fast increased in spring (due to the spring precipitation), and then drastically decreased in summer. Based on this information, we can conclude that A2 is no more than 0.25*A1, and P2 is slightly larger than P1.

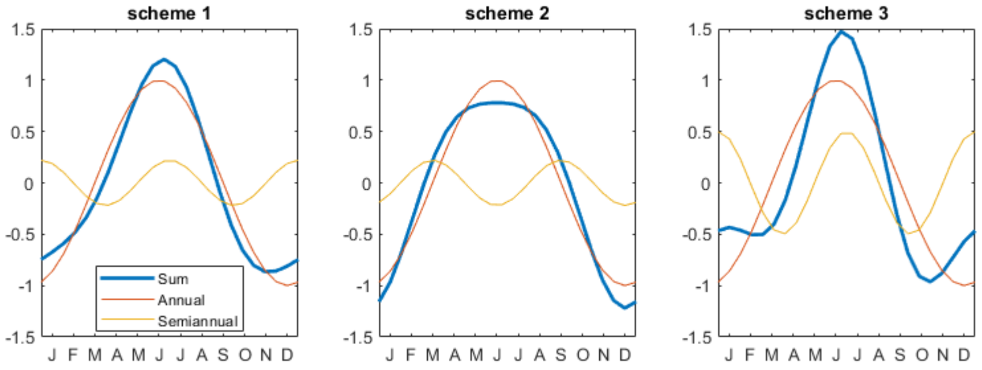
We explain it by showing three schemes of As and Ps below [refer to Fig. 2].

Scheme 1: A2 = 0.22*A1, P2 = P1+half-a-month; this is what we get from GRACE PC_2. The shape of the series matches our understanding of glacier mass change here.

Scheme 2: A2 = 0.22*A1, P2 = P1+three-month; this is the case when P1 and P2 are quite different. This signal is symmetric with a flat peak and a sharp trough (similarly we can construct a signal with a flat trough and a sharp peak).

Scheme 3: A2 = 0.5*A1, P2 = P1+half-a-month; this is the case when A2 is larger. As a result, the signal has double peaks in a year.

The signals by scheme 2 and 3 are unreasonable to explain the glacier and snow mass change here. We then have a good reason to follow the relationship between annual and semiannual variation obtained from GRACE PC_2.



[Fig. 2. Three schemes for simulation of seasonal variations]

With the extra semiannual variation, the leakage error is little changed (relative difference is 3%). If higher frequencies are included for a more elaborate seasonal variation, the influence is expected to be negligible considering their even smaller magnitude. Therefore, we update the simulation with more accurate changes in glacier and snow mass, and the conclusion still holds.

C1:

[We updated the simulation in the supporting materials based on the information shown above]

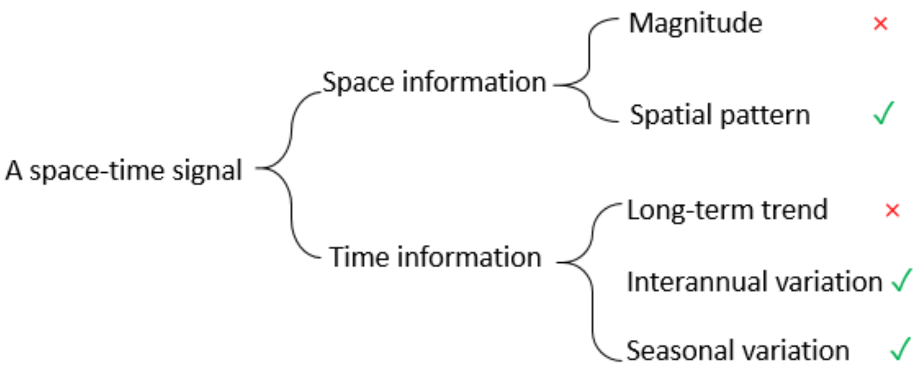
Q2:

Instead (a) and (c) should be the focus of the validation. For example, the use of soil moisture alone in (a) needs to be justified. The notable mismatch in terms of magnitude and pattern between Fig. 3a and Fig. 5c needs be addressed. Note that the large signal in Fig. 3a likely results from a combination of water demand from irrigation and a decrease in precipitation. How about using detrended time series for the EOF analysis, would it improve the agreement?

A2:

Terrestrial water storage consists of soil moisture, surface water, snow and groundwater. For the explanation of the first mode, we should also include surface water and groundwater. However, the surface water is difficult to estimate due to the changeable boundaries of the braided river, and the groundwater storage is also difficult due to its invisibility.

A space-time signal can be separate into five aspects as below [Fig. 3]. Because the absence of surface water and ground water, we cannot match the magnitude and trend of the signals and that is what we avoided to do. The agreement in the other three aspects can also support the explanation of the first mode, although not completely. That's the reason we adopted two products for comparison. In this sense, the mismatch in magnitude is inherent, and the detrended EOF analysis is not helpful.



[Fig. 3. Five aspects of a space-time signal]

If we have all the five pieces of information of land water storage change, it means that we can fully quantify it. In this situation, this study would be straightforward—we just need to remove this information from GRACE observations and the residuals would mostly be glacial and snow signals.

C2:

[section 4.3 is rewritten to explain the rationality of the comparison]

[We have stressed this problem in the manuscript:]

The exclusion of unavailable surface water and groundwater in the GLDAS result also causes a weaker strength of its EOF_1 compared to that of GRACE.

Detailed comments:

Q3:

Line 91. Note that A et al., 2013 does not include a Little Ice Age model. Not accounting for the post-LIA GIA signal will likely affect your results, especially trends.

A3:

Considering the large uncertainty of the Little Ice Age model, we only added it in the uncertainty estimates. The result of uncertainty estimates is moved from the supporting materials to the manuscript in this version.

Q4:

Lines 94-95. This is an oversimplified treatment of GRACE error. Common sources of error in GRACE application (e.g. measurement error, GIA uncertainty, leakage, etc.) have all been formally treated in the literature, and they should be considered in the study.

A4:

We have considered different error sources in the supporting materials for the long-term trend estimate (this part is moved to the main text). As you may find, many error sources are negligible in the seasonal variation, so we only consider three error sources: data solution, smoothing techniques and leakage (previously we only considered the former two sources). Therefore, we used 6 combinations of datasets/filters to estimate the monthly uncertainties and the leakage effect on seasonal variation is estimated to be up to 11% (based on simulation results). A more comprehensive uncertainty estimate is given on the long-term trend.

C4:

[We move the uncertainty estimation for the long-term trend from the supporting materials to the main text. We add an extra leakage error of 11% to seasonal variations, so most figures are regenerated].

Q5:

Line 100. Is this study focused on the glacier area? References used in the introduction sample both the upper and the entire basin (Lutz et al., 2014 vs. Huss et al., 2017). I think it is better to clarify the study area in the introduction. This could have implication for the snow and glacier mass balance calculation and for the underly hydrological regimes (e.g. mass vs. energy input limitation) that govern meltwater variability.

A5:

The glacierized zone only exist in the upper basin, so their estimates of absolute melt water are comparable in these studies. We have added a sentence to explain the situation here.

C5:

[We also addressed our study region in the end of the introduction:] Then we will use the empirical orthogonal function (EOF) analysis to decompose the hydrological and GS signals in our study region, where 85% of the meltwater runs into the Brahmaputra and 83% of glaciers in this basin locate.

[Besides, it is restressed in section 5.3 where we made the comparison]

Q6:

Line 151. Note that the spread of precipitation estimates (Fig S5) is quite large.

A6:

The spread reflects the standard deviation of values in the same month in different years, so it indicates that the seasonal pattern is not so stable. The long-term monthly average reflects the tendency of precipitation pattern. We have clarified this in the caption.

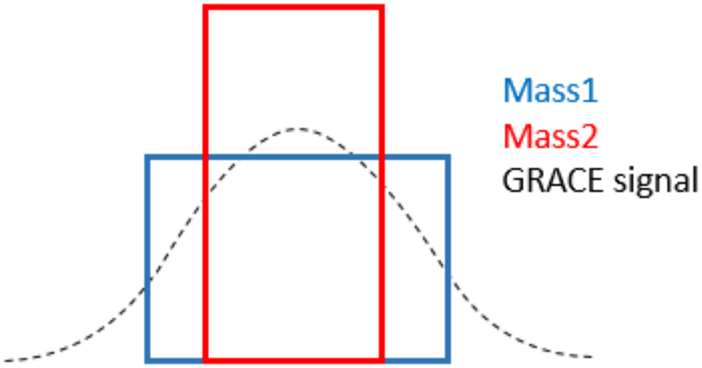
Q7:

Lines 190-191. This seems to assume that all mass changes occur in the glacier area, but the snow cover (therefore the snow mass change) extends beyond the glacier area.

The rationale of this treatment needs clarification. It is also unclear if this treatment will introduce leakage.

A7:

This step will not cause leakage, since the glacial signal has already been extracted by the EOF decomposition. A different mask for mass inversion does not influence the total mass either, as shown below [Fig. 4]. The gravity signals of mass1 and mass2 (mass1 equals mass2 in total mass) fit the GRACE observations equally well and GRACE cannot decide which one is better due to its poor spatial resolution. But we usually only care about the total mass. Since the snow area varies in different years and seasons, it is safe to use the glacierized area.



[Fig. 4. A GRACE signals fitted by two different mass distributions]

We add one explanation in the manuscript:

C7:

By this way we also assume the snow signal comes from the glacierzied area, but it does not influence the total mass estimates.

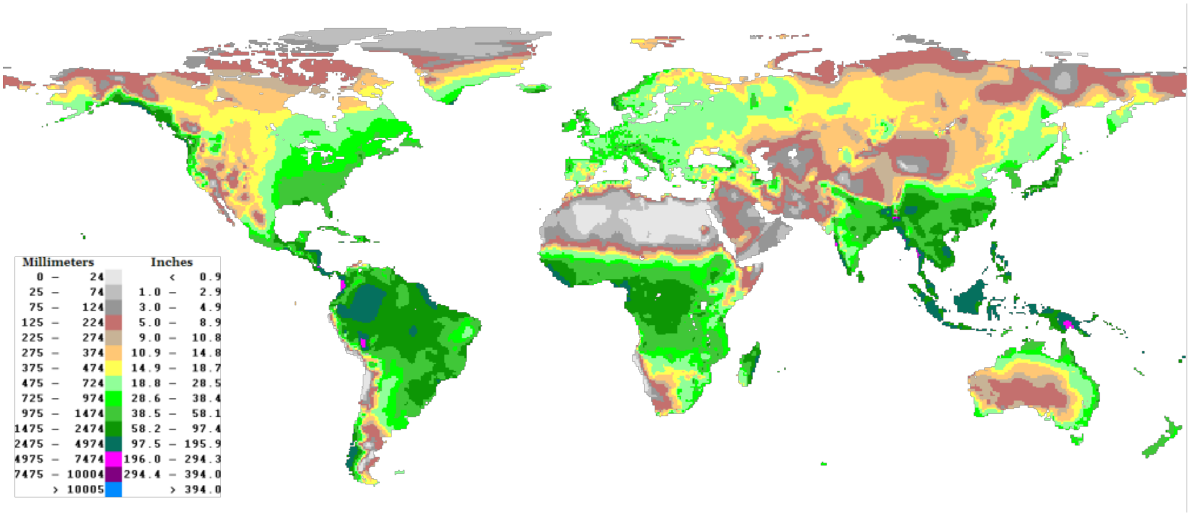
Q8:

Line 197. Hydrological components such as surface water and groundwater are not considered here. The rationale needs clarification. It is unclear to me why precipitation is included in the comparison given that precipitation affects both snow/glacier mass balance and other water storage components. Precipitation estimates are also known to be uncertain in this area.

A8:

As explained above, surface water and groundwater are excluded due to their unavailability. The precipitation in the study region is one of the strongest in the world (see the map of global precipitation shown in Fig. 5, the dark green region), and the consequent result is that the water storage change, driving by the tremendous precipitation, plays the dominant role in the gravity change here. We could not give a full estimation of water storage change, so we did it in an indirect way: we chose a main component of TWS (soil moisture accounts for over 50% of TWS change) and its major driving force (i.e., precipitation).

The precipitation here can be separated into the widespread monsoon-caused summer one and the regional spring one. The former is so strong that it has a very high signal-noise-ratio. We feel this result is quite reliable since different precipitation products give high agreement. This is the driving force of the mode 1, so we think it is reasonable to validate the mode 1 by it. We agree that precipitation products cannot well capture the regional spring one here, which is also a conclusion given in the manuscript, but this regional uncertainty does not influence the reliability of the overwhelming monsoon-caused precipitation. Even if the precipitation product can well reflect the spring one, which greatly influence snow/glacier mass balance, the spring precipitation should be mostly in the second mode.



[Fig. 5. Map of global precipitation. (Image source: https://www.eldoradoweather.com/climate/world-maps/world-annual-precip-map.html)]

Q9:

Lines 211-215. The logic here is questionable (see my earlier comment on validating the methodology).

A9:

Here we discussed the orthogonality in hydrological and glacial signals. This problem has been responded above.

Q10:

Lines 231-232. Showing the seasonality of the second mode in the GRACE series might help with this argument.

A10:

Here we wrote that although the snowfall begins in September (as MODIS data indicates the snow area increases since then), the total mass does not increase much because of small snow heights. The seasonal variation from GRACE PC_2 is given in Fig. 1 in this file, we can only see the total mass increases moderately in the winter and then rapidly in the spring.

R10:

[It has been rewritten to:]

The MODIS result indicates that the snow coverage increases rapidly since September (Figure 6~~Figure 6~~b), while the GRACE PC_2 series show a moderate increase after October.

Q11:

Line 249-250. This is a bit confusing. Are you accumulating the GRACE anomalies? These anomalies are state variables, and the difference of the anomalies (between the start and the end of each of these periods) should provide the mass change estimates. Please clarify.

A11:

Here, “monthly anomalies” mean the states relative to the long-term mean, while “monthly change” means the difference between two successive months. It has been rewritten for clarity.

C11:

We calculate annual mass increase and decrease by the difference of mass anomalies between November and May and between June and October, respectively.

Q12:

Line 255. This statement seems important but not well developed. What impact, specifically?

A12:

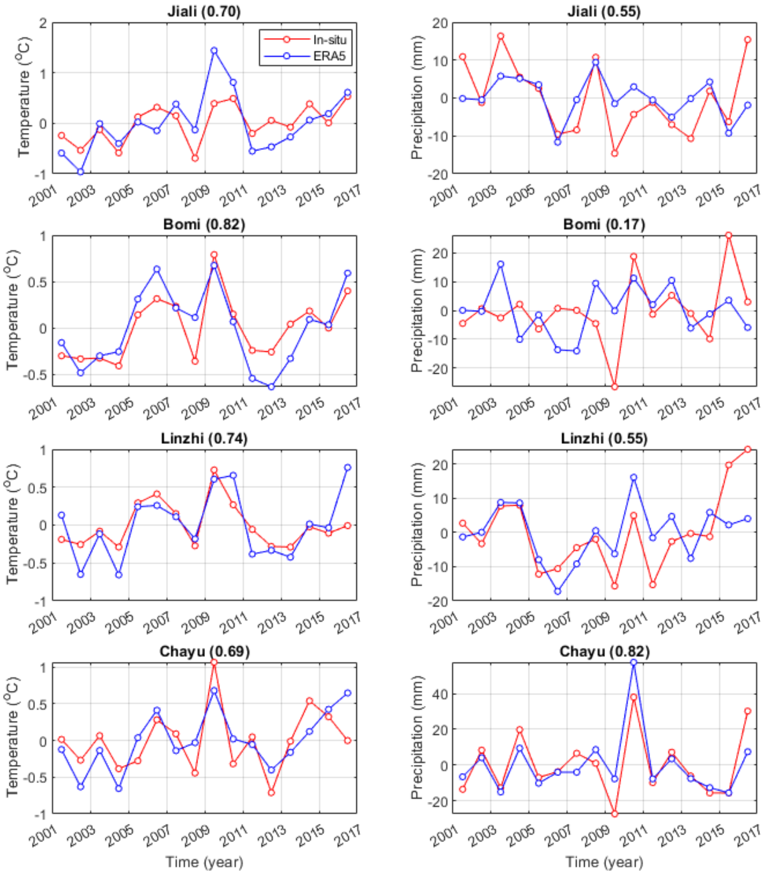
The impact is on the amount of streamflow. It has been rewritten to "Without the buffering effect of the seasonal variation, there will be a tremendous reduction in the streamflow in summer and autumn, …"

Q13:

Line 259. Using the average temperature from four meteorological stations might cause a representativeness issue. This should be either discussed or addressed in the manuscript. How about temperature from reanalysis, if possible, backed by a comparison with the station data?

A13:

Thanks for your advice. In this reversion we adopt temperature data from the ERA5 dataset by ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The dataset is compared with the station observations. The correlation in temperature ranges from 0.69 to 0.82, indicating the reanalysis temperature data is reliable here. However, the precipitation data from ERA5 and In-situ do not agree well. The conclusion is little changed after this data update. The comparison is given in Fig. 6.



[Fig. 6. Comparison of annual temperature (left) and precipitation (right) records from ERA5 and in-situ observations. The correlation coefficient is given in the title. The mean value of the whole period is removed so only anomalies are shown here.]

C13:

[The data part is changed]

Only four in-situ temperature records may not represent the overall condition of the glacierzied zone, so we adopt the gridded temperature product from the ERA5 reanalysis data processed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data is available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The reliability of this gridded data is tested by comparing with station observations and the correlation index ranges from 0.69 to 0.82 in the interannual variation, indicating a good consistency.

Q14:

Line 304. What does the realistic GS melt refer to? Please clarify.

A14:

We find a more proper word is “real”. “real GS melt” means the amount of melt really happens. As we cannot separate mass ablation/accumulation in GRACE observations, so the mass ablation is a bit offset by the mass accumulation.

Q15:

Lines 307-310. This argument needs some clarification. How are these numbers de- rived, the 2nd EOF from GRACE? Note that Lutz et al. partitioned runoff while this study calculated mass balance. Are you assuming all of the summer mass changes contribute to meltwater (without evapotranspiration)?

A15:

The result of GS is based on the 2nd EOF. Here we ignored evaporation. The assumption of neglecting evaporation in maritime glaciers was also made in Ohno et al. (1992). We have added these sentences to explain the reason:

C15:

GS mass loss may be caused by processes of flow, melting, and evaporation, while the last process does not contribute to river flow. Evaporation is important for continental-type glaciers where the climate is usually cold and dry. E.g., it accounts for 12% of the glacier ablation in Tianshan (Ohno et al., 1992). However, the importance of evaporation is greatly reduced in our maritime glaciers due to the extremely humid air and rapid melting. Therefore, we suppose that the mass loss is completely turned into meltwater and can be compared with analogous outputs from models.

[We also add a warning on the potential bias:]

Although extrapolated mass changes for the undetected 17% of glaciers and the neglected summer evaporation may reduce our estimates of summer meltwater, they definitely cannot explain the difference of more than 100%.

Ohno, H., Ohata, T. and Higuchi, K.: The influence of humidity on the ablation of continental-type glaciers. Annals of Glaciology, 16, pp.107-114, 1992.

Q16:

Lines 311-316. Note that this manuscript and the referenced studies (Lutz et al. and Huss et al.) focused on different study domains. Would that cause inconsistency in snowmelt estimates?

A16:

Their difference is mainly caused by whether the lower Brahmaputra is included or not. Since the meltwater only comes from the upper basin and both studies cover this region, we think their estimates on meltwater is comparable. We have added such a description in the introduction.

C16:

Although these two studies covered different areas, the glacierized zone in the basin was both well enclosed so the estimates should not be so different.

Technical comments:

Q17:

Lines 202-203. Why not use detrended cumulative precipitation?

A17:

The mathematical expression of precipitation integration is

$$IntP(j) = [\sum_{i=1}^{N} P(j-i+1) * W(N-i+1)] \,/\, \sum_{i=1}^{N} W(i),$$

where IntP represents the integrated precipitation in the jth month, P is short for precipitation, W is the weight for the integration, and N is the integration window.

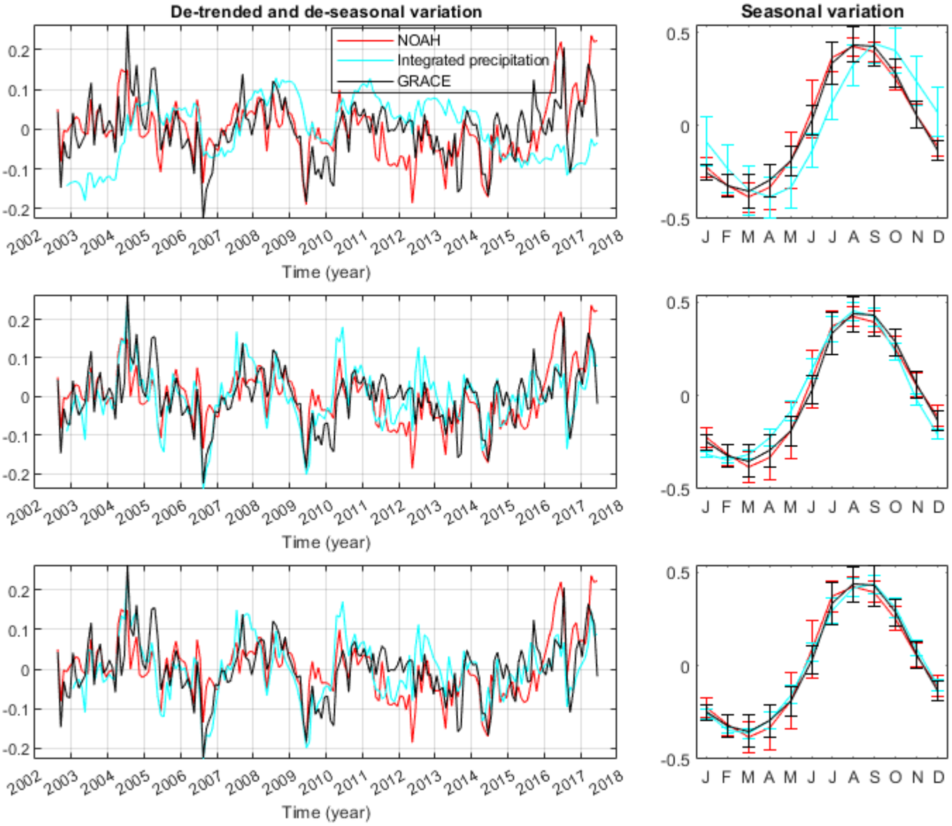
The key parameters are N and W. Below we tried three schemes. (upper), N = j, W(i) = 1; (middle), N = 4, W = [0.4,0.6,0.8,1]; (below), N = 6, W = [1,2,3,4,5,6];

The first scheme is cumulative precipitation (as you suggested). This one does not work well, because it assumes the impact of precipitation in this month is the same as that in months ago, which is not reasonable.

The second scheme is the one used in the previous version.

The third scheme is a new one with a wider integration window. We find it puts few effects on the interannual variation, but improves the agreement in the seasonal variation, so we will change to this scheme in the revision.

265 The plots are given in Fig. 7.



[Fig. 7. Different methods for precipitation integration]

Q18:

Line 212. Should specify SI text 3.1 and Figs S9-10 here. Incidentally, I notice there is a discussion about error in the supplementary material. They should be referenced in the main text. 270

A18:

It has been specified. We also have moved the error estimation to the manuscript.

Q19:

Line 485. Should be (b, d) instead of (column, d).

A19:

It has been corrected.

Response to the 2nd reviewer:

Below, the black texts are comments, the blue is our response, and the orange is the revision in the manuscript.

The reviewer raised six major concerns. The first one is about the undetected western glaciers in the basin. We find there are 17% of glaciers undetected so we estimate the total meltwater by dividing a ratio of 1/0.83. The second is a suggestion of using temperature reanalysis products. We follow this advice and adopt the ERA5 dataset. The third one is why canopy and snowpack in GLDAS is not used. We explain that canopy is three orders of magnitude smaller and snowpack belongs to the second mode. The fourth is how to deal with the glaciers outside the basin. We answer that these glaciers had already been excluded in the basin-scale estimation. The fifth is about uncertainty estimation in GRACE and possible leakage from adjacent regions. We add the content on uncertainty estimation and show that the signals raised by the reviewer are too far to cause a leakage. The sixth is why evaporation was neglected. We discuss that evaporation is supposed to be zero in the maritime glaciers.

This study evaluates the contribution by meltwater (Glacier Melt + Snowmelt) to the total runoff of the Brahmaputra river basin. By employing monthly observations of time-variable gravity from the NASA/DLR GRACE mission, the authors try to partition the total runoff (water transfer in the form of river streamflow from the upstream to the downstream areas of the basin) between by glacier melt, and direct runoff from precip- itation. According to the methodology proposed in the study, given the different phases characterizing the annual variation of snowpack, glacier, and terrestrial hydrology, their contribution to temporal changes in terrestrial water storage in the region can be separated by employing an Empirical Orthogonal Function analysis approach. To validate their findings, the authors employ data from independent ground- and satellite-based observations like glacier mass balance estimates from the NASA ICESat mission and monthly precipitation from the NASA/TRMM project and the HAR reanalysis model. Finally, the authors compare seasonal changes in glacier mass with temperature from 4 atmospheric stations available within the region in order to evaluate the sensitivity of glacier mass balance to changes in temperature. I find that the study fits the scope of the journal and that the approach presented here of interest for the scientific com- munity since findings by previous studies are in large disagreement and characterized by large uncertainties. However, the author's claims are not completely justified by the results presented here. I will present my main observations below:

1) The study focuses on the Brahmaputra river basin. However, the results presented here are relative to the eastern side of the catchment (the authors explicitly refer to the mass balance of the Nyenchen Tonglha Mountains and South-Eastern Himalayas glaciers). The glaciers located on the West are never even mentioned in the article. Even though the total area of these glaciers is significantly smaller than the area of glaciers situated in the east, the effect of their mass change on the final estimates should be considered in the total budget. Note also that the exclusion of these glaciers in the presented evaluation could influence the results of the comparisons with previous studies. The authors should at least explain the reasons for their exclusion from the

analysis should be discussed in the article (e.g., given that GRACE coarse resolution, the signal originated from this side of the basin can hardly be separated from signals originated within the surrounding regions).

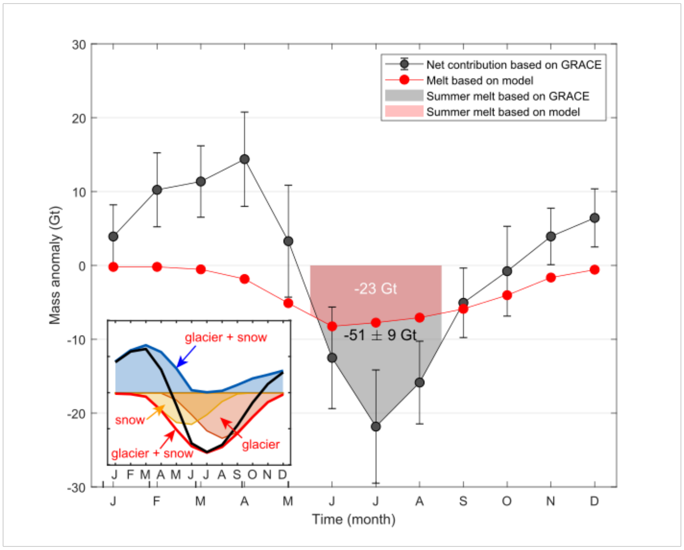
Thanks for the advice. We had written in the previous version that “In our study region, 85% of its meltwater (estimated according to the area proportion) runs into the Brahmaputra and this area accounts for 83% of total glaciers in this basin (9,912 km^2)” and we simply ignored the undetected 17% of glaciers due to their sparse distribution. In this version, we scale our result to consider this part by assuming a similar GS mass change rate.

[We add an explanation in section 5.3:]

Assuming that the unobserved 17% of glaciers hold the similar rate of GS mass change, our estimate of mass change is scaled by a ratio of $1 \times 0.85/0.83 = 1.02$ to represent the GS mass change of the entire Brahmaputra Basin.

[Besides, it is restressed in section 5.3 where we made the comparison]

[Fig. 8 is updated. (previously the scaling ratio is 0.85, here the ratio is 1.02)]



[Fig. 1. Updated version of Fig. 8 in the manuscript]

[We also add a warning on the potential bias:]

Although extrapolated mass changes for the undetected 17% of glaciers and the neglected summer evaporation may reduce our estimates of summer meltwater, they definitely cannot explain the difference of more than 100%.

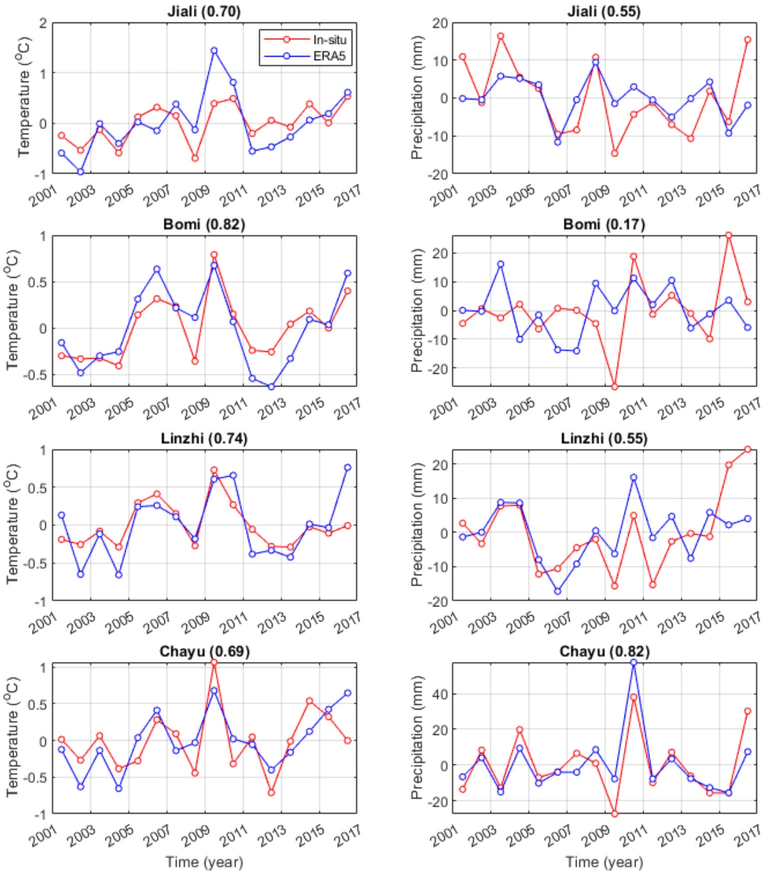
2) Climatological data: to prove their claims, the authors employ data from 4 meteo- rological stations available in the region and precipitation estimates from TRMM and HAR.

2a)In the case of the meteorological stations, their distribution is not sufficient to provide an evaluation of atmospheric temperature variability at a regional scale (considering the large variability of local relief in the area). Data from stations should be used with caution in the evaluation of the gridded datasets given their intrinsic bias toward low elevations and underestimation of solid precipitation.

Due to the harsh environment, only four stations are available here. We agree that the precipitation condition is not well represented by these four stations due to the manifest spatial and altitudinal variations. In this version, we adopt the ERA5 reanalysis data for temperature variations and the details are shown below.

2b) Regarding the gridded datasets used here, the authors briefly mention the limita- tions of these two data products (Underestimation of solid precipitation in the case of TRMM and the presence of long-term biases in precipitation trend in the case of HAR). I think that adding other datasets to the analysis could help to make the analysis more robust and help to assess the uncertainty associated with these estimates. Why not using outputs from gridded temperature datasets like APHRODITE, ERA-Interim, etc. ?

APHRODITE ended in 2007, so it is not helpful for this study. The ERA-Interim has been superseded by the ERA5, so we take precipitation data from the ERA5 reanalysis dataset by ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The dataset is compared with the station observations. The correlation in temperature ranges from 0.69 to 0.82, indicating the reanalysis temperature data is reliable here. However, the precipitation data from ERA5 and In-situ do not agree well. The conclusion is little changed after this data update.



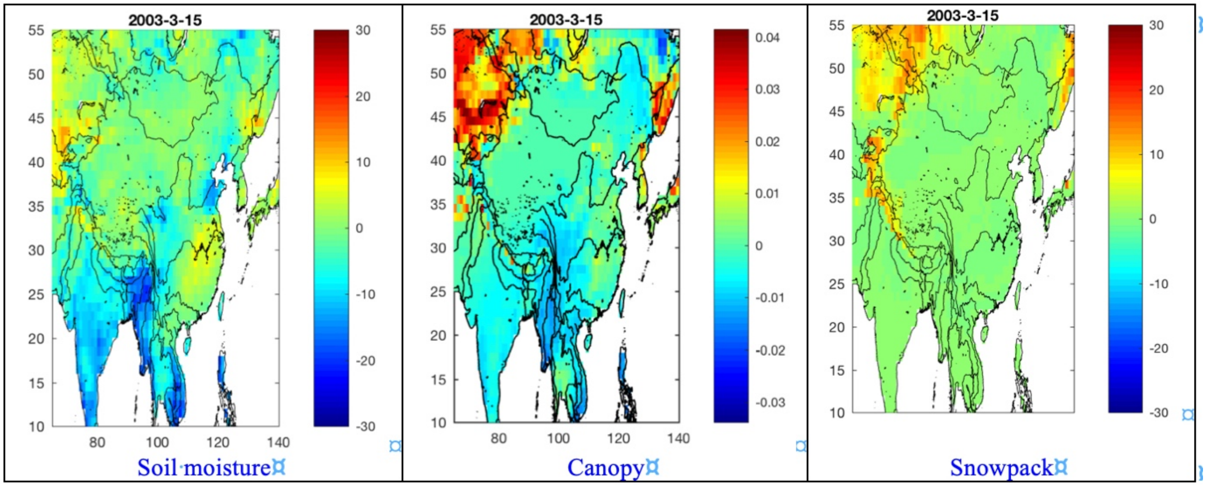
[Fig. 2. Comparison of annual temperature (left) and precipitation (right) records from ERA5 and in-situ observations. The correlation coefficient is given in the title. The mean value of the whole period is removed so only anomalies are shown here.]

[The data part is changed]

Only four in-situ temperature records may not represent the overall condition of the glacierized zone, so we adopt the gridded temperature product from the ERA5 reanalysis data processed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data is available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The reliability of this gridded data is tested by comparing with station observations and the correlation index ranges from 0.69 to 0.82 in the interannual variation, indicating a good consistency.

3) Validation of Mode 1: why is only soil moisture from GLDAS used to validate this mode1. The contribution of the other TWS components in the model (snowpack and canopy) should be included in the comparison. In any case, groundwater would not be considered in the equation. Figures 3 and 5 show a significant difference in amplitude between GRACE and GLDAS. The discussion would probably benefit from a picture showing the monthly time series from GRACE and GLADS. Note also that the negative trend observed in this mode can't be attributed only to decreasing precipitation.

The reason of excluding canopy component is that the mass changes induced by the canopy component is nearly negligible comparing with hydrological or glacial mass changes in this region. The result of March 2003 is shown as an example below (units are equivalent water height in cm). Note the strength of canopy is three orders of magnitude smaller than the others. The snowpack is almost zero throughout the year in the study region as well. Even if it is not zero, we should not include it in the validation of hydrological signals (mode 1), but in that of glacial signals (mode 2).



Soil moisture

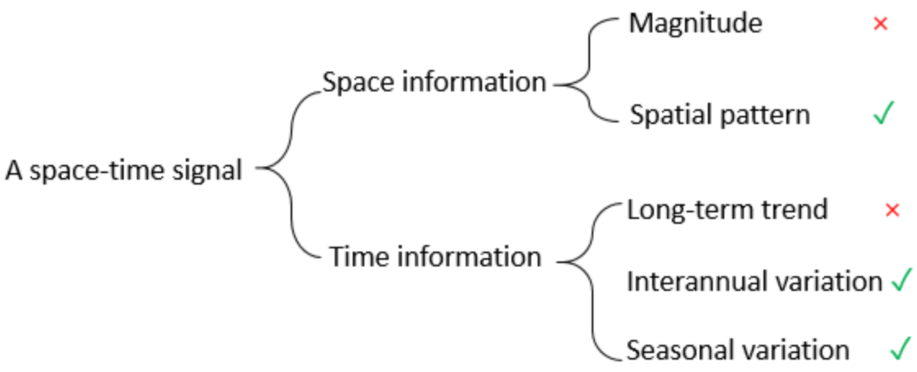
Canopy

Snowpack

[Fig. 3. Components of soil moisture, canopy and snowpack in China and surrounding by using GLDAS.]

Terrestrial water storage consists of soil moisture, surface water, snow and groundwater. For the explanation of the first mode, we should also include surface water and groundwater. However, the surface water is difficult to estimate due to the changeable boundaries of the braided river, and the groundwater storage is also difficult to get due to its invisibility.

A space-time signal can be separate into five parts as below. Because the absence of surface water and ground water, we cannot match the magnitude and trend of the signals and that is what we avoided to do. The agreement in the other three aspects can also support the explanation of the first mode, although not completely. That's the reason we adopted two products for comparison.



[Fig. 4. Five aspects of a space-time signal]

If we have all these five pieces of information of land water storage change, it means that we can fully estimate it. In this situation, this study would be straightforward—we just need to remove this information from GRACE observations and the residuals would mostly be glacial and snow signals.

The time series of GRACE and GLDAS had been decomposed into interannual and seasonal time scales and compared in Fig. 5e and Fig. 5f. If you feel interested in the original time series, the original time series are overwhelmed by the strong seasonal variations (the magnitude of GRACE nearly doubles that of GLDAS) so they are difficult for more detailed comparison.

We had already explained the source of the negative trend in the first mode by both precipitation and groundwater pumping: *The negative trend in the first mode is likely due to decreasing precipitation in recent years (Figure S8) and intense groundwater pumping (Shamsudduha et al., 2012).*

[section 4.3 is rewritten to explain the rationality of the comparison]

[We have stressed the difference in the magnitude of EOF1 in the manuscript:]

The exclusion of unavailable surface water and groundwater in the GLDAS result also causes a weaker strength of its EOF_1 compared to that of GRACE.

4) GS mass estimation from mode 2: figure 4e shows that the mask used to extract the glacier mass change signal exceeds the basin boundaries. Therefore, the glacier mass change time series presented in the study is representative also glaciers outside the river catchment. Is this approximation considered in the uncertainty evaluation?

We explained that 85% of the total meltwater runs into the Brahmaputra in Section 5.3. We reemphasized this problem in the introduction in this version.

GRACE Processing:

- As briefly mentioned before, the main limitation with using GRACE in the in this region is that considering the coarse resolution of gravity observations, the GS signal from the Western side of the upper basin can't be resolved or separated from the signal relative to the upper basin of the Ganges river on the South and Tibetan Plateau on the North. The authors focus their analysis on the eastern side of the basin not providing, in this way, a complete evaluation of the glaciers and snow contribution to the total runoff. This limitation in the presented analysis should, at least, be discussed in the paper or in the discussion section. A possible solution could be to consider the effect on river runoff only on the NTM glaciers which is what the authors actually do. This limitation should be discussed in the article.

This problem has been responded above.

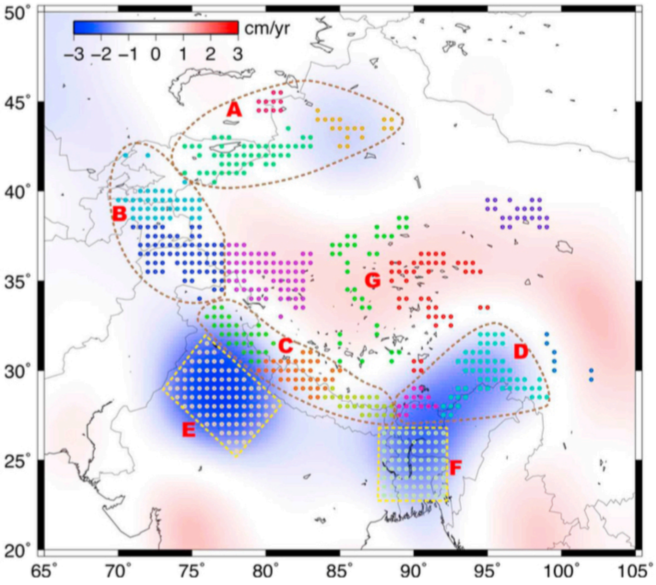
- Considering the standard of 6 gravity field solution seem to be a simplistic approach to evaluate the uncertainty affecting the TWS anomaly measurements. Error terms like the GRACE Measurement Error and Leakage from hydrological and glaciological signals originated from regions surrounding the region of interest should be considered.

We have considered different error sources in the supporting materials for the long-term trend estimate (this part is moved to the main text). As you may find, many error sources are negligible in the seasonal variation, so we only consider three error sources: data solution, smoothing techniques and leakage (previously we only considered the former two sources). Therefore, we used 6 combinations of datasets/filters to estimate the monthly uncertainties and the leakage effect on seasonal variation is estimated to be up to 11% (based on simulation results). A more comprehensive uncertainty estimate is given on the long-term trend.

[We move the uncertainty estimation for the long-term trend from the supporting materials to the main text. We add an extra leakage error of 11% to seasonal variations].

- In the case of the leakage error, the authors discuss only the effect of the signal leaking between the two main EOF modes (see supplementary material). At the same time, more attention should be paid to the impact of signal leaking from other regions that, in this area, is not negligible. See Anthropogenic water depletion over the Indian Plains and TWS changes of other ice-covered regions of Western and Central Asia. This effect is non-negligible not only when talking about long-term variations but also when analyzing the seasonal changes in TWS and can significantly affect the results of the presented analysis.

The other signals are thousands of kilometers away and their influence on our study region is negligible. As shown below, the location of the North India groundwater depletion is in region E, while here region D and F are studied. The figure is from Yi and Sun (2014).



[Fig. 5. Trend of gravity change in Tibet using GRACE. The figure is excerpted from Yi and Sun (2014)]

- Considering that the authors use GRACE to quantify the average annual contribution by meltwater to the total river runoff, the effect of the application of different smoothing strategies should be quantified or at least discussed.

We considered two widely used filters in the estimates and their difference is included in the trend error estimation. From Fig. S7, you may find the difference between different filters is smaller compared to that between different data solutions.

- I would add the error estimation section, available in the supplementary material, to the main text.

The error estimation has been moved to the manuscript by following your suggestion.

Average summer contribution by GS to the total river runoff: In the final section of the article, the authors use the glacier mass loss measured by GRACE during the sum- mer months to estimate the average contribution by meltwater to river discharge. This approach does not consider the effect of evaporation and other hydrological processes that should be accounted for in this evaluation. The entire evaluation should be, there- fore, reviewed. Also, the comparison with Lutz et al. should be considered with caution since, as discussed above, the glacier areas considered in the two studies are different.

We have added these descriptions to show the reason of neglecting evaporation. The assumption of neglecting evaporation in maritime glaciers was also made in Ohno et al. (1992).

GS mass loss may be caused by processes of flow, melting, and evaporation, while the last process does not contribute to river flow. Evaporation is important for continental-type glaciers where the climate is usually cold and dry. E.g., it accounts for 12% of the glacier ablation in Tianshan (Ohno et al., 1992). However, the importance of evaporation is greatly reduced in our maritime glaciers due to the extremely humid air and rapid melting. Therefore, we suppose that the mass loss is completely turned into meltwater and can be compared with analogous outputs from models.

[We also add a warning on the potential bias:]

Although extrapolated mass changes for the undetected 17% of glaciers and the neglected summer evaporation may reduce our estimates of summer meltwater, they definitely cannot explain the difference of more than 100%.

Ohno, H., Ohata, T. and Higuchi, K.: The influence of humidity on the ablation of continental-type glaciers. Annals of Glaciology, 16, pp.107-114, 1992.

Minor Comments:

Line 13: using retreating instead of reducing would probably work better.

It has been changed.

Line 15: low temporal resolutions of what?

It has been changed to "the low temporal resolutions in previous observations of GS mass balance"

Line 16: We find that the "spring-accumulation" . . . Rephrase

It has been rewritten as:

We find that the “spring-accumulation type” glaciers and snow in the SETP reach their maximum in May.

Line 26: I would change regarded to considered.

It has been changed.

Line 27: “The sustainable . . .” rephrase

It has been rewritten as:

The GS melt is susceptible to climate change, while its sustainable supply is the key to the local freshwater security, flood prevention and control, and hydroelectric development

Line 39: change calibrated by streamflow to calibrated by employing streamflow data.

It has been changed.

Line 50: Rephrase.

It has been written as:

The first two geodetic approaches require the average ice density to convert volume changes into mass changes.

Line 57: Observations at a monthly temporal resolution. . .

It has been change.

Line 75: Rephrase

It has been rewritten as:

Therefore, according to the climate stations near NTM, we can observe that there are two peaks in precipitation throughout the year.

Line 136: “The method of this study. . ..”: rephrase.

It has been rewritten as:

The method of this study is based on the fact that the change in GS mass driven by spring precipitation is earlier than the change in hydrological signals

Line 138: Using rain gauges to compare winter summer precipitation could be a risky approach considering the intrinsic underestimation of solid their intrinsic bias toward low elevation.

We agree with you here. It is difficult to make a quantitative comparison. Here we only present whether spring precipitation is detectable or not.

Line 158: more or less?

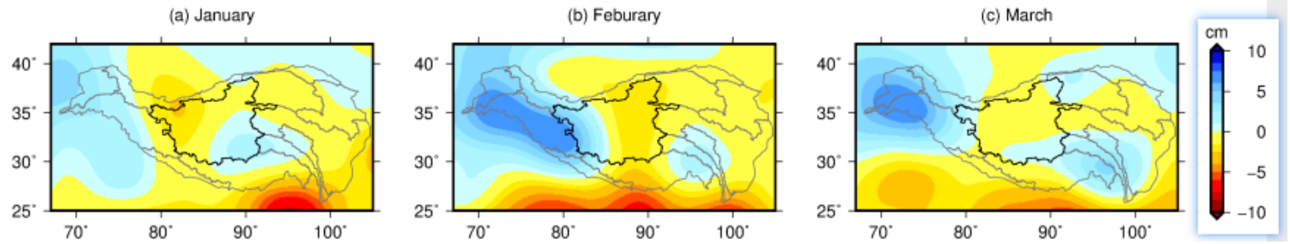
This sentence has been rewritten as:

These results show that spring precipitation can only be partially captured by various measurements/products.

Line 160: The authors discuss the difference in moths of seasonal changes between the northern and the southern side of the basin as a proof of the orthogonality between the signal associated with glacier and terrestrial hydrology temporal changes. In order to prove this claim, the author could perform the same analysis on the regions located on the western side of the Tibetan Plateau where an even more massive presence of glaciers and a minor exposition to monsoonal precipitation should show the same variation pattern.

I guess you mean the Pamir Plateau. As you may find in Figure below (units are cm in equivalent water height), the westerly brings strong gravity increase there in winter (ahead of gravity increase in our study region). That region is mostly free from the monsoonal precipitation, so the hydrological and glacial signals are synchronized due their identical driving force. Therefore, our method is not applicable there. In fact, it is impossible to separate them without other data.

The study region in this work is quite particular as the intersection of two distinct climatic systems.


(a) January
(b) Feburary
(c) March

[Fig. 6. Mass anomalies in Tibet from January to March by using GRACE]

Line 175: What is the effect of TWS mass loss in the Indian Plains region on this negative trend? Can this mass loss be attributed just to glacier mass balance?

I suppose you referred to the trend in the first mode (I could not find contents about a trend in this line) and the mass loss in the north Indian Plains. As explained above, the north Indian Plains are too far away to put an influence here. We discussed in the SI about the possible leakage between signals of water storage and glaciers and concluded that the leakage must be small.

Line 190: the glacier mask presented in figure 4e covers glaciers outside the river catchments. Is this considered in the uncertainty evaluation?

We excluded glaciers outside the basin and we had explained it in the result part. We have reemphasized it in the end of the introduction.

Line 200: The methodology used to cumulate monthly precipitation data should be clarified.

The method to integrate monthly precipitation is widely used in the comparison of GRACE data with precipitation data, so we did not repeat its exact expression here. For example:
- Crowley, John W., et al. "Annual variations in water storage and precipitation in the Amazon Basin." Journal of Geodesy 82.1 (2008): 9-13.
- Reager, J. T., and J. S. Famiglietti. "Global terrestrial water storage capacity and flood potential using GRACE." *Geophysical Research Letters* 36.23 (2009).

Its mathematical expression is

$$IntP(j) = \left[\sum_{i=1}^{N} P(j-i+1) * W(N-i+1)\right] / \sum_{i=1}^{N} W(i),$$

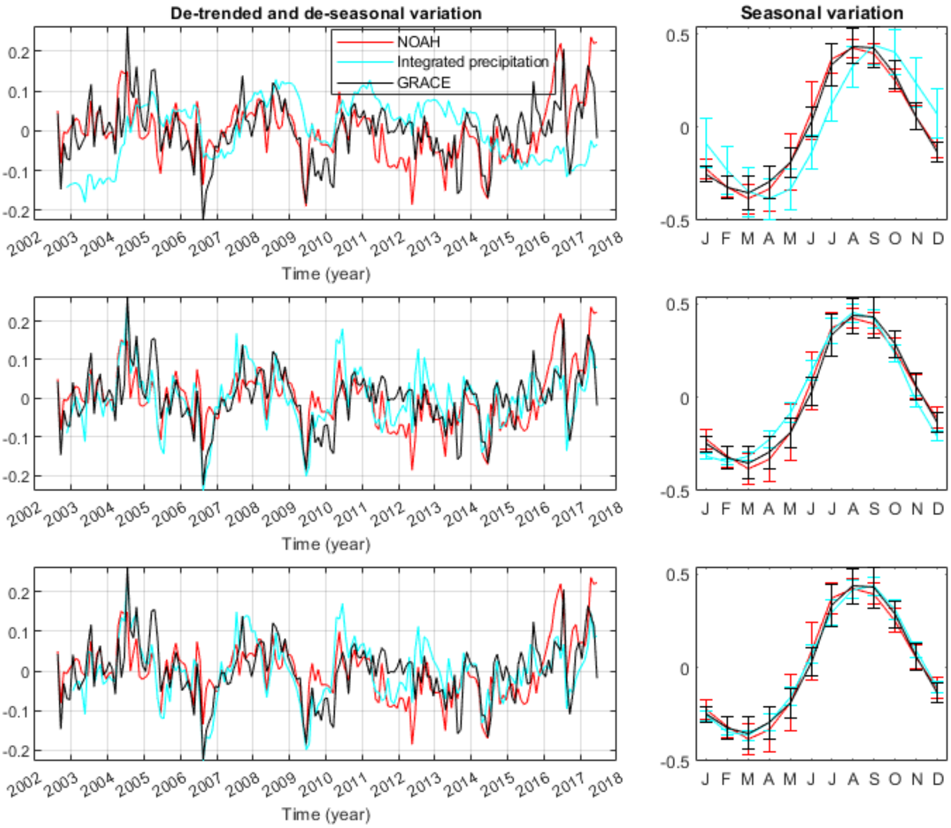
where IntP represents the integrated precipitation in the jth month, P is short for precipitation, W is the weight for the integration, and N is the integration window.

The key parameters are N and W. Below we tried three schemes. (upper), N = j, W(i) = 1; (middle), N = 4, W = [0.4,0.6,0.8,1]; (below), N = 6, W = [1,2,3,4,5,6];

The first scheme is precipitation accumulation. This one does not work well, because it assumes the impact of precipitation in this month is the same as that in months ago, which is not reasonable.

The second scheme is the one used in the previous version.

The third scheme is a new one with a wider integration window. We find it puts few effects on the interannual variation, but improves the agreement in the seasonal variation, so we will change to this scheme in the revision.



[Fig. 7. Different methods for precipitation integration]

Line 220: The same as line 200 – this is an assumption that the authors should prove with further evidence and provide them with a proper evaluation of the relative un- certainty. The trend observed here is determined also by the groundwater depletion observed in other studies,

Here we wrote the negative trend in the first mode is caused by both decreased precipitation and groundwater pumping. I think it is troublesome to quantify this trend, which is influenced by spatial range, time span and accurate modeling of the influence of climatic factors/human activities. Although there have been some studies in groundwater depletion in specific regions, they are not helpful given the larger unknowns. Besides, the 1st mode is not the focus of this study. I am sorry that we cannot provide more accurate evaluation here.

Line 225: what is the value used as “glacier density” here?

We explained in section 2.2 that glacier density is 850 +- 60 kg/m3 from Huss (2013)

Line 249-246: As mentioned above, the numbers from Lutz et al. can’t be really com- pared with the number presented here.

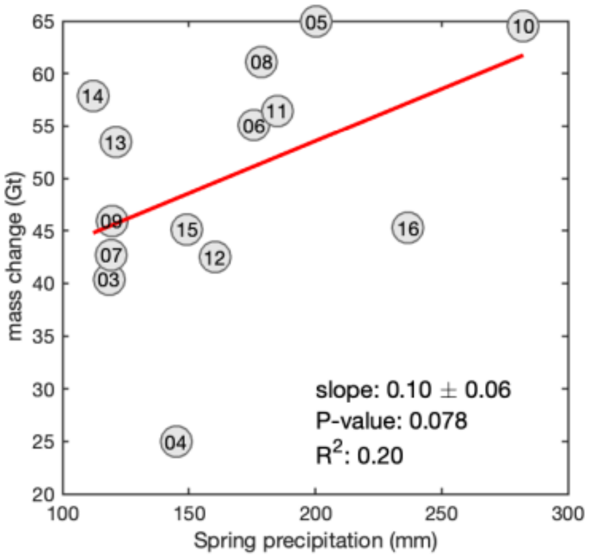
This problem has been responded above.

Line 254: From where does the -6.5 Gt come from? Please clarify.

It is from this study. It has been clarified.

Section 5.2 A high correlation between summer mass loss and atmospheric temperature is expected but what is the effect of other climatic variables on the interannual variation of glacier mass balance?

Another frequently investigated variable is precipitation. However, we could not find a significant correlation between mass gain and spring precipitation (shown below), so this result was not given in the manuscript. The possible cause may be that our data cannot reflect the complex distribution of precipitation well.



[Fig. 8. Correlation between spring precipitation and GS mass change in the southeast Tibet]

We have added one sentence to explain why the correlation between mass and precipitation changes is not scrutinized:

We could not find a significant relationship between the mass and precipitation changes, probably because our data fail to reflect the strong orographic effect in precipitation, and/or the GS mass gain process is too complex to be attributed to precipitation alone.

Response to the 3rd reviewer:

Below, the black texts are comments, the blue is our response, and the orange is the revision in the manuscript.

The reviewer raised four main concerns. The first one is the novelty of this manuscript. We reorganize and restate the novelty of this research in the Introduction and Conclusion sections to highlight that it provides the first separation result of monthly glacier and snow mass balance in this region. The second one is to add the citations of more-recent work. The third one is about the reliability of the ICESat results (a suspicious jump in the result is questioned). We argue that its reliability has been widely discussed in previous studies and the jump is reasonable. The fourth is the method to integrate precipitation, on which more details are provide to support it.

Received and published: 10 January 2020

General comments:

This study aims to estimate glacier and snow mass balance in the Upper Brahmaputra River basin in China using GRACE data with the empirical orthogonal function (EOF) method and then the results of glacier and snow mass changes were compared with estimates from ICESat. The authors also demonstrated that spring precipitation-driven glacier/snow mass changes can be detected by GRACE. This topic would be of interest to readers of this journal. However, the method used in this study lacks novelty and the conclusions offer no new insight into this topic. Also, the authors need to pay attention to a lot of language issues in the manuscript.

This work aims to provide a comprehensive investigation on glacier and snow mass changes between 2002 and 2017 in the southeastern Tibetan Plateau with multiple ground and space-born measurements. By overcoming previous difficulties in data processing, this is the first presence of region-wide (~10,000 km^2) glacier and snow mass balance down to the monthly timescale. The result would be greatly beneficial for the calibration of glaciological and hydrological models in this region, which were ever only indirectly calibrated by streamflow discharge and thus diverge widely. The strong seasonal glacier and snow mass variation, which has not been recognized before, provides considerable water supply for streamflow in the Brahmaputra and is found to be sensitive to temperature rise. The calibration from our detailed glacier and snow mass balance estimate may also improve the performance of models in other glacierized regions where measurements are still scarce.

This work also has innovations in terms of methodology. Despite of the good spatial coverage and high temporal resolution, the product of satellite gravimetry GRACE has been notorious for its poor spatial resolution (>300 km) which impedes its application in many fields. Therefore, it is previously impossible to extract the glacial signal from the background of the hydrological signal in our study region due to their proximity. However, we find the good temporal orthogonality between these two signals make it possible to separate them in the temporal domain. The temporal decomposition provides a new idea to overcome the spatial limitation of GRACE and may inspire its application in other regions.

Despite either GRACE data or EOF analysis has been widely used, they are seldom combined for the purpose of separating the signals from glacier and snow mass changes. Besides, we put a lot of focus on the validation from other datasets.

We summarize the contribution of this work as the following four points:

1. Comprehensive investigation on glacier and snow in the southeast Tibet with multiple data sources
2. We find temporal orthogonality in glacial and hydrological signals
3. The first presence of monthly region-wide glacier and snow mass balance
4. The result of monthly mass balance is compared with climatic variables and comparative model estimates.

We are sorry for the language problem. We have tried our best to polish the manuscript thoroughly.

Specific comments:

1.The Abstract and much of the manuscript are not associated with the title's emphasis of meltwater contribution. It seems that the manuscript is much focused on glacier mass balance. Only summer meltwater contribution was shown in the abstract (line 21) and it is not expressed as a percent which prevents readers from direct comparison with other studies.

The title is changed to "Satellite-observed monthly glacier and snow mass changes in Southeast Tibet: implication for substantial meltwater contribution to the Brahmaputra." We also add more information about the mass balance in the abstract.

Our results show a long-term trend of -6.5 ± 0.8 Gt yr^{-1} (or 0.67 ± 0.08 w.e. m/yr) and annual mass decreases ranging from -43.4 Gt to -73.1 Gt with an average of -57.6 Gt in the SETP between August 2002 and June 2017. The contribution of summer meltwater to the Brahmaputra streamflow is estimated to be 51 ± 9 Gt.

As we explained in the manuscript, it is difficult to give the amount of the total meltwater by observations. We have written this part to further clarity it.

GRACE only detects the net change in GS and cannot separate mass ablation and accumulation (see the inset in Figure 8~~Figure 8~~). Because these two processes concur simultaneously in transitional seasons and offset to some extent, the annual mass decrease is smaller than the real GS melt. As a result, the annual mass decrease provides a lower bound on annual GS melt each year, rather than an accurate estimate. Instead, the amount of GS melt can be better determined during the summer (from June to August), when the accumulation is supposed to be small. This value can be used to validate the model output.

2.The introduction could be improved (lines 38-42) with some more up-to-date literatures. Many studies estimate contributions of seasonal meltwater using modeling approaches. The hydrologic model was not only calibrated by streamflow but also by other relevant water component products. Furthermore, hydrologic modeling could provide meltwater time series with much higher temporal resolution than GRACE data. The reason why this study used remote sensing data to calculate meltwater contributions needs to be articulated.

We cite two recent work that adopted the latest model (Wijngaard et al., 2017; Biemans et al., 2019). The calibration and validation from glacier and snow mass balance was highlighted and attempted by these studies. However, as we describe below, their calibration and validation data have large room for improvement, especially for the regions with rugged topography and rare ground measurements.

We agree that there are many model-based estimates and their results are finer in temporal resolution. However, as we elaborated in the second paragraph of the Introduction and Table 1, the problem of model-based estimates is that their results cannot reach an agreement. We feel the only way to address these large discrepancies is to adopt calibration and validation of glacier and snow mass balance. The latest model is evolved in this direction, and our result of glacier and snow mass balance is much more detailed in time than before.

Such huge discrepancies in previous estimates make it imperative to incorporate the calibration from GS mass balance observations into future modelling experiments. Actually, the concept of assimilating more GS observations has begun to be implemented in the state-of-the-art models (Wijngaard et al., 2017; Biemans et al., 2019), but their glacier results suffered from coarse temporal resolution (two observations over a 5-year span) and the snow mass changes were partially constrained by area changes.

Biemans, H., Siderius, C., Lutz, A., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R., Wester, P., Shrestha, A. and Immerzeel, W.: Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability, 2(7), pp.594-601, 2019.

Wijngaard, R., Lutz, A., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. and Immerzeel, W.: Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. PloS one, 12(12), 2017.

3.Why did the authors use TRMM and HAR to analyze precipitation? In many studies on the evaluations of remote sensing precipitation products, TRMM did not perform well on the Tibetan Plateau. Figure S5 shows that both TRMM and HAR cannot capture spring precipitation well. In addition, the precipitation in spring is from March to May, not January to March (line 144).

The spring precipitation was recognized from records at ground stations, so readers may feel curious that whether gridded precipitation products can see it or not. These two datasets (TRMM and HAR) have higher spatial resolution than other products so they were used for this localized study. After comparison, we agree that the precipitation products do not well capture the impact zone of the spring precipitation, but they indeed show that precipitation increases in spring.

Here we tried to show how the spring precipitation formed and evolved, so the result begins from January. We have rewritten this sentence for clarity (here we only use the TRMM and HAR results from January to March in Figure 2~~Figure 2~~ to show the initiation of spring precipitation). The result in Apr. and May is quite similar as that in Mar., so we did not show here.

4.There are large uncertainties in glacier mass changes derived from ICESat. For example, glaciers in 2009 should have been melted substantially, but the results showed a positive balance (Figure 6). Why did you compare the glacier mass balance derived from ICESat that involves large uncertainty with that estimated from GRACE?

In our knowledge, there is no other data that can work better in the regional-scale validation of GRACE result than ICESat currently. ICESat has been widely used in this region, and its reliability has been widely discussed. for example:

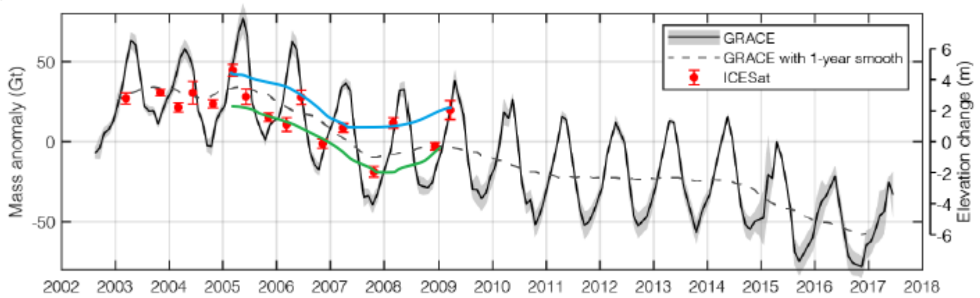
Kääb, A., et al. "Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya." *The Cryosphere* 9.2 (2015): 557-564.

Neckel, Niklas, et al. "Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements." *Environmental research letters* 9.1 (2014): 014009.

Kääb, Andreas, et al. "Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas." *Nature* 488.7412 (2012): 495.

Gardner, Alex S., et al. "A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009." *science* 340.6134 (2013): 852-857.

ICESat results show a height increase in 2009, which is mostly due to seasonal variation. If we connect the ICESat results in the accumulation and ablation seasons separately (the blue and green lines below), we can find they show a similar trend as the smoothed GRACE series.



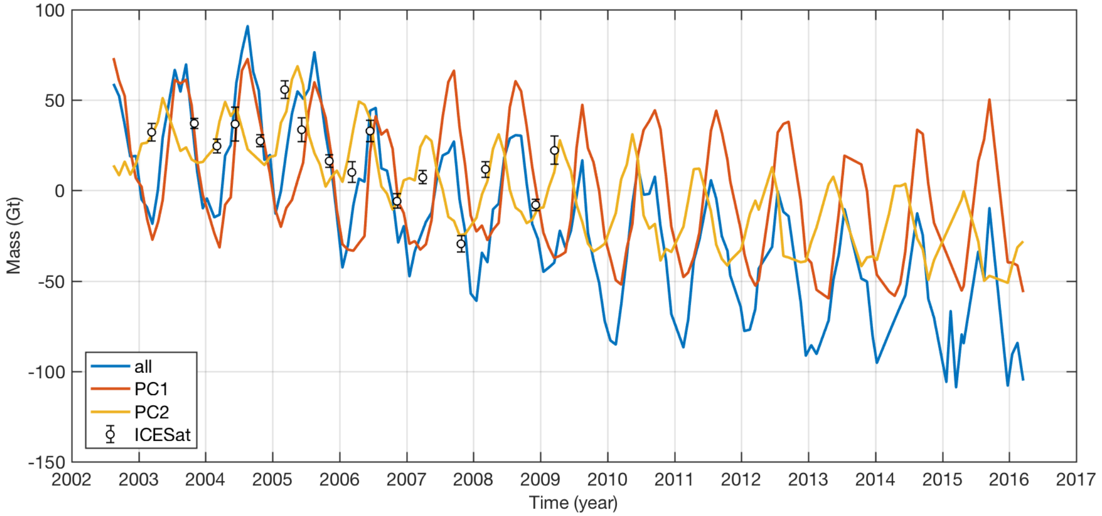
[Fig. 1. GS mass balance estimates by using GRACE and ICESat]

5.Line 176: I don't think it's the reason of "the first mode is much stronger than the second one". The first mode is stronger because it explains the larger portion of the total variance.

I feel our explanation is the same to yours. The 1st mode explains the larger portion of the total variance because most grids have the changing pattern of the 1st mode, while only a few grids in glacierized zone has the changing pattern of the 2nd mode, i.e., the 2nd mode is more localized.

6.Lines 175-177: I cannot see that these two modes are comparable on both seasonal and secular temporal scales. Please give more explanations.

The sentence describes what we found in the result. The time series of the first two modes in the glacierzied zone is show below. You may find the orange and yellow lines have a comparable trend and seasonal variation.



[Fig. 2. Mass changes in different PCs of GRACE and comparison with ICESat.]

7.Lines 182-184: I think it is too sloppy to conclude that the first mode represents hydrologic signals and the second mode represents glaciers. More solid evidence should be provided.

We agree with you that it should be careful to explain the result of EOF. That’s why we cautiously added the adverb “seemingly” here. In the later part we adopted other datasets to validate this assumption.

8.Line 195: Why did the authors choose soil moisture and precipitation data sets to validate mode 1? Maybe air temperature is also strongly correlated to mode 1.

Generally, the majority of gravity change detected by GRACE comes from water storage change and glacier/ice mass change, which corresponds to the 1st and 2nd mode here. Considering the tremendous precipitation (one of the largest in the world) here, there is no doubt that water storage change plays the leading role in the gravity change in this place. Air temperature does not result in mass change, but it may induce a mass change by influencing the rate of water evaporation or ice melting. Then, we come back to the water storage change and ice mass change.

Although the theoretical relationship exists, air temperature is often not investigated not only because it is indirectly correlated (as the reason given above), but also because its influence on evaporation or melting is quite complex. Other factors, like humidity and wind speed, may greatly alter the influence of air temperature.

9.Line 203: I am puzzled by the weights (0.4, 0.6, 0.8, and 1). Why don’t these values add up to one? Some citations should also be provided although the weights are determined empirically.

After summed up, they will be divide by the total weight, so the total weight is actually one. We write it this way, because it is more straightforward compared to [0.1429, 0.2143, 0.2857, 0.3571].

The method to integrate monthly precipitation is widely used in the comparison of GRACE data with precipitation data, so we did not repeat its exact expression here. For example:

- Crowley, John W., et al. "Annual variations in water storage and precipitation in the Amazon Basin." Journal of Geodesy 82.1 (2008): 9-13.
- Reager, J. T., and J. S. Famiglietti. "Global terrestrial water storage capacity and flood potential using GRACE." *Geophysical Research Letters* 36.23 (2009).

Its mathematical expression is

$$IntP(j) = \left[\sum_{i=1}^{N} P(j-i+1) * W(N-i+1)\right] / \sum_{i=1}^{N} W(i),$$

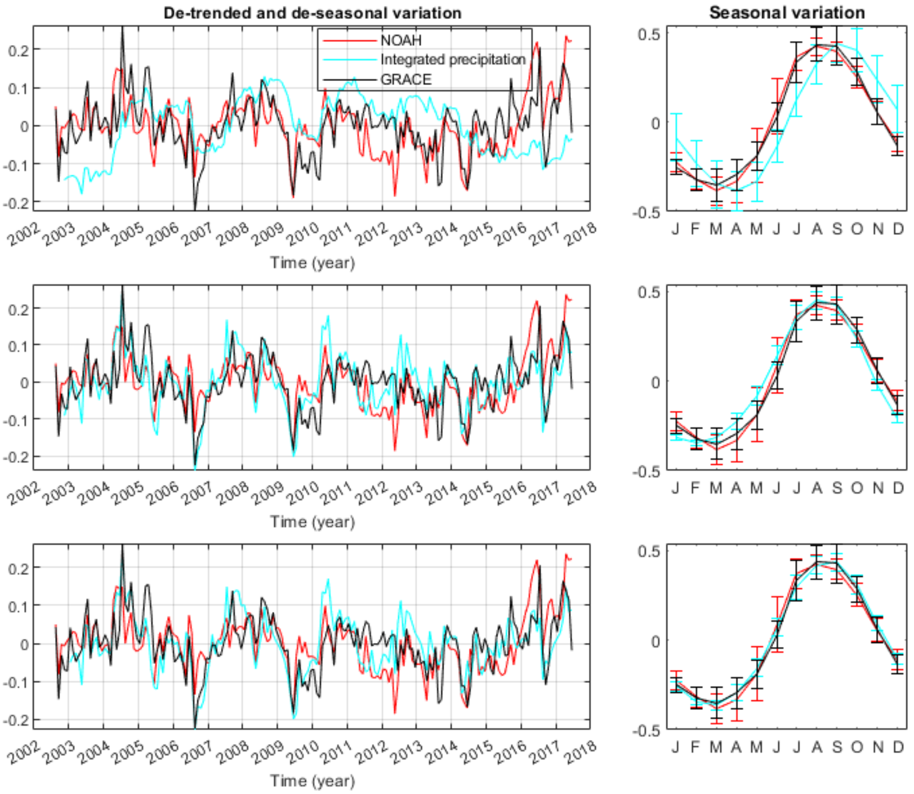
where IntP represents the integrated precipitation in jth month, P is short for precipitation, W is the weight for the integration, and N is the integration window.

The key parameters are N and W. Below we tried three schemes. (upper), N = j, W(i) = 1; (middle), N = 4, W = [0.4,0.6,0.8,1]; (below), N = 6, W = [1,2,3,4,5,6];

The first scheme is precipitation accumulation. This one does not work well, because it assumes the impact of precipitation in this month is the same as that in months ago, which is not reasonable.

The second scheme is the one used in the previous version.

The third scheme is a new one with a wider integration window. We find it puts few effects on the interannual variation, but improves the agreement in the seasonal variation, so we will change to this scheme in the revision.



[Fig. 3. Different methods for precipitation integration]

10.Line 217: "Atmosphere contribution has already been removed from GRACE observations. . .." This should be more clearly explained.

In the GRACE products for hydrological and glaciological application, atmosphere change has been modeled and removed. We have added a reference here. You may see the details if you feel interested.

[We add a new reference]

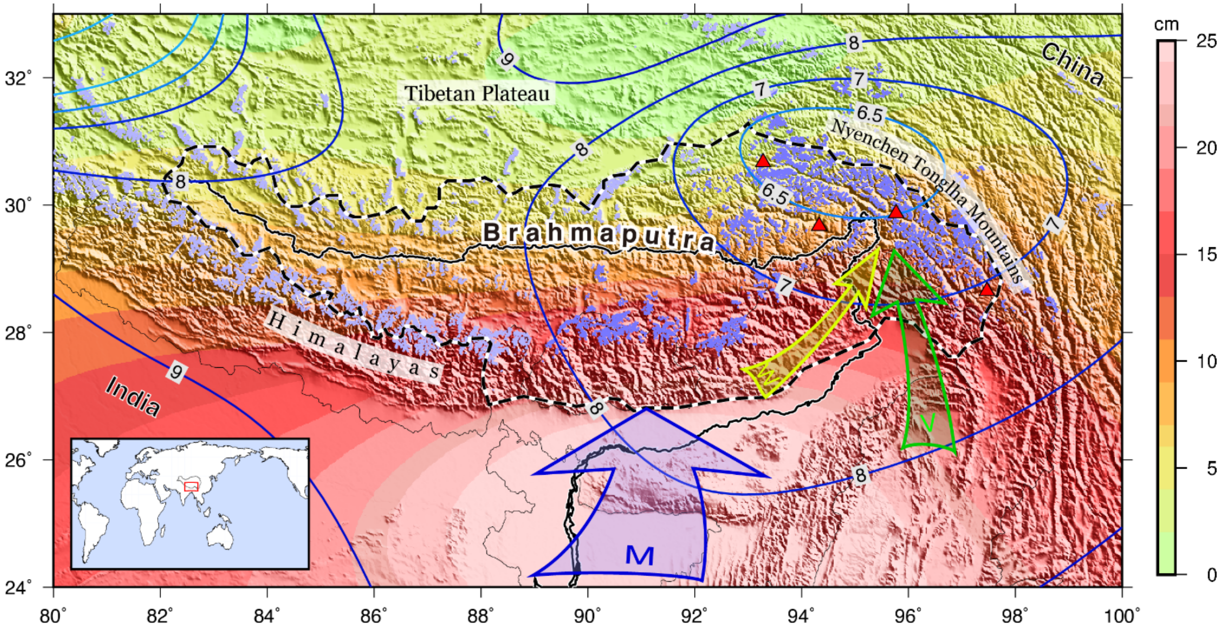
Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., and Flechtner, F.: AOD1B Product Description Document for Product Release 06 (Rev. 6.1, October 19, 2017), 2017.

Technical corrections:

11.Figure 1: This figure is not clear enough to read.

This figure contains too much information and thus it may need to zoom in to see more clearly. We follow the suggestion and have enlarged the minimum font size and increased the contrast between the texts and their background. If you still find it is not clear, could you please be more specific about the problem (which line, or which text)?

[We update Fig. 1]



[Fig. 4. Updated version of Fig. 1 of the manuscript]

Response to the 4th reviewer:

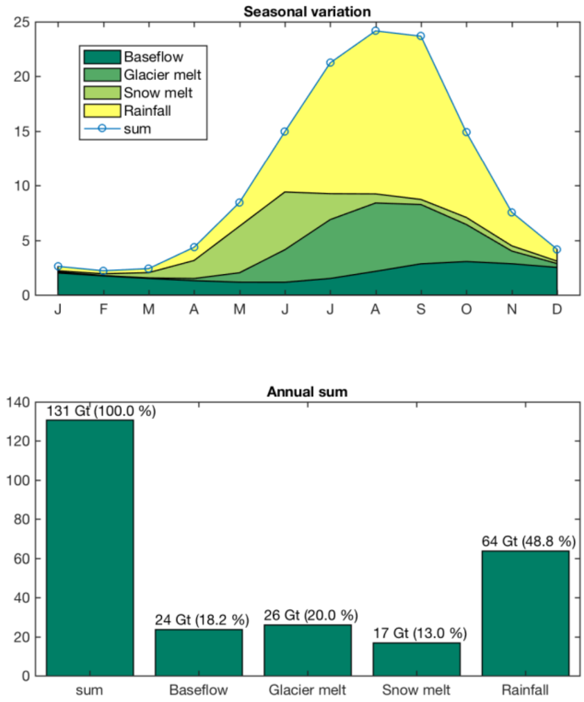
Below, ‘Q’ is the question/comment, ‘R’ is our response, and ‘C’ is the revision in the manuscript.

Q1:

Page 2: Line 40: (Table 1): Glacier and snowmelt contribution to the total discharge of Upper Brahmaputra river basin is 34% from Lutz et al. 2014 in Table 1. Whereas, Lutz et al. 2014 have indicated the contribution to a total runoff as 24.9% (15.9% from glacier melt and 9.0% from snowmelt: Table S3: Basin characteristics). I am not sure where 34% have come from. Please check this.

A1:

The authors kindly provided us the monthly runoff data, as shown below (y-axis in Gt, or km^3). I wrote to the authors to inquire why this discrepancy happened, and I was told that 24.9% is the result for Brahmaputra with several tributaries (the red area in the second figure below, from Fig. 1 of their paper). Therefore, the value of 34% is correct here.



[Fig. 1. Contribution of various components to streamflow in the Brahmaputra.]

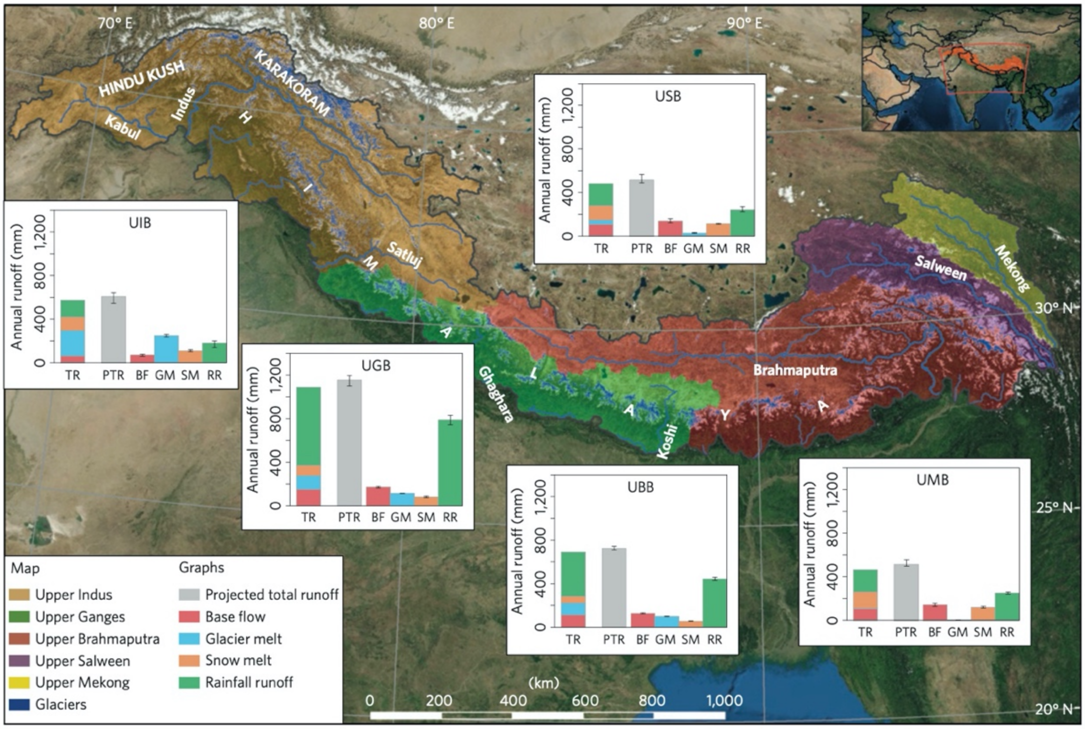


Figure 1 | The upstream basins of Indus, Ganges, Brahmaputra, Salween and Mekong. Bar plots show the average annual runoff generation (TR) for the reference period (1998–2007, REF; first column). The second column shows the mean projected annual total runoff (PTR) for the future (2041–2050 RCP4.5) when the model is forced with an ensemble of 4 GCMs. In the subsequent columns, PTR is split into four contributors (BF: baseflow, GM: glacier melt, SM: snow melt, RR: rainfall runoff). Error bars indicate the spread in model outputs for the model forced by the ensemble of 4 GCMs.

[Fig. 2. Excerpt of Fig. 1 from Lutz. 2014].

Q2:

Page 9, 282-286: you are comparing GRACE based estimate (in Gt/year) with other studies (m w.e. /year). Does it make sense to also provide the GRACE values in m w.e./year so that the readers can compare the results?

A2:

GRACE directly detects gravity change, so it is straightforward to give a mass change (1 Gt = 1 km^3 of water). Therefore, we can convert the mass value into equivalent water height change by dividing the glacierized area of 9.679 km^2. We have provided the long-term trend in this form in the introduction.

C2:

Our results show a long-term trend of -6.5 ± 0.8 Gt yr^{-1} (or 0.67 ± 0.08 w.e. m/yr) between August 2002 and June 2017

Q3:

Line 9: 301: 33% of GS melt contribution in Brahmaputra river. It is 34% in Page 1, Line40. Please see my first comment in the major comment section

A3:

We are sorry for the typo. It should be 33%, as you may find in the figure above.

Q4:

Page 1: Line 27: Please add Lutz et al. (2014) in the reference

A4:

It has been added.

Q5:

Page 1: Line 31: Please indicate a seasonal aspect of the snow cover here (instead of ‘snow coverage’ only)

A5:

It has been changed to “widespread seasonal snow coverage of up to 100,000 km^2”.

Q6:

Page 1: Line 37: I think the word ‘concern’ should be ‘concerns’ here

A6:

It has been changed to the plural form

Q7:

Page 2: Line 56: The last sentence seems a bit off, please elaborate on how the glaciological model suffers from calibration and validation.

A7:

We cite two recent work that adopted the latest model (Wijngaard et al., 2017; Biemans et al., 2019) to explain the situation. Nonetheless, this sentence is removed.

C7:

Such huge discrepancies in previous estimates make it imperative to incorporate the calibration from GS mass balance observations into future modelling experiments. Actually, the concept of assimilating more GS observations has begun to be implemented in the state-of-the-art models (Wijngaard et al., 2017; Biemans et al., 2019), but their glacier results suffered from coarse temporal resolution (two observations over a 5-year span) and the snow mass changes were partially constrained by area changes.

Biemans, H., Siderius, C., Lutz, A., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R., Wester, P., Shrestha, A. and Immerzeel, W.: Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability, 2(7), pp.594-601, 2019.

Wijngaard, R., Lutz, A., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. and Immerzeel, W.: Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. PloS one, 12(12), 2017.

Q8:

Page 9, 285: Please specify that GRACE mass balance is from this study.

A8:

It has been clarified by adding “in this study”.

Q9:

Page 10: Line 287-289: ASTER you mean (Brun et al. 2017). Please specify which publication refer to -5.5+- 2.2 Gt yr-1.

A9:

We had explained in the text that “… glacier mass change of -5.5 ± 2.2 Gt yr^{-1} by using ASTER (the area-averaged rate in NTM and Bhutan multiplied by the glacierized area of 9,679 km^2)”

The paper only provided height change, so we derived this value by multiplication of the area-averaged rate in NTM (-0.62 m/yr in 6,378 km^2) and Bhutan (-0.42 m/yr in 2,291 km^2) by the glacierized area of 9,679 km^2. The trends and areas were from Table 1 of their paper.

Q10:

Page 10: Line 308: Instead of ‘Lutz’s model’, please indicated ‘Lutz et al .2014.

A10:

It has been changed..

Track changes

~~Substantial~~Satellite-observed monthly glacier and snow mass changes in Southeast Tibet: implication for substantial meltwater contribution to the Brahmaputra~~ revealed by satellite gravimetry~~

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Correspondence to: Shuang Yi (shuangyi.geo@gmail.com)

Abstract. High Asia glaciers were observed to be ~~reducing~~retreating the fastest in the southeastern Tibet Plateau (SETP), where vast amounts of glacier and snow (GS) feed the streamflow of the Brahmaputra, a transboundary river linking the world's two most populous countries China and India. However, the low temporal resolutions in previous ~~studies~~observations of GS mass balance obscured the seasonal accumulation/ablation variations, and their modelling estimates were divergent. Here we use monthly satellite gravimetry observations from August 2002 to June 2017 to estimate GS mass variation in the SETP. We find that the "spring-accumulation type" glaciers and ~~winter~~ snow in the SETP ~~are the most abundant~~reach their maximum in May. This is in stark contrast to seasonal variations in terrestrial water storage, which ~~reaches its maximum in August and~~ is controlled by summer precipitation and reaches the maximum in August. These two seasonal variations are mutually orthogonal and can be easily separated in time-variable gravity observations. Our results show a ~~summer meltwater contribution of 43±8 Gt to the Brahmaputra. This value~~long-term trend of -6.5 ± 0.8 Gt yr^{-1} (or 0.67 ± 0.08 w.e. m/yr) and annual mass decreases ranging from -43.4 Gt to -73.1 Gt with an average of -57.6 Gt in the SETP between August 2002 and June 2017. The contribution of summer meltwater to the Brahmaputra streamflow is estimated to be 51 ± 9 Gt. This result could help to resolve previous divergent modelling estimates and underlines the importance of meltwater to the Brahmaputra streamflow. The high sensitivity between GS melting and temperature on both annual and monthly scales suggests that the Brahmaputra will suffer from not only changes in total annual discharge, but also an earlier runoff peak due to the ongoing global warming.

1 Introduction

The Tibetan Plateau, ~~regarded~~considered as the Asian water tower, is the source of several major river systems. Their upper streams are fed by rainfall, base flow and widespread glaciers and snow (GS) melt (Barnett et al., 2005; Immerzeel et al., 2010; Jansson et al., 2003; Lutz et al., 2014). The ~~sustainable supply of~~ GS melt~~, which~~ is susceptible to climate change, whereas its sustainable supply is ~~the key~~critical to the local freshwater security, flood prevention and control, and hydroelectric development (Bolch et al., 2012; Kaser et al., 2010; Yao et al., 2012). The southeastern Tibet Plateau (SETP), including the Nyenchen Tonglha Mountains (NTM) and eastern Himalayas, holds 10,439 glaciers with a total area of 9,679 km^2 (RGI Consortium, 2017) and widespread seasonal snow coverage of up to 100,000 km^2. These maritime glaciers are characterized by low equilibrium-line altitudes with large topographic gradients (Yao et al., 2012) and the most severe mass loss in High Mountain Asia (HMA) (Brun et al., 2017; Kääb et al., 2015). The GS melt serves as an essential water supplier for the Brahmaputra river system (e.g., Immerzeel et al., 2010; Lutz et al., 2014), which runs through three densely populated countries, China, India and Bangladesh (~~Figure 1~~Figure 1). The ~~manifesting~~revealed vulnerability of glaciers in the Brahmaputra Basin to global warming and emerging controversies over water allocation (e.g., dam building (Tanck and Fazani, 2010)) are increasingly attracting scientific and public ~~concern~~concerns.

Due to the lack of observational data, most of the previous estimates on the contribution of seasonal meltwater to the upstream flow of the Brahmaputra River were based on modelling approaches that were only calibrated by ~~the~~employing streamflow~~, and the absence of direct constraints on GS mass balance leads to a wide range~~ data. Resultingly, the previous estimates disagree widely from 19% to 35% ~~in their estimates~~ (Table 1) due to different forcing data and approaches without direct constraints on GS mass balance (Bookhagen and Burbank, 2010; Chen et al., 2017; Huss et al., 2017; Immerzeel et al., 2010; Lutz et al., 2014; Zhang et al., 2013). The amount of meltwater could be even more divergent. For example, Huss et al. (2017) estimated that the amount of annual GS melt to the Brahmaputra River was 138 w.e. (water equivalent) km^3 yr^{-1}, which is however triple the estimate of 43 w.e. km^3 yr^{-1} by Lutz et al. (2014). Although these two studies covered different ranges, the glacierized zone in the basin was both well enclosed so the estimates should not be so different. Such huge discrepancies in previous estimates make ~~the inclusion of~~it imperative to incorporate the calibration from GS mass balance observations ~~an urgent task~~into future modelling experiments. Actually, the concept of assimilating more GS observations has begun to be implemented in the state-of-the-art models (Wijngaard et al., 2017; Biemans et al., 2019), but their glacier results suffered from coarse temporal resolution (two observations over 5 years) and the snow mass changes were partially constrained by area changes.

Spaceborne sensors can be helpful in this desolate mountain region. Remote sensing techniques for region-wide GS mass balance measurements can be divided into three categories: laser altimetry (e.g., Ice, Cloud and land Elevation Satellite (ICESat) (Kääb et al., 2012)), multi-temporal digital elevation models (e.g., SPOT (Gardelle et al., 2013), ASTER (Brun et al., 2017)), and space gravimetry (Gravity Recovery and Climate Experiment (GRACE) (Matsuo and Heki, 2010; Yi and Sun, 2014)). The first two ~~employ~~ geodetic ~~approach (glacier surface height variation), and we need to determine~~approaches require the average ice density to convert volume changes into mass changes. The ICESat observation suffers from short operation period (2003–2009) and sparse spatial sampling, both of which can be overcome by the stereo-imagery approach~~. However,~~, which is becoming popular for the ~~stereo-imagery strategy has only~~whole HMA study recently ~~been applied to the entire HMA region.~~(Brun et al., 2017; Dehecq et al., 2018). Brun et al. (2017) provided an estimate of the detailed glacier mass balance trends over HMA between 2000 and 2016 and highlighted the regional dissimilarity. Despite recent improvements in spatial resolution in HMA glacier mass change studies, there has been little advance in their temporal resolution. ~~This is even more crucial for calibration and validation of glaciological models.~~

Observations ~~of~~at a monthly ~~time~~temporal resolution are necessary to separately quantify summer and winter mass balances, two processes dominating the annual glacier mass balance (Cogley et al., 2011)~~.~~, and thus crucial for the calibration and validation of glaciological models. The amplitude of seasonal variation of the glaciers in the SETP is up to ~3 m w.e. (Wang et al., 2017), far exceeding their net annual change of ~ 0.6 m w.e. (Brun et al., 2017). Hence, the long-term trend of GS mass changes only reflects a small net imbalance of their ablation and accumulation. High time-resolution monthly observations by GRACE since its launch in 2002 (Tapley et al., 2004) are promising in identifying these two processes. Up to now, the application of GRACE in HMA glaciers has been focusing on their secular changes with little attention to the seasonal variations (Gardner et al., 2013; Matsuo and Heki, 2010; Yi and Sun, 2014). This is ~~partly~~mostly due to the poor spatial resolution of GRACE (> 300 km) and ~~to~~ the dominance of terrestrial hydrological signals in the seasonal gravity signals, which is difficult to ~~separate~~eliminate from glacial signals. The latter is particularly severe in ~~regions~~the SETP with intense monsoon ~~precipitation such as the SETP.~~precipitations. The ~~seasonal~~ GS and hydrological mass changes (mainly including mass changes in rivers, soil moisture and groundwater) dominate the ~~regional~~seasonal gravity signals in the SETP observed by GRACE. Despite the general difficulty in separating them in the spatial domain, we find it possible to separate the two signals in the time domain ~~in the SETP~~, owing to their contrasting seasonal behaviours.

Precipitation in the SETP is controlled by various atmospheric circulation systems in different seasons, with westerly winds and Bay of Bengal vortex in winter/spring and Indian monsoon in summer (Wu et al., 2011; Yang et al., 2013; Yao et al., 2012). The former two systems were found to drive the spring precipitation in the SETP along the Brahmaputra River, thus forming a ‘spring-accumulation’ type of glaciers (Yang et al., 2013). The Indian monsoon prevails from June to September and brings intense precipitation on the southern side of the Himalayas, where terrestrial water storage shows tremendous seasonal changes and peaks in late summer. Therefore, according to the climate stations near NTM, we can observe ~~two peaks in the~~ bimodal precipitation ~~seasonality based on~~variations throughout the ~~climatological stations near the NTM~~year (Yang et al., 2013).

In this work, we will first introduce the precipitation characteristics ~~of~~in this region by both meteorological stations and global precipitation products. We will then use the empirical orthogonal function (EOF) analysis to decompose hydrological and GS signals~~. After obtaining the GS signal, the monthly GS mass balance will be compared to the glacier mass balance measured from ICESat.~~ in our study region, which does not exactly coincide with the range of glacierized zone in the Brahmaputra Basin. Our study region covers only 83% of the basin glaciers (the 17% undetected ones are in the western part) and 15% of non-Brahmaputra glaciers. We will scale our results by a ratio of $1 \times \frac{0.85}{0.83} = 1.02$ to get the total meltwater in the Brahmaputra, assuming that our observations can represent the basin-wide average. The hydrological and GS signals are further compared to the results of other datasets to validate their physical meanings. Such high time-resolution observations also allow us to compare GS mass variations with temperature records during the ablation season, and to study the sensitivity of GS mass change in response to the temperature change. Finally, we will compare our results to previous estimates ~~on a~~at monthly, annual, and interannual scales.

2 Data

2.1 GRACE data and preprocessing

We adopt the monthly GRACE spherical harmonics Release 06 products from August 2002 to June 2017. The three datasets are solved respectively by three organizations: Center for Space Research (CSR) at the University of Texas, GeoForschungsZentrum (GFZ) in Potsdam, and the Jet Propulsion Laboratory (JPL). These datasets are available at ftp://podaac.jpl.nasa.gov/allData/grace/L2/. The degree 1 terms, which are absent in original GRACE releases, have been added based on the technique proposed by Swenson et al. (2008). The C_{20} terms have been replaced by those from satellite laser ranging (Cheng et al., 2011), which are considered to be more reliable. A widely used Glacial Isostatic Adjustment (GIA) model by A et al. (2013) is adopted to correct the GIA effect caused by historical polar ice sheet changes.

Two different filtering strategies, a combination of P4M6 decorrelation (Swenson and Wahr, 2006) and 300km Gaussian filter (hereafter short for G300+P4M6) and a DDK4 filter (Kusche et al., 2009), are applied separately. Therefore, there are six combinations and their average values (with uniform weights) are ~~given. The standard deviations among these six datasets are taken as the uncertainties of the mass estimate, assuming that other sources of uncertainty are negligible.~~used in the following figures.

~~2.2~~2.2 GRACE error estimation

We adopt different uncertainty estimation strategies for the seasonal variation and the trend due to their intrinsically different error sources. The error of seasonal variation consists of the standard deviations among these six datasets (i.e., errors from the data solution and smoothing methods) and the leakage error, while that of the long-term trend also includes other potentially uncorrected signals. The leakage error is determined by how effectively the hydrological and glacial signals are separated by the EOF technique. Based on the modelled and recovered glacier mass changes, their residuals are estimated to have a seasonal variation of up to 11% of the modelled glacier mass change (refer to section 3.1 in the supporting materials), which is used to calculate the seasonal leakage error.

For the long-term trend error, the three different solutions and two smoothing techniques have a total effect of 0.44 Gt/yr. There are potential errors from other signal sources, like glacial isostatic adjustment (GIA), little ice age (LIA) and weather denudation. The GIA effect which originates from the polar regions has been corrected by A's GIA model (A et al., 2013), although its influence on the trend is as small as 0.02 Gt/yr. The main reason is that the spatial pattern of GIA is quite smooth, so it mainly influences the first mode and rarely leaks into the second one. This feature is also applicable for other signal sources: unless they exactly locate in the glacierized area, their influence will be reduced by the EOF decomposition. In the southern and southeastern Tibetan Plateau (over 500,000 km^2), the effects of LIA and denudation are estimated to be -1 ± 1 Gt/yr (Jacob et al., 2012) and 1.6 Gt/yr (assuming the sediment has a density of 2 Gt/km^3) (Sun et al., 2009), respectively. Our glacierized zone and surroundings have an area of about 100,000 km^2, accounting for one-fifth of the whole region, so we suppose their contribution to the GS mass estimate is also proportionally 1/5. However, as we explain above, we could not precisely quantify their contribution without knowing their spatial distribution, and they are more likely to be absorbed by the first mode, so we only include their contribution in the error estimation rather than correcting them in the trend. Table 2 summarizes the sum of GRACE error estimates in the secular trend.

2.3 ICESat altimetry

Version 34 of the ICESat Global Land Surface Altimetry Data is used to derive glacier height changes. The data span is from 2003 to 2009, with two or three observation campaigns per year (Figure S1). The processing of ICESat data includes the following steps. (1) Orthometric heights are obtained from original elevation data based on the Earth's gravity model 2008. (2) Footprints on glaciers are identified based on RGI 6.0 glacier outlines. (3) For each ICESat footprint, SRTM (Farr et al., 2007) elevations and slopes are extracted by bilinear interpolation of the DEM grid cells. Glacier height variation is defined as the elevation differences between the footprints and the SRTM data. (4) We exclude footprints over SRTM voids, footprints with slopes higher than 30°, and footprints with height change larger than 100 m (which are attributed to biases caused by cloud cover during the ICESat acquisition). (5) We also discard the calibration campaign L1AB (March 2003) and the incomplete campaign L2F (October 2009). (6) Glacier height variations are averaged and interpolated along the altitude to alleviate the uneven sampling problem in space, and an uncertainty of 0.06 m/yr (Kääb et al., 2012) is chosen to account for the uneven sampling bias in time. The steps have been used in previous work (Wang et al., 2017) and have also been described in earlier studies (Gardner et al., 2013; Kääb et al., 2012). The footprint information is given in ~~Fig.~~Figure S2.

ICESat has shown good ability to solve snow variation in flat regions (Treichler and Kääb, 2017), but applying the same technique in mountainous areas with high terrain heterogeneity is cumbersome. Therefore, here ICESat is only used to estimate changes in glacier mass. Although our GRACE estimate includes both glaciers and snow, the estimates by GRACE and ICESat are comparable in the late ablation season (i.e., the October/November campaign of ICESat), when the contribution of seasonal snow meltwater is negligible. To convert the glacier thickness changes into mass changes, two parameters are required, i.e., glacier density and total glacier areas. We assume an average glacier density of 850 ± 60 kg m^{-3} (Huss, 2013). According to the glacier inventory RGI 6.0 (RGI Consortium, 2017), the area has a glacierized area of 9,679 km^2.

2.~~3~~4 Other auxiliary data

~~There are~~ To analyse the impact of temperature and precipitation on GS and water mass balance here, we adopt two types of datasets, the gridded reanalysis products and in-situ measurements from four meteorological stations ~~in this mountainous area. Their~~ (their locations are labelled in Figure ~~S3~~1, and ~~their spatial information is~~coordinates are listed in Table S1~~.~~). Precipitation and temperature records for each site from 2003 to 2016 (Figure S4) are available from the China Meteorological Data Service Center (http://data.cma.cn/data/weatherBk.html). ~~To maintain consistency, the site temperature is converted to an elevation of 5500 m (averaged equilibrium line altitude) by a lapse rate of -0.006 °C/m (Li et al., 2013). This conversion has little effect on~~ Only four in-situ temperature records may not represent the ~~results of this study as only~~overall condition of the glacierized zone, so we adopt the gridded temperature ~~anomalies are~~product from the ERA5 reanalysis data processed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data is available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The gridded data is compared with station observations and the correlation index ranges from 0.69 to 0.82 in the interannual variation (Figure S6), indicating a good consistency. The average values in the glacierized zone from the ERA5 temperature product will be used~~.~~ to represent the temperature condition here.

~~Moderate-resolution imaging spectroradiometer (MODIS) data MOD10 (Hall et al., 2006) is used to investigate snow coverage here. The MOD10CM product has a temporal resolution of 1 month and spatial resolution of 0.05-degree.~~

~~The land surface model Global Land Data Assimilation System (GLDAS)-NOAH (Rodell et al., 2004) is adopted to inspect soil moisture changes, which can be compared to changes in total terrestrial water storage estimated by GRACE. Here, the version 2.1 monthly product with 1.0-degree spatial resolution is used (available at https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/GLDAS_NOAH10_M.2.1/).~~

Global gridded precipitation data Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2014) is used to examine the influence of precipitation on water storage. The data is available at https://pmm.nasa.gov/data-access/downloads/trmm. Although such a global product is unable to capture the localized spring precipitation in our study area (shown later), it can be used for the investigation of large-scale monsoon precipitation. We also use High Asia Refined analysis (HAR) precipitation product generated using the atmospheric model WRF (Maussion et al., 2014). In this product, long-term precipitation trends are not recommended, but its 10 km spatial resolved seasonal variation is informative to investigate the spatial extent of spring precipitation. The HAR data is available at http://www.klima-ds.tu-berlin.de/har/.

Moderate-resolution imaging spectroradiometer (MODIS) data MOD10 (Hall et al., 2006) is used to investigate snow coverage here. The MOD10CM product has a temporal resolution of 1 month and spatial resolution of 0.05-degree. The land surface model Global Land Data Assimilation System (GLDAS)-NOAH (Rodell et al., 2004) is adopted to inspect soil moisture changes, which can be compared to changes in total terrestrial water storage estimated by GRACE. Here, the version 2.1 monthly product with 1.0-degree spatial resolution is used (available at https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/GLDAS_NOAH10_M.2.1/).

3 Spring precipitation and mass increase

The method of this study is based on the fact that the change in GS mass driven by spring precipitation ~~driven glacial/snow mass changes earlier than~~precedes the change in hydrological signals. Therefore, before introducing the method, we want to demonstrate that GRACE can detect mass changes caused by spring precipitation~~ and its associated mass changes are detectable by GRACE.~~. At two out of four stations (Bomi and Chayu), spring precipitation is noticeable, even surpassing the summer/autumn precipitation brought by the Indian monsoon (Figure S4). Yang et al. (2013) provided precipitation records ~~for~~at 22 sites in a broader area~~. Based on these data, they~~ and outlined the boundary of the impact zone of the spring precipitation, which roughly covers the glacierized area studied here. Summer precipitation and its associated hydrological mass change are enormous and well recognized, ~~so~~while the spring one is not. Therefore, here we only use the TRMM and HAR results from January to March in Figure 2~~Figure 2~~ to show the initiation of spring precipitation~~ evolving from January to March by TRMM and HAR in Figure 2.~~. The precipitation begins to spread south and ~~westward~~west since April, when the ~~monsoons~~monsoon gradually ~~increase~~increases (not shown here). The TRMM results show a boundary along the latitude 29° N, ~~and~~where the precipitation ~~in the north~~ suddenly decreases~~.~~ to the north. This ~~reduced~~ boundary of change is irrelevant to the terrain and seems to be artificial. This phenomenon cannot be found in the HAR result, which ~~clearly~~ shows abundant precipitation in the glacierized zone in these months. The bottom ~~gives~~plots give the GRACE monthly mass anomalies from March to May (two months later than the precipitation), because we found such a time lag in the response of mass change to precipitation. An earlier mass increase from April can be identified in the southeastern part of the Tibetan Plateau.

~~Our station measurements evaluate the~~ The performance of TRMM and HAR is compared with our station measurements in Figure S5. According to the ~~measurements of our observatory~~in-situ records, the spring precipitation~~ of~~, as a part of the bimodal variation, is obvious at the Bomi and Chayu stations~~ is obvious, and bimodal changes can be identified.~~. TRMM is capable of revealing the condition ~~of~~at Chaya at 28.65° N, but ~~it does not perform well~~performs poorly in regions north of 29° N. The HAR data ~~do not represent a good bimodal change, which~~ seems to slightly underestimate the precipitation in April ~~and~~but overestimate in Autumn and Winter~~.~~, and thus does not present a clear bimodal change.

These results show that spring precipitation can be captured ~~more or less~~to a limited extent by various ~~measurements/~~reanalysis products and the 'spring-accumulation' pattern of GS mass change in the SETP ~~glaciers can be recognized~~is recognizable in GRACE observations. The amplitude and phase of the seasonal mass variation from the equivalent water height (EWH) of GRACE are compared in the background of~~ Figure 1~~. The seasonal amplitude has a spatial distribution ~~of the seasonal amplitude is~~ similar to that ~~the~~ ~~influence zone~~ of the Indian monsoon affected area. This pattern reflects the predominance of the monsoon-controlled hydrological process and the weaker glacial signals in this region. However, the peak month of seasonal changes (the contours in Figure 1~~Figure 1~~) ~~shows a distinct pattern, with peaks~~divergently appears earliest in June in the NTM and ~~appearing later as we go south. The peak comes in~~gradually delays to August in the southern Himalayas, where the annual amplitude reaches its maximum. The shift in peak months reflects the increasing/decreasing contribution from the sinusoid of the hydrological/GS seasonal variation. A key point ~~should be~~

~~pointed~~to point out is that their peaks have a three-month time window ~~shift~~offset (we will demonstrate it later), ~~that~~which is ~~one-fourth~~a quarter of the annual oscillation ~~period~~cycle and means that the two signals are mathematically orthogonal.

4 Decomposition of GRACE signals

4.1 EOF analysis of GRACE

GS and hydrological mass changes dominate the seasonal gravity signals observed by GRACE in this region and they are mathematically orthogonal ~~by~~due to different phases. Therefore, we employ the EOF technique (see the supporting material for mathematic expressions) (Björnsson and Venegas, 1997) to decompose hydrological and glacial signals in the ~~six combinations of three~~ GRACE datasets ~~by two filters, and the average result is illustrated in~~ (Figure 3~~Figure 3.~~). We thus extract two modes ~~which have an~~ with significantly higher explained ~~variance higher~~ variances than the other modes (i.e., two significant modes are obtained). ~~Comparing the results~~Results of different datasets and filters~~, they~~ show good consistency, indicating that the first two modes are robust.

Each mode consists of one EOF (the spatial pattern) and one PC (the temporal evolution). Only the first two modes~~ are presented, and they explain~~, respectively accounting for 79 ± 5% and 12 ± 4% of the total variance~~, respectively.~~ explanation, are shown. Although ~~overall,~~ the first mode is much stronger than the second mode (because the second ~~mode~~one is more localized), their signal strength in the glacierized region is comparable on both seasonal and secular temporal scales. Modes above 2 are weak and ~~irregular and~~irregularly show much~~a lot of~~ noise, so they are discarded here.

The trends of the GRACE observation and its decomposed modes are shown in Figure 4~~Figure 4~~. The GRACE ~~observations show~~observation shows a significant mass loss, which is ~~split~~divided into the first two modes. In the glacierized zone, ~ 2/3 of the negative trend comes from the 2nd mode and ~1/3 comes from the 1st mode. The trend of higher modes (> 2) is quite weak (Figure 4~~Figure 4~~d).

According to the spatial ~~coverage~~coverages (EOF$_1$ and EOF$_2$) and their temporal ~~variation~~variations (PC$_1$ and PC$_2$), the first mode covering the low altitude areas on the south of the plateau with a peak month in August/September seemingly represents hydrologic signals and the second mode concentrating in the glacierized region with a peak month in May (the peak month of June in Figure 1 is the mixed result of the first two modes) seemingly represents glaciers. We will verify these hypotheses below.

4.2 GS mass estimation from mode 2

~~We choose the second mode to estimate GS mass change. The EOF$_2$~~GRACE results only ~~shows a~~show smooth mass ~~pattern~~patterns and we need some strategy to recover ~~its~~the original ~~mass. To~~amount of mass changes. If we adopt the second mode to estimate GS mass change, this ~~end~~step is necessary. Therefore, a forward modelling method (Yi et al., 2016) is chosen to ~~iteratively~~ recover the mass in a~~n~~ pre-defined region iteratively. This method has been widely used (Chen et al., 2015; Wouters et al., 2008), especially in the study of polar ice sheets. In the first step, we divide the glacier mask based on the glacier distribution recorded in RGI 6.0 (RGI Consortium, 2017) (Figure 4~~Figure 4~~e). The lattices have a resolution of 0.5° by 0.5° and are located in glacierized area~~.~~ (by this way we assume the snow signal also comes from the glacierized area, but it does not influence the total mass estimates). In the second step, the mass in each lattice is iteratively adjusted until its smoothing signal (Figure 4~~Figure 4~~f) well matches the GRACE observation (Figure 4~~Figure 4~~c). The details of each combination of datasets and filters are presented in Figure ~~S6~~S7 and ~~S7~~S8. Therefore, we solve the mass in each combination (Figure ~~S7~~S8). The mass is multiplied by the PC$_2$ series to derive the glacier mass series, and their average is taken as the mass estimate, which will be compared with ICESat observations to test our hypothesis on its physical meaning.

4.3 Validation of mode 1 by soil moisture and precipitation datasets

To validate the hypothesis that the first mode represents hydrological signals, we ~~apply EOF analysis to~~compare it with EOF decomposition results of two other datasets, soil moisture from GLDAS/NOAH and precipitation data from TRMM (Figure 5~~Figure 5~~). To make them comparable to GRACE in terms of spatial resolution, they are expanded into spherical harmonics, truncated at degree 60, and smoothed by the same filter. Their results are shown in Figure 5~~Figure 5~~. Different from GRACE that has two significant modes, they only have one~~,~~ due to the lack of a glacial signal. The EOF$_1$ of GLDAS/NOAH and TRMM is ~~clearly~~ consistent with that of GRACE. The PCs are compared at interannual and seasonal scales as well. Note that precipitation is an instantaneous amount, while water storage is a state value, so the former should be integrated in time to make it comparable to the latter. Here, we integrate precipitation in successive ~~four~~six months by an empirical weight function of (~~0.~~1, 2, 3, 4, ~~0.~~5, 6~~, 0.8, 1)~~), which will be normalized, and the value is attributed to the ~~fourth~~sixth month. ~~The~~Different integration methods are tested in the supporting materials.

Of note, mass contributions from the Brahmaputra River and groundwater are absent (and they are troublesome to obtain) and precipitation is assumed as the dominant driver of water storage change without considering the influence of runoff and evaporation (Humphrey et al., 2016)~~.~~, so we do not expect that we can reach a thorough agreement between different datasets. This is acceptable if ~~only~~ their temporal consistency is ~~studied~~targeted. However, long-term trends in runoff, evaporation and groundwater cannot be ignored~~ anymore~~ and they are differently reflected in these three products, so their trends have been removed before the comparison. ~~The good resemblance in both the EOF$_1$ (spatial pattern) and PC$_1$ (~~The exclusion of unavailable surface water and groundwater in the GLDAS result also causes a weaker strength of its EOF$_1$ compared to that of GRACE. We conclude that these datasets should be comparable in terms of seasonal and interannual variations and the pattern of spatial distribution, but not in the long-term trend and the amplitude of the spatial distribution. The good resemblance in both the EOF$_1$ (spatial pattern) and PC$_1$ (seasonal and interannual temporal evolution) between GRACE, GLDAS/NOAH and TRMM indicates that they reflect similar geophysical processes, i.e., hydrological variations.

4.4 Method feasibility and reliability

The phase difference of 3 months is a prerequisite for this method and can be verified retrospectively. We tested different phase differences between hydrological and GS signals and decomposed them by the EOF method (refer to section 3.1 in the supporting material). Two conclusions are obtained: only when the GS mass change peaks in May (3 months before the peak month of the hydrological signal) can our simulated result agree with the GRACE observation; the EOF decomposition can well restore both seasonal variation and the trend of the GS signal if the orthogonality is satisfied.

Only hydrological and GS signals can explain the first two modes considering their spatial and temporal patterns. Atmosphere contribution has already been removed in GRACE observations (Dobslaw et al., 2017) and mass transports of solid earth are unlikely to have such strong seasonal variations. We cannot quantify the contribution of groundwater in the second mode, but groundwater is apt to be modulated by stronger ~~rainfall~~rainfalls in summer (Andermann et al., 2012), rather than ~~snowfall~~snowfalls in winter-spring, and groundwater activity will be reduced ~~here~~ in winter-spring when the ground is frozen. Therefore, the groundwater component is inclined to exist only in the first mode. The negative trend in the first mode is ~~likely~~mostly due to decreasing precipitation in recent years (Figure ~~S8~~S9) and intense groundwater pumping (Shamsudduha et al., 2012). The negative trend in the second mode is supposed to represent GS melting and can be used for estimating GS mass balance.

5. Results and discussion

5.1 Glacier and snow mass balance

The glacier surface elevation changes measured by the ICESat are compared with our GRACE-based estimates. We interpolate the series of GRACE estimates (2002–~~2016~~2017) into the observation epochs of ICESat (2003–2009) and plot mass changes ~~(~~by GRACE~~)~~ as a function of elevation changes ~~(~~by ICESat~~)~~ (Figure 6~~Figure 6~~a). After divided by the glacier density, the slope of the elevation-mass regression line represents the inventorial glacierized area by RGI 6.0. The observations in October/November (blue squares) coincide with the line, indicating the good consistency between ICESat and GRACE in the late ablation season between 2003 and 2009. The MODIS result indicates that the snow coverage increases rapidly since September (Figure 6~~Figure 6~~b~~).~~), while the GRACE PC$_2$ series show a moderate increase after October. We speculate that the snow height does not increase much in the first few months so the contribution of snow mass is not significant. The observations in March and June, as expected, are well above the line, implying an extra snow mass contribution, which can be inferred from the point-to-line vertical distance. The snow contribution relative to the total mass anomalies varies drastically between 0% and 62% with a mean value of 38% within our observation time windows.

The difference between GRACE and ICESat-based estimates of mass change indicates that the snowpack outside the glaciers is a non-negligible contributor to the seasonal mass variation. This is quite different from previous glacier trend estimates, where ~~only glacierized area needs to be considered.~~non-glacier snow was neglected. Based on MODIS observations, the snow coverage area in this region varies from approximately 80,000 km^2 in winter to 30,000 km^2 in summer, both of which are much larger than the inventoried glacier area (Figure 6~~Figure 6~~b). However, heterogeneous snow depths (Das and Sarwade, 2008) and densities across the vast and rugged area make it difficult to measure their mass change by a non-gravimetric way.

Figure 6~~Figure 6~~c compares the time series of glacial mass in the SETP from GRACE (~~Aug.~~August 2002~~ to Dec. 2016~~–June 2017) and ICESat (2003–2009). The times series from two sensors are consistent in seasonal and interannual variations, despite ~~that~~the absence of the snow component ~~is absent~~ in the ICESat result. Monthly mass change shows that the ablation season is generally ~~from~~between June ~~to~~and October~~, but its~~ with slightly varied initiation and duration ~~may vary with different years (Figure 6d).~~from year to year. The maximum mass increase (10–20 Gt) usually occurs in April, when the spring precipitation peaks, and the severest mass loss (-15 – -30 Gt) usually occurs in July when the temperature peaks. ~~With~~As the ~~increase of~~ temperature rises from April to July, the monthly mass change curve drops steeply from the peak down to the trough, but the ascending process with mass accumulation is relatively ~~more~~ moderate and continuous.

We calculate annual mass increase and decrease by ~~accumulating monthly~~the difference of mass ~~change from~~anomalies between November ~~to~~and May and ~~from~~between June ~~to~~and October, respectively. From 2002 to ~~2016~~2017, the annual mass decrease ranged from -43.4 Gt to -73.1 Gt with an average of -57.6 Gt, and the annual mass increase ranged from 35.7 Gt to 63.4 Gt with an average of 50.5 Gt. The seasonal ~~glacier and snow~~GS mass changes postpone the runoff of ~~the~~ ~50 Gt of winter-spring solid precipitation ~~of ~50 Gt~~ for several months. This amount plays a vital role in the annual streamflow (130.7 Gt on average) of the upper Brahmaputra (Lutz et al., 2014)~~. Without this buffering effect, it would impose an impact~~ and is almost ten times ~~as large as~~ the annual net meltwater ~~(-6.5 Gt) does on~~. Without the buffering effect of the seasonal variation, there will be a tremendous reduction in the streamflow in summer and autumn, when the water demand is high, and adaptive management on the dams in the Brahmaputra will be required to reduce seasonal irregularities in the streamflow (Barnett et al., 2005).

5.2 Quantifying the sensitivity of glacier and snow melt to temperature

Temperature is a dominant factor influencing the melting of glaciers (Cogley et al., 2011). Here, the monthly temperature records ~~averaged~~ from ~~four meteorological stations (~~the ~~red triangles in Figure 1)~~ERA5 product are compared with month-to-month mass changes by GRACE to investigate the sensitivity of the GS mass balance in response to temperature change (Figure 7~~Figure 7~~). Mass changes are negatively correlated with the temperature anomalies by a factor of -~~2~~1.9 ± 0.~~3~~2 Gt degree^{-1} during the ablation season (from May to October) but no correlation is found during the accumulation season (from November to April). The mass peaks around May, when either glacier accumulation or ablation could happen. The temperature averaged in this transitional month is taken as the reference for the temperature anomalies used in the figure and their mass changes are annotated. ~~We did not get a good linear regression in the May results, but the glaciers in May generally experience ablation/accumulation during positive/negative temperature anomalies and there are only 3 exceptions out of 14 cases. This implies that the initiation of the ablation process may be temperature sensitive and that the glacier ablation period is expected to shift to an earlier time in the case of warmer climates.~~ The highest sensitivity of monthly mass changes in response to temperature is observed in July (~~4.6~~3.1 ± 2.5 Gt degree^{-1}~~, P-value: 0.028~~), when the largest monthly mass loss occurs.

To investigate the impact of climatic variables on the interannual variations of GS mass, we compare annual mass losses (from May to October) with summer temperatures (from June to August) (Figure 7~~Figure 7~~b). The annual mass loss is significantly correlated with the summer temperature, with a slope of -10.~~3~~7 ± 4.~~1~~2 Gt degree^{-1} (P-value: 0.~~021~~025, R^2-value: 0.35), indicating that the annual GS mass balance is sensitive to summer temperature. The small value of R^2 is partly due to the relatively large uncertainties of our mass estimate (10 Gt) in this modest range of variation (30 Gt) and the neglect of other factors influencing GS mass balance. The sensitivity index was provided by a previous study (Sakai and Fujita, 2017), where the whole HMA was examined and the SETP shows a widespread high sensitivity with an average value of -1.23 m w.e. degree^{-1}. Based on the glacierized area of 9,679 km^2, our estimation is -1.~~08~~10 ± 0.~~42~~43 m w.e. degree^{-1}, which is comparable with the earlier study of Sakai and Fujita (2017). It should be pointed out that annual net mass balance was used in Sakai and Fujita (2017) in comparison with the annual mass loss used in this study, although annual net mass balance is mainly driven by summer melt (Ohmura, 2011).

We could not find a significant relationship between the mass and precipitation changes, probably because our data fail to reflect the strong orographic effect in precipitation, and/or the GS mass gain process is too complex to be attributed to precipitation alone.

5.3 Comparison with previous estimations on glacier and snow meltwater

The trend of glacier elevation change by ICESat in this study is -0.65 ± 0.20 m w.e. yr^{-1} during 2003–2009, which lies between the values of -0.30 ± 0.07 m w.e. yr^{-1} (Gardner et al., 2013) and -1.34 ± 0.29 m w.e. yr^{-1} (Kääb et al., 2015) in eastern NTM by using alike ICESat dataset~~,~~ (but of an older version), and is close to the trend of -0.62 ± 0.23 m w.e. yr^{-1} during 2000–2016 by using ASTER (Brun et al., 2017). The trend of GS mass change in this study by using GRACE is -6.5 ± 0.8 Gt yr^{-1} between August 2002 and June 2017. The mass contribution from snow is ~~only~~ considerable at the seasonal scale ~~and is~~but negligible over 15 years, so the secular trend by using GRACE mainly represents the glacier mass change. Our GRACE trend ~~is in good consistency~~consists well with the derived glacier mass change of -5.5 ± 2.2 Gt yr^{-1} by using ASTER (the area-averaged rate in NTM and Bhutan multiplied by the glacierized area of 9,679 km^2). In conclusion, both of our ICESat and GRACE estimates agree well with the previous ASTER result in terms of secular trend.

A recent result on changes in interannual glacier flow in this region (Dehecq et al., 2018) indicates a strong correlation between ice flow rate and changes in glacial thickness. ~~The~~ The interannual variation of GRACE-based mass changes (the 1-year smoothed sequence ~~of GRACE-derived mass changes~~ in Figure 6~~Figure 6~~c~~ has no seasonal variation and reflects interannual variations. A notable feature is the balance~~) notably shows equilibrium during periods of 2003-2005 and 2011-2014. According to the previous study (Dehecq et al., 2018), thinning glaciers reduce their flow rate ~~due to the~~by weakening gravitational driving stress; therefore, this balanced mass state may slow down the decreasing flow rate. Coincidentally, we can identify such decelerating phase ~~during~~in the decline of glacier flow rate during 2004-2006 and 2012-2015 (~~Fig.~~Figure 1 in Dehecq et al., 2018).

GS mass loss is caused by flow, melting, and evaporation processes, while the last one does not contribute to the river flow. Evaporation is important for continental-type glaciers where the climate is usually cold and dry. E.g., it accounts for 12% of the glacier ablation in Tianshan (Ohno et al., 1992). However, the importance of evaporation is greatly reduced in our maritime glaciers due to the extremely humid air and rapid melting. Therefore, we suppose that the mass loss is completely turned into meltwater and can be compared with analogous outputs from models. In our study region, 85% of its meltwater (estimated according to the area proportion) runs into the Brahmaputra and this area accounts for 83% of total glaciers in this basin (9,912 km^2). Assuming that the unobserved 17% of glaciers hold the similar rate of GS mass change, our estimate of mass change is scaled by a ratio of $1 \times 0.85/0.83 = 1.02$ to represent the GS mass change of the entire Brahmaputra Basin. Monthly changes of meltwater estimated by month-to-month difference in GRACE results are compared with model results of Lutz et al. (2014), which showed that GS melt constitutes 33% of the total discharge in the Brahmaputra and that 50% of the annual melt occurs in the summer (Figure 8~~Figure 8~~). GRACE only detects the net change in GS and cannot separate mass ablation and accumulation (see the inset in Figure 8~~Figure 8~~). Because these two processes concur simultaneously in transitional seasons and offset to some extent, the annual mass decrease (total mass loss in a year; here, ranges from ~~36.9~~44.5 km^3 to ~~62.1~~74.8 km^3 with an average of ~~49~~59.0 km^3) is smaller than the ~~realistic~~real GS melt. ~~Therefore, we cannot accurately estimate~~As a result, the ~~amount of~~annual mass decrease provides a lower bound on annual GS melt each year, rather than an accurate estimate. Instead, the amount of GS melt can be better determined during the summer (from June to August), when the accumulation is supposed to be small. This value can be used to validate the model output. Our result shows that the summer melt ranges from ~~31.0 km^3 to 52.2 km^3 with an average of 42.8 km^3, which is over 80% larger than the 23 km^3 GS mass change given in Lutz's model (Figure 8). Among all model estimates, Lutz's model~~37.3 km^3 to 62.9 km^3 with an average of 51.6 km^3, which is over 100% larger than the 23 km^3 GS mass change given in the model of Lutz et al. (2014) (Figure 8~~Figure 8~~). Although extrapolated mass changes for the undetected 17% of glaciers and the neglected summer evaporation may reduce our estimates of summer meltwater, they definitely cannot explain the difference of more than 100%. Among all model estimates, the model of Lutz et al. (2014) reported one of the largest proportions of GS melt contribution (33%), but still largely underestimated the amount of summer meltwater, according to our estimate from satellite observations.

Our annual mass decrease (average 49.0 Gt) is still much smaller than the 137 Gt annual meltwater given by Huss et al. (2017). However, this enormous value even exceeds the annual streamflow of 130.7 km^3 in the upper Brahmaputra where all GS meltwater is included (Lutz et al., 2014). The upper streamflow at the Nuxia station (ahead of the main glacier supply area) is ~ 60 km^3. Therefore, the difference in streamflow between the main glacier supply area is ~ 70 km^3, and the annual meltwater is unlikely to exceed this value, considering the additional contribution of precipitation. These values generally represent decadal averages at the beginning of this century (Table 1) and they are therefore comparable.

6 Conclusion

In this study, we use GRACE gravimetry to estimate the ~~glacier and snow~~GS mass balance in the SETP from August 2002 to June 2017. The second EOF mode of GRACE observations is attributed to changes in GS mass, which can be validated in the following three steps. First, simulation experiment shows that two signals with peaks in August and May can be decomposed unbiasedly by EOF. Second, the ~~attribution of the~~ first decomposed mode ~~to hydrological processes can be well~~

~~explained by the physical components, showing~~shows consistent spatio-temporal patterns with the soil moisture and precipitation variations from the GLDAS and TRMM data~~, respectively.~~ and thus can be reasonably attributed to hydrological processes. Thirdly, the second mode of GRACE signal with a peak in May ~~can be explained reasonably as the GS mass variation, which~~ temporally corresponds to the glacier/snow accumulation and ablation processes and spatially coincides with the glacier distribution, ~~and~~which is also supported by the spring precipitation pattern observed by meteorological stations. Glacier mass change measured by ICESat is further adopted to compare with our GRACE-based GS estimates, and good agreement is reached in the ablation season when the snow contribution is negligible. The ICESat measurements also show that the ~~annual variation in~~seasonal glacier mass variation is large, which is consistent with our finding that GS mass change in this region peaks in May.

The ~~decomposed~~ GRACE ~~time series~~-based GS mass balance not only shows a ~~secular mass~~ long-term decreasing trend of -6.5 ± 0.8 Gt yr^{-1}, generally comparable with previous studies on glacier mass balance in the SETP, but also newly reveals a strong seasonal variation which postpones water supply of about 50 Gt from winter and spring to summer and autumn. The high sensitivity of glacier mass changes responding to temperature shows that warming climate will exert strong impacts on the glacier and snow mass balance from two aspects. On the one hand, under the current glacier condition, the increase in summer temperature will enhance the annual meltwater by a factor of -10.~~3~~7 ± 4.2 Gt ℃$^{-1}$; On the other hand, the seasonal meltwater will shift earlier and reduce its supply in summer and autumn, which is potentially ten times the amount of annual glacier melting. Our estimates of monthly GS meltwater can also give an elaborate calibration on the glacier accumulation and ablation processes in hydrological and glaciological models of the Brahmaputra Basin, which were ~~only~~barely calibrated ~~indirectly~~ by ~~sparsely sampled streamflow discharges~~GS mass observations and diverged largely on the proportion of seasonal meltwater contribution. ~~The~~Given the high vulnerability to warming temperature, the greater contribution of meltwater to the Brahmaputra streamflow ~~to warming temperatures is higher~~ than ~~previously recognized, suggesting~~most model estimates indicates that ~~there~~ its water resource allocation will ~~be~~face ominous tension ~~in the allocation of its water resource~~ in the future.

Data availability

The data that support this study are mostly publicly open and their sources are indicated in the data section. The meteorological data and the series of glacier mass balance estimate are available upon request to the corresponding author.

Author contributions

S.Y. conceived the study and conducted the calculations. S.Y. and C.S. analyzed the results and wrote the manuscript. K.H. discussed and revised the manuscript. S.K. discussed and suggested the experiment. Q.W. processed the ICESat data. L.C. processed the MODIS data.

Competing financial interest

The authors declare no competing financial interests.

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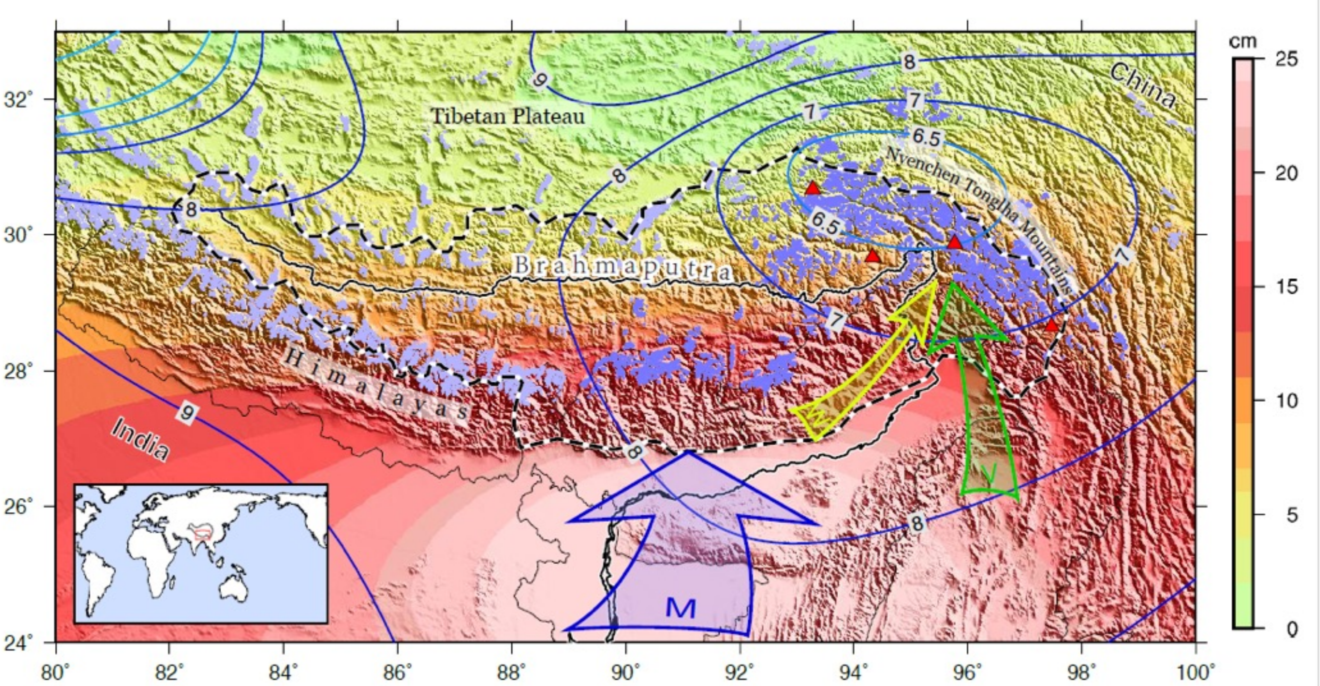
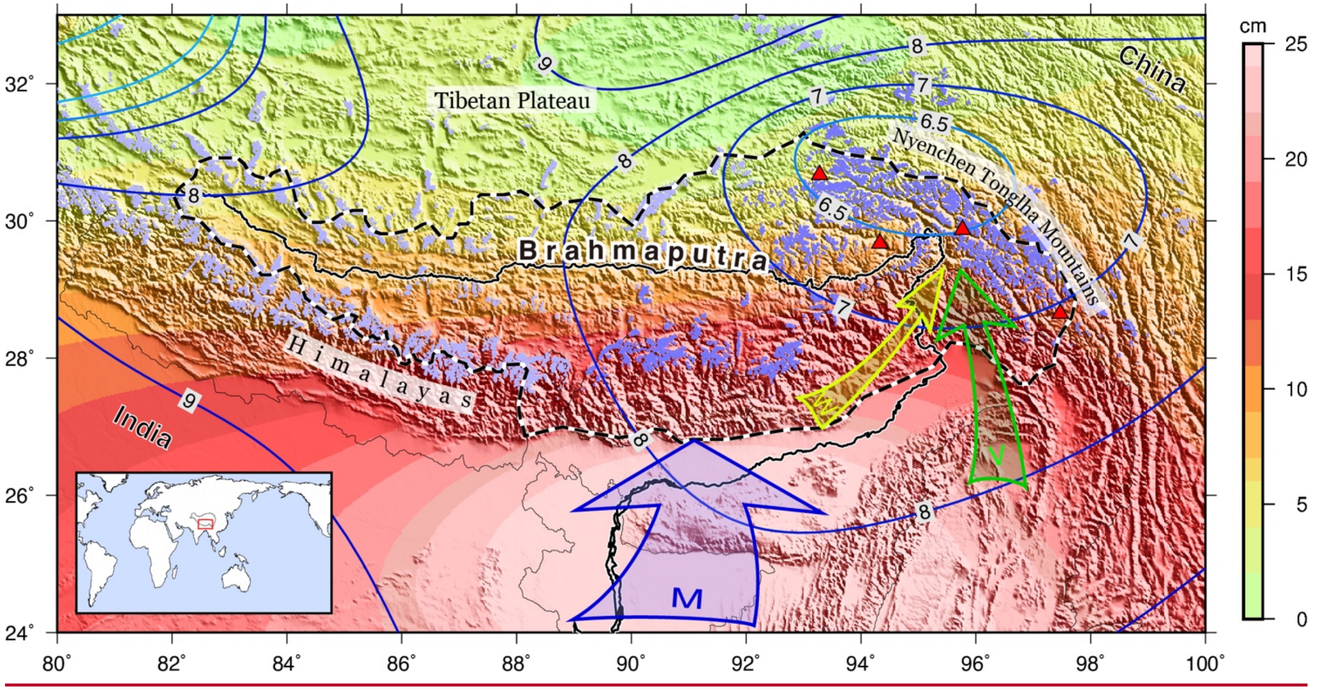

cm
25
20
15
10
5
0
Tibetan Plateau
China
Nyenchen Tonglha Mountains
Brahmaputra
Himalayas
India
M
V
9
8
7
6.5
32°
30°
28°
26°
24°
80°
82°
84°
86°
88°
90°
92°
94°
96°
98°
100°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Nyenchen Tonglha Mountains
Brahmaputra
Himalayas
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86°
88°
90°
92°
94°
96°
98°
100°

Figure 1. Geographic environment of the upper Brahmaputra Basin. The boundary of the basin is outlined by the black dashed line. The violet areas in the plateau represent mountain glaciers, but only the darker ones (9,679 km^2 in total) are studied here. The background color shows the amplitudes of annual variation in terms of equivalent water height from GRACE, and their peak months (the month with the peak value in a year) are indicated using contours (e.g. 9 means September). The red triangles mark the location of four meteorological stations. The colored arrows illustrate major climatic factors influencing this region (M: Indian Monsoon; W: Westerly winds; V: Bay of Bengal Vortex). The red box in the inset map marks the location of the study area.

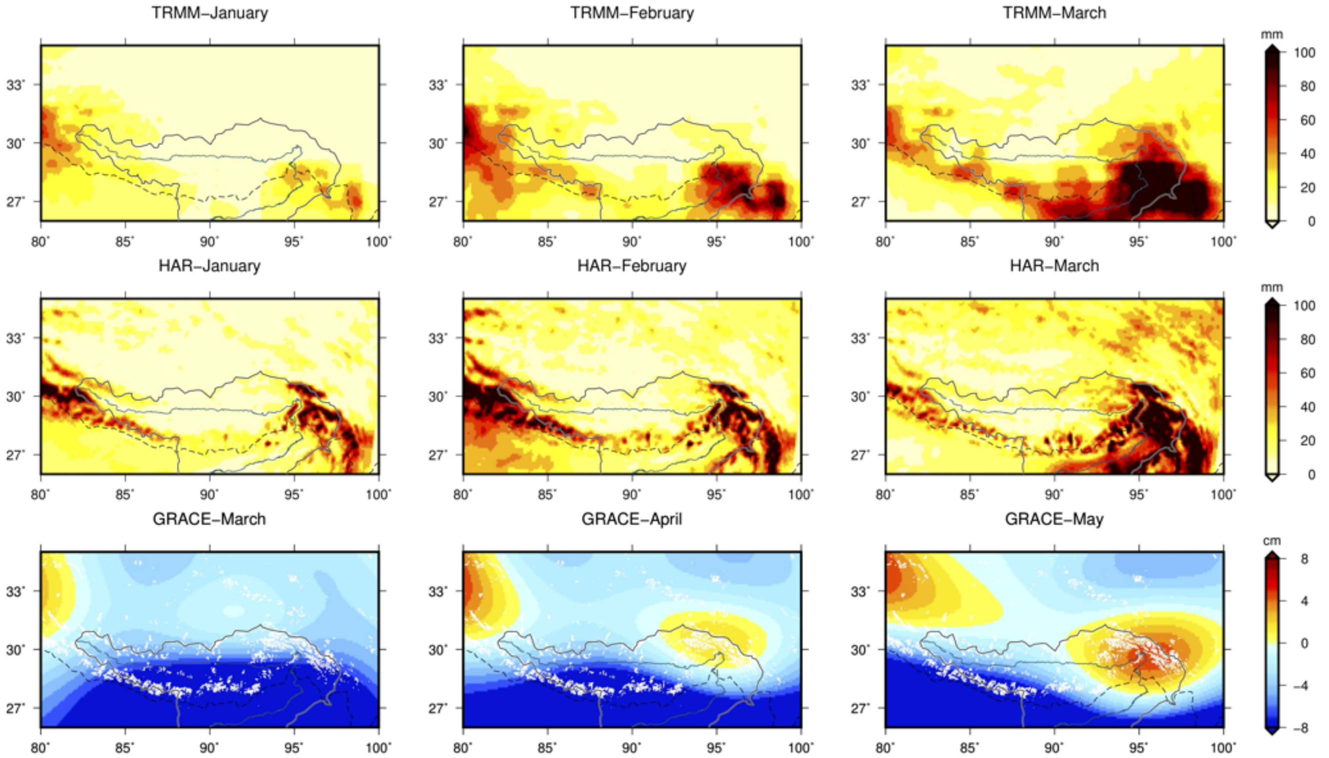


Figure 2. Monthly precipitation from January to March by TRMM and HAR and mass anomalies from March to May by GRACE. The Brahmaputra and its basin boundary are marked. The white dots in the bottom plots represent glaciers.

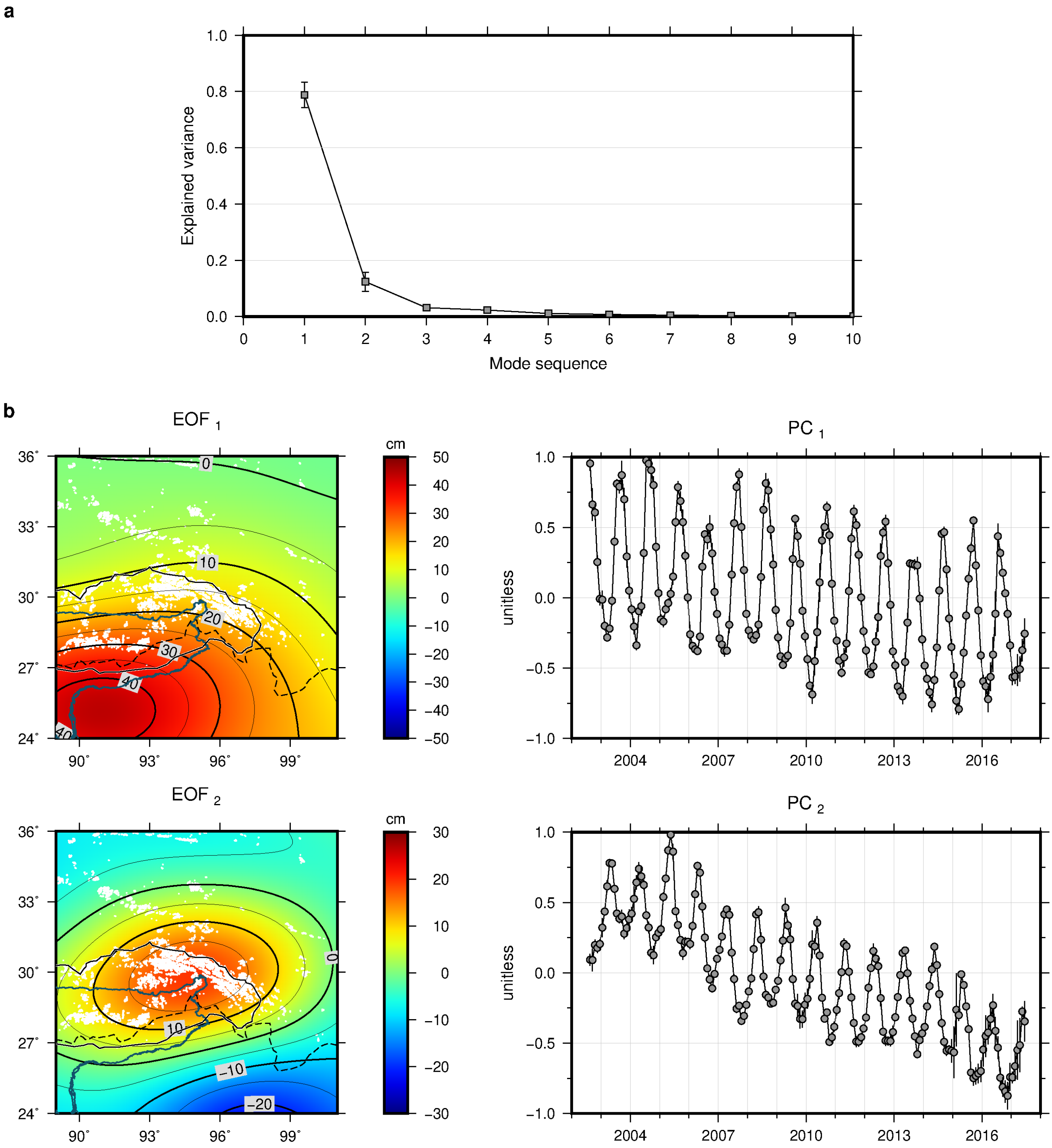


Figure 3. EOF decomposition of GRACE observations in the form of EWH in the study region. Six combinations are averaged to generate these plots and uncertainties are estimated based on the dispersions. (a) Weight of the first 10 components. (b) Spatial distribution (EOF) and temporal variation (PC) of the first two components. The white dots represent locations of glaciers.

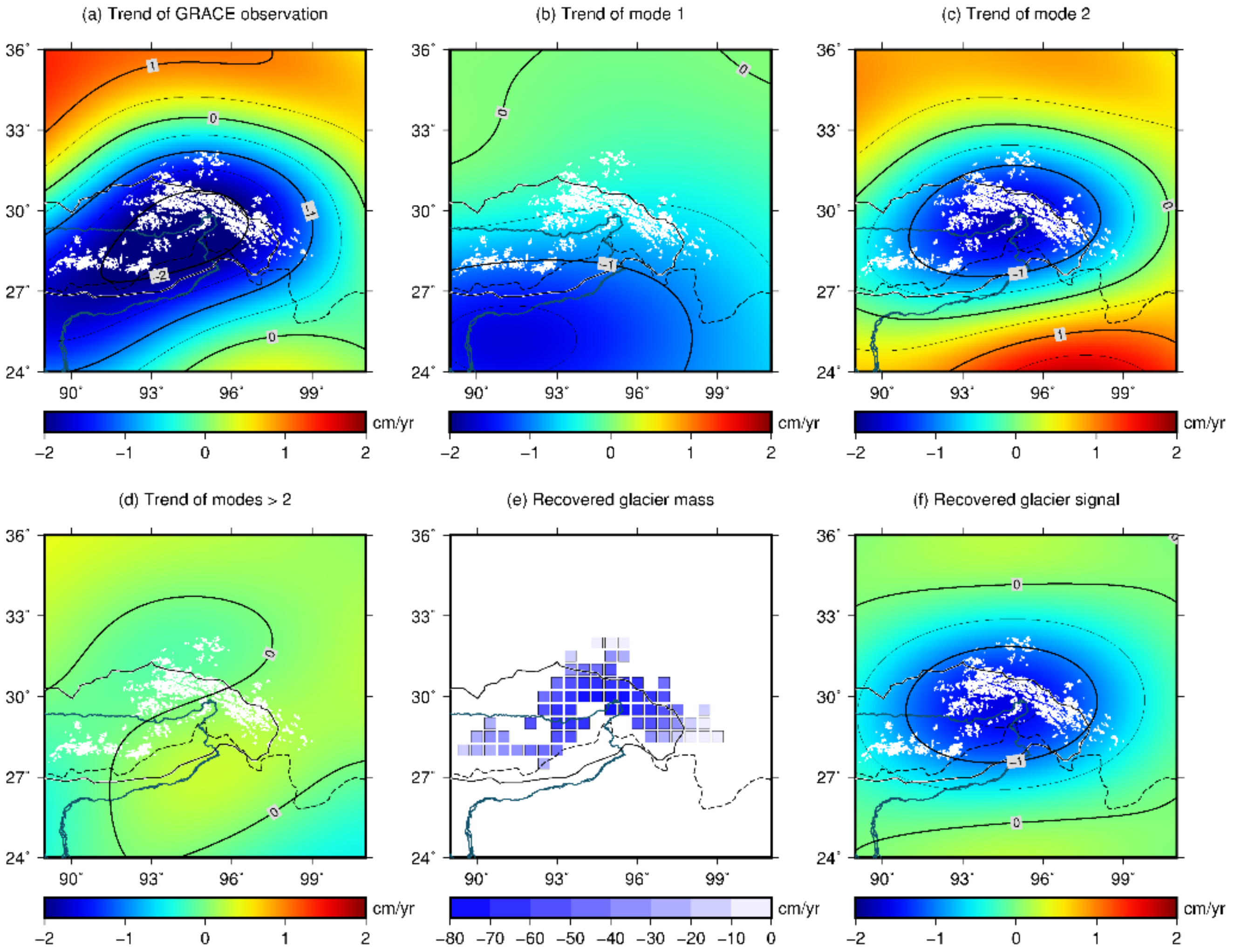
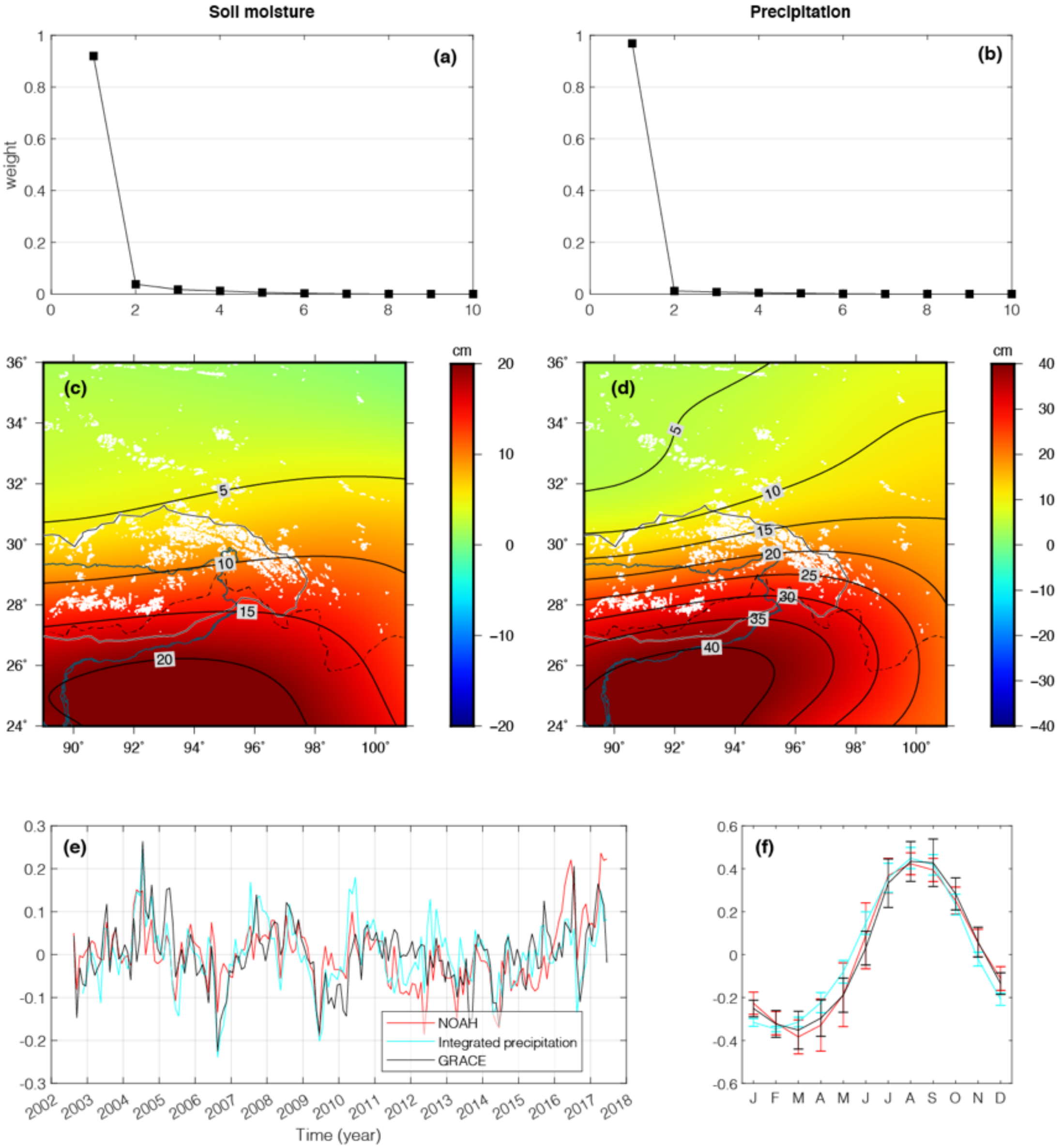


Figure 4. Trend of GRACE signals and the GS mass estimation. The CSR product with DDK4 filter is used here. (a) the trend of GRACE EWH observations between Aug 2002 and June 2017, is decomposed into (b), (c) and (d). Using the mass changes shown in (e), we obtained (f) by the forward modelling method to reproduce (c). The white dots represent glacier distribution. The black solid curve marks the basin boundary and the dashed curve marks the plateau boundary.


Soil moisture
Precipitation
(a)
(b)
weight
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
(c)
(d)
cm
20
10
0
−10
−20
40
30
20
10
0
−10
−20
−30
−40
5
10
15
20
25
30
35
40
36°
34°
32°
30°
28°
26°
24°
90°
92°
94°
96°
98°
100°
(e)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
NOAH
Integrated precipitation
GRACE
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Time (year)
(f)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
J
F
M
A
M
J
J
A
S
O
N
D

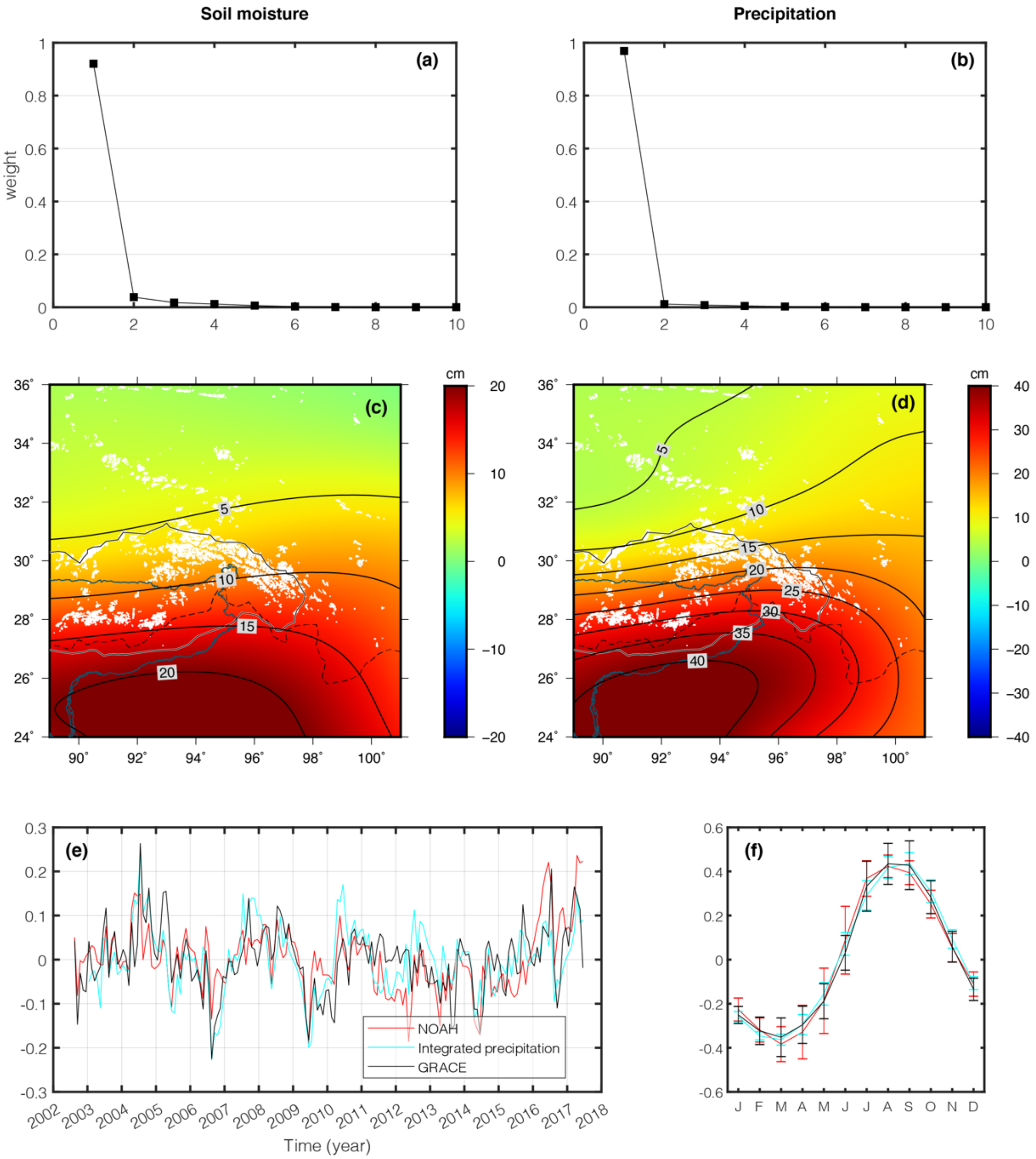
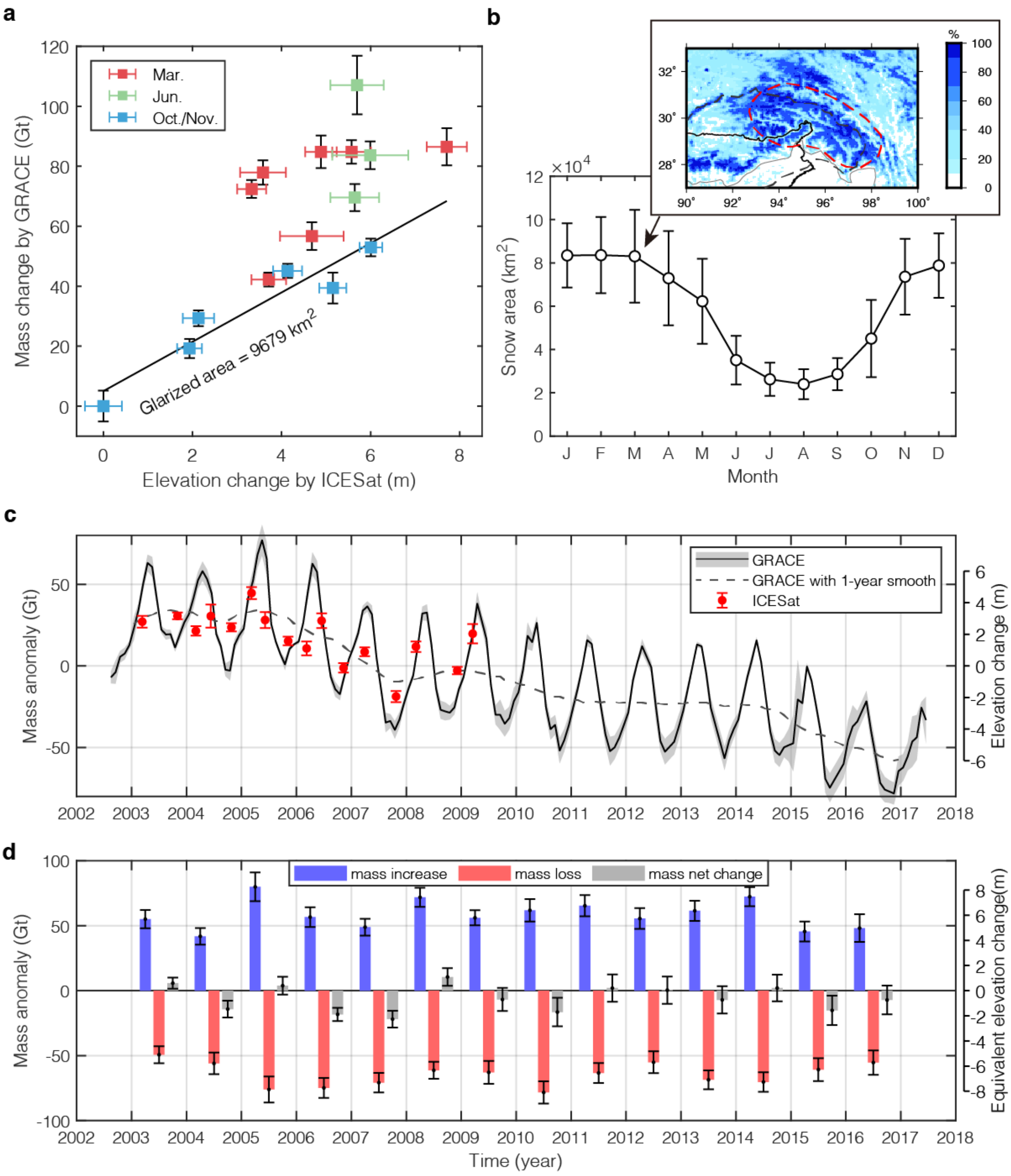


Figure 5. EOF analysis of soil moisture using GLDAS/NOAH (a, c) and of precipitation using TRMM (~~column~~b, d). The weights of the first 10 modes are shown in the upper panels. The first EOFs and PCs are shown in the middle and bottom panels. The PCs are separated into detrended interannual (e) and annual (f) for better comparison.


a
Mass change by GRACE (Gt)
Elevation change by ICESat (m)
Mar.
Jun.
Oct./Nov.
Glarized area = 9679 km^2
b
Snow area (km^2)
$\times10^4$
Month
J F M A M J J A S O N D
%
90° 92° 94° 96° 98° 100°
28° 30° 32°
c
Mass anomaly (Gt)
Elevation change (m)
GRACE
GRACE with 1-year smooth
ICESat
d
mass increase
mass loss
mass net change
Mass anomaly (Gt)
Equivalent elevation change(m)
Time (year)
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

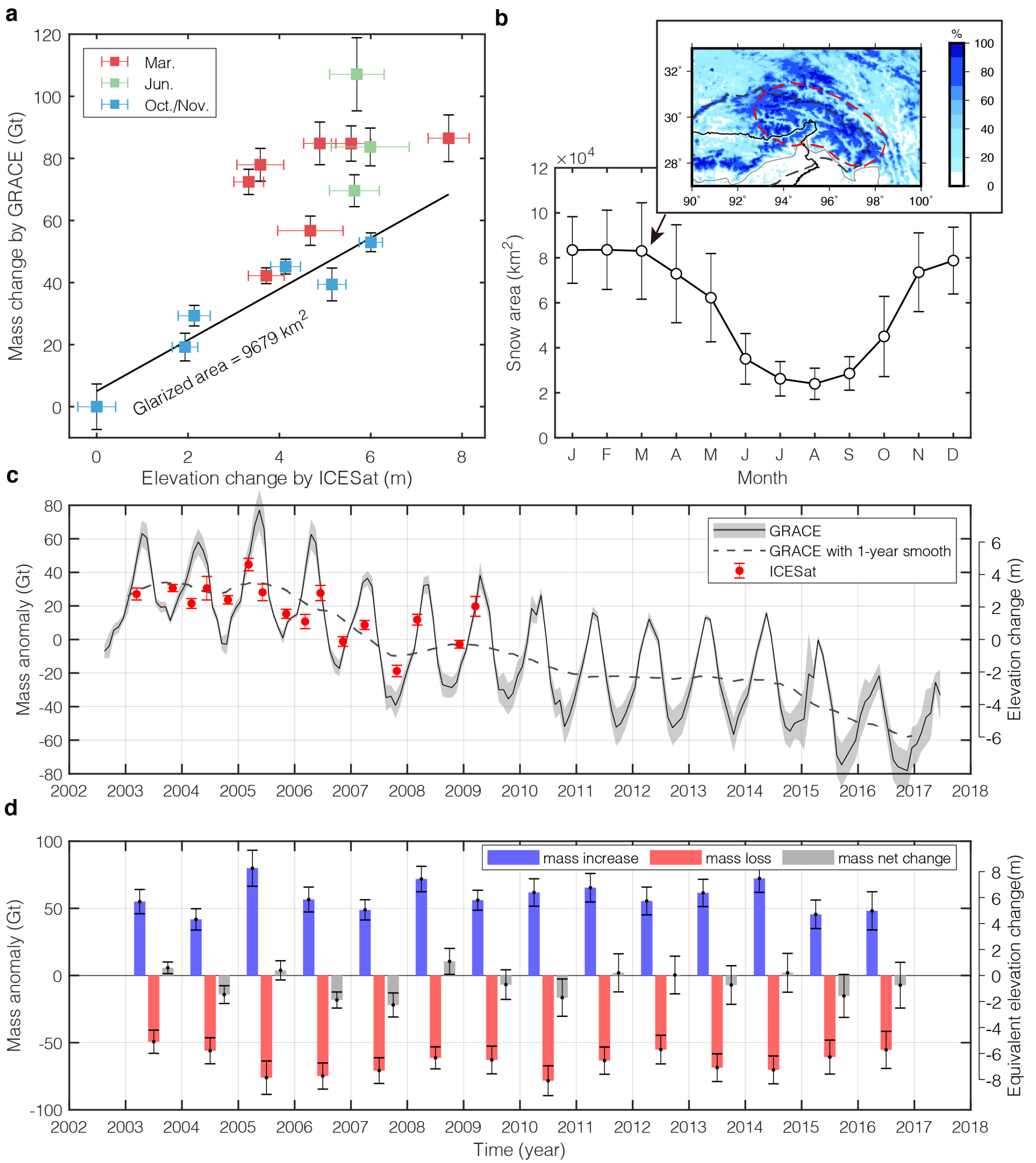
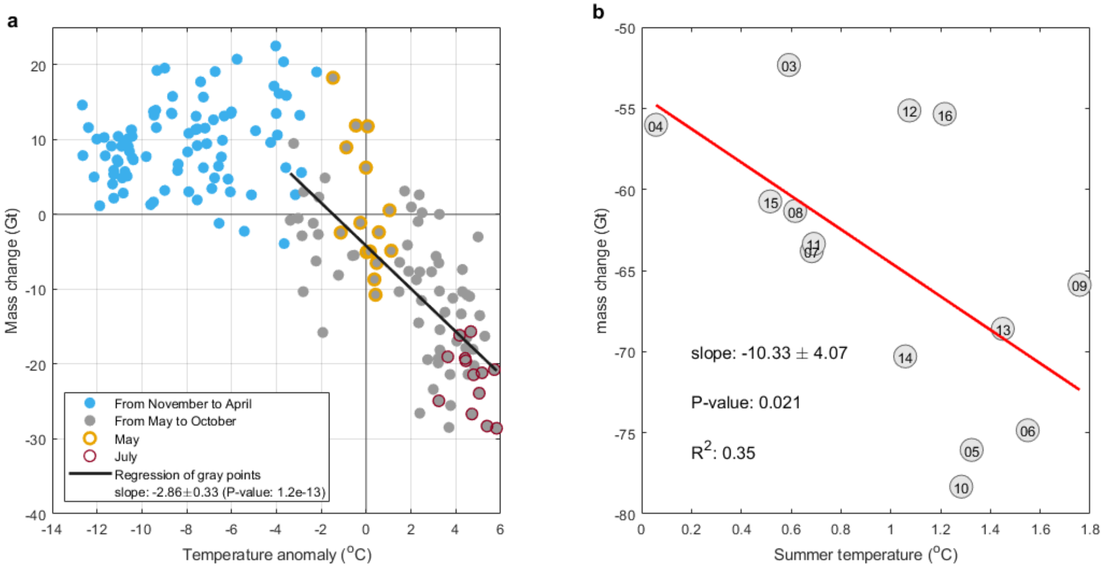


Figure 6. GS mass balance in the SETP. (a) GS mass change by GRACE as a function of elevation change from ICESat. The values are anomalies relative to the minimum in October 2007. (b) Seasonal snow coverage changes. The error bars are calculated by the dispersions in the same month among years from 2003 to 2016. The coverage in March is given in the inset. The red dashed circle marks the region used for the calculation of snow area. (c) Time series of GS mass change estimated by GRACE and glacier mas change by ICESat. The glacierized area of 9,679 km^2 is used to convert thickness change into mass change. (d) Annual mass increase/decrease from 2003 to 2016 by GRACE.


a
Mass change (Gt)
20
10
0
-10
-20
-30
-40
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
Temperature anomaly (°C)
From November to April
From May to October
May
July
Regression of gray points
slope: -2.86±0.33 (P-value: 1.2e-13)
b
mass change (Gt)
-50
-55
-60
-65
-70
-75
-80
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Summer temperature (°C)
03
12
16
04
15
08
11
07
09
13
14
06
05
10
slope: -10.33 ± 4.07
P-value: 0.021
R²: 0.35

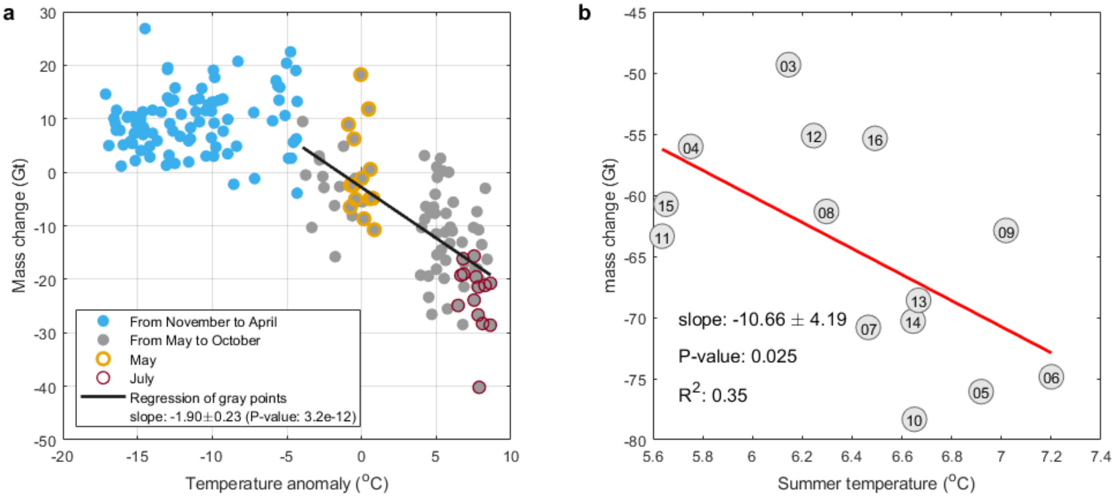
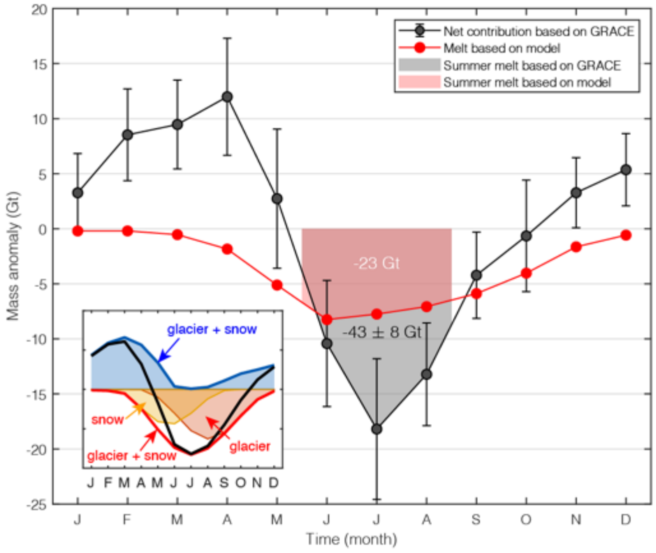


Figure 7. Regression between mass change and temperature. (a) Monthly mass changes as a function of monthly temperature anomalies. (b) Linear regression between annual mass decreases and summer temperatures. The number in the circle represents the year of the data (e.g. "15" shows 2015).



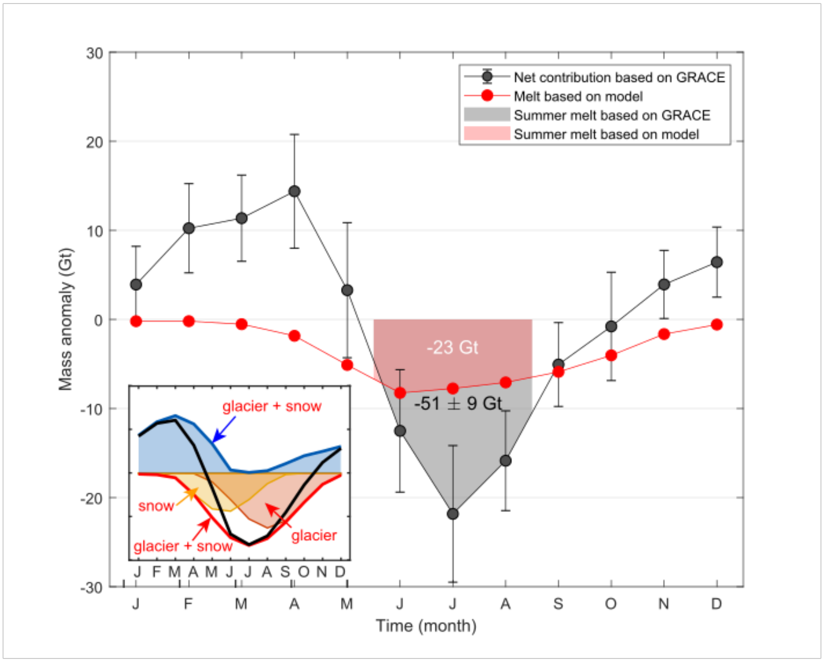


Figure 8. Monthly mass change from GS in the upper Brahmaputra Basin estimated by GRACE and by the model of Lutz et al. (2014). Negative values mean a net increase of meltwater (i.e., more glacier and snow melt than accumulation). Note that Lutz's model only estimated the melt component, while GRACE detects the net change including both melt and accumulation. The estimates of summer melt are annotated. A schematic diagram of seasonal mass balance is shown in the inset (Blue text represents mass accumulation, red represents ablation, and the black curve represents the net change). Note 85% of the meltwater in our study

region runs into the Brahmaputra and this amount comes from 83% of glacierized area in this basin, we scale our result by 1×0.85/0.83 to be comparable with the model estimate.

Table 1. Previous model-based estimates of meltwater contribution to the Brahmaputra discharge.

Study literature	**Time span**	**Drainage area (km^2)**	**Amount of meltwater (w.e. km^3 yr^{-1})**	**Total discharge (km^3 yr^{-1})**	**Meltwater/total discharge (%)**
Immerzeel et al. 2010	2000–2007	525,797	62	230	27
Bookhagen and Burbank, 2010	1998–2007	255,929	55	161	34
Zhang et al., 2013	1961–1999	201,200*	20	58	35
Lutz et al., 2014	1998–2007	360,000	43	131	~~34~~33
Huss et al., 2017	2002–2011**	533,000	138	732	19
Chen et al., 2017b	2003–2014	240,000*	12	60	21

* The NTM is almost not included.

** The time spans vary a bit in different datasets.

Table 2. GRACE error sources for the long-term trend. (Unit: Gt/yr)

Source	**Error**	**Remark**
Linear Fit	0.14	Calculated from fitting residuals of a linear and trigonometric model
Data solution and smoothing errors	0.44	Estimated from the dispersion among CSR, GFZ and JPL with DDK4/G300+P4M6
Leakage error	0.51	The average peak date may vary from May 6th to May 16th
GIA	0.02	Difference between results with and without A's GIA model (A et al., 2013)
LIA	0.20	The total LIA effect in the whole Himalaya range and southeastern Tibet is -1±1 Gt/yr
Denudation	0.32	The total denudation effect in the eastern and southeastern Tibetan Plateau is 0.8 km^3/yr
Total	0.78	