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

Anonymous Referee #3

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 will try 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) between August 2002 and June 2017 and a summer meltwater contribution of 43 ± 8 Gt to the Brahmaputra.

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 **Error! Reference source not found.**). 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.

Recently, calibration and validation of glacier mass balance and snow area changes have begun to be incorporated into the state-of-the-art model (Wijngaard et al., 2017; Biemans et al., 2019), but the glacier observations suffer from coarse temporal resolution (two observations over a 5-year span) and the snow area changes are only partially correlated with its volume 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 show the initiation of the spring precipitation by results of TRMM and HAR from January to March in Figure 2). 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:

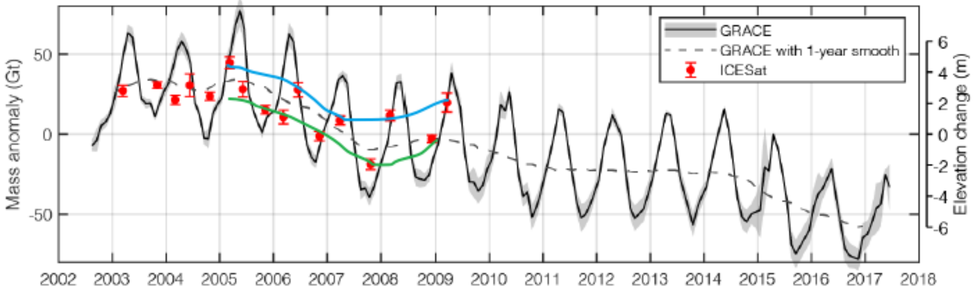
Kääb, A., et al. "Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya." *The Cryosphere* 9.2 (2015): 557-564.

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.



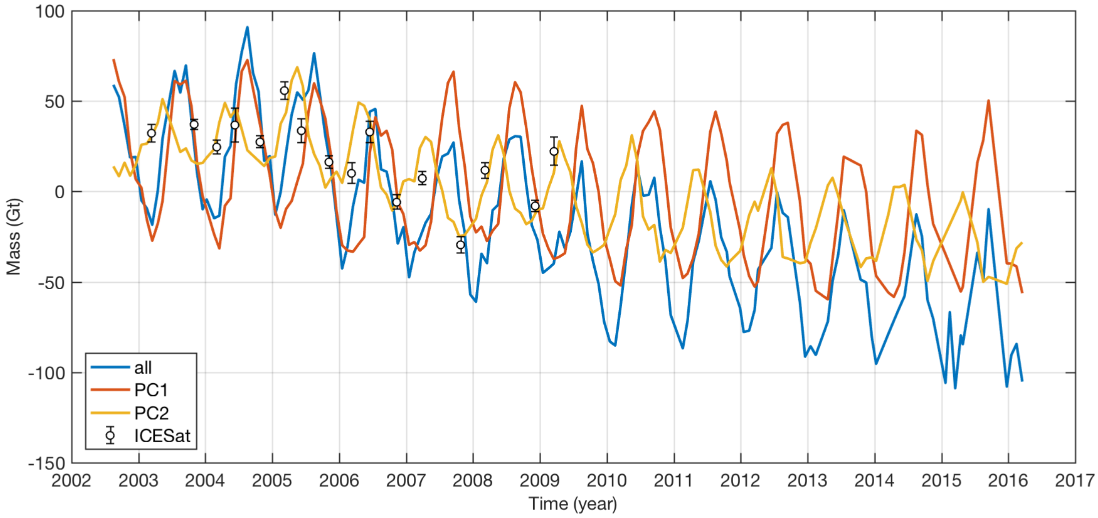
[Fig. 1. GS mass balance estimates by using GRACE and ICESat]

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

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

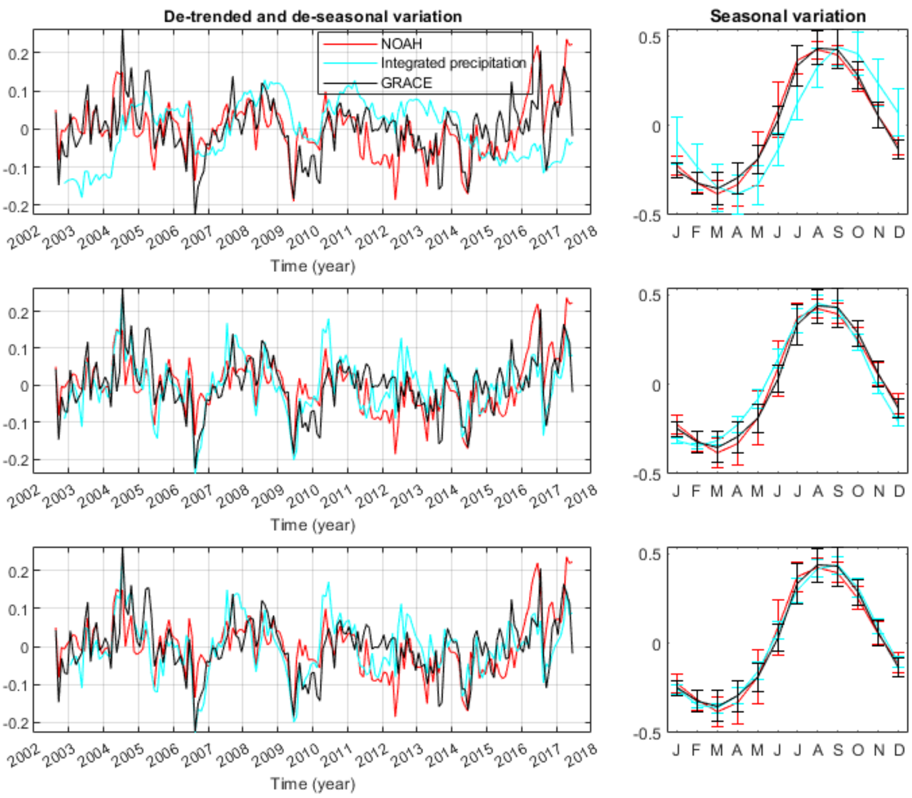
where IntP represents the integrated precipitation in jth month, P is short for precipitation, W is the weight for the integration, and N is the integration window.

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 little effect 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]

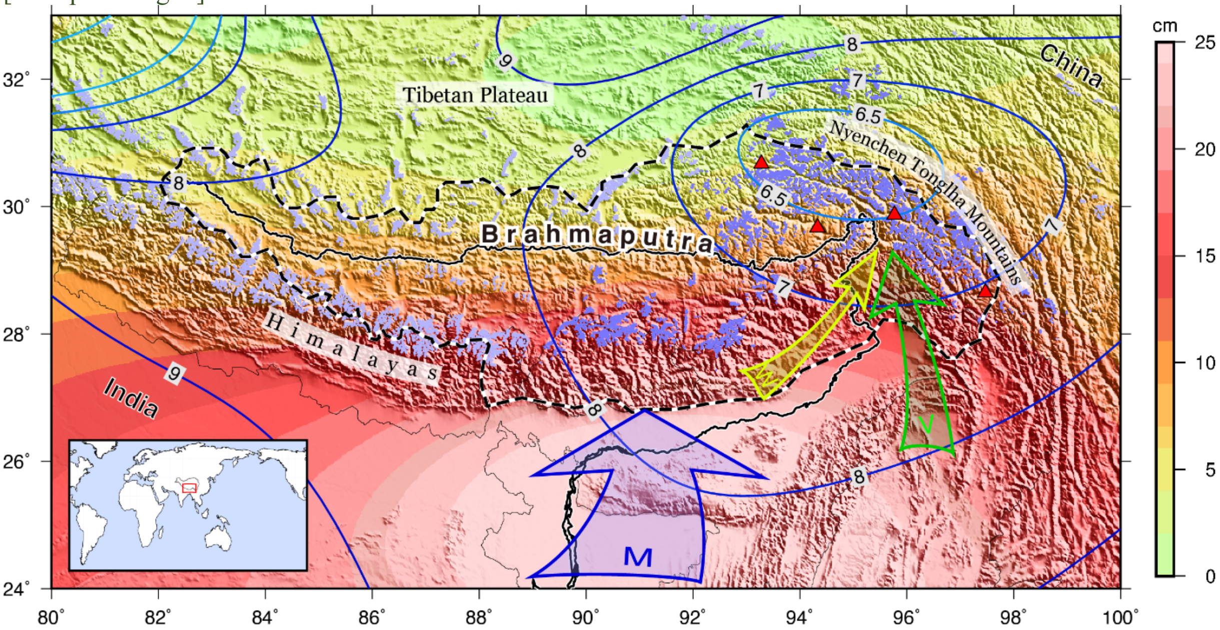
Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., and Flechtner, F.: AOD1B Product Description Document for Product Release 06 (Rev. 6.1, October 19, 2017), 2017.

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]