Author’s responses to Reviewer #1

Dear Reviewer,

We are very grateful to your constructive comments, which provided help for improving our manuscript. We have carefully addressed the issues raised by you and modified our manuscript accordingly. Detailed responses (marked in blue font) are summarized in the following sections with the original comments (marked in black font). The corresponding changes in the revised draft of the manuscript are listed in red italics font.

Sincerely,

Zhiguang Tang

Interactive comment on “Investigating spatiotemporal patterns of snowline altitude at the end of melting season in High Mountain Asia, using cloud-free MODIS snow cover product, 2001–2016” by Zhiguang Tang et al.

Anonymous Referee #1

Received and published: 30 July 2019

The manuscript presents a remote sensing study, aiming to detect large-scale patterns of snowline altitude at the end of melting seasons for High Mountain Asia and the period 2001 to 2016. The proposed method is based on MODIS fractional snow cover data that are processed using a previously published routine to remove cloud cover. This method is extended by an approach to estimate perennial snow by empirically matching MODIS-derived snow-covered days to glacier mass balances and Landsat-based snow cover estimates. Strongly generalized results are then analyzed towards intrinsic trends and correlations with meteorological station data by applying basic statistic tools, i.e. linear regression and correlation coefficients. As such, the overall topic of the manuscript is relevant and fitting TC’s scope but the methods and data hardly satisfy basic standards. The actual result data is not included with the submission, so that an assessment of their quality is not possible. I find this particularly problematic since the manuscript is widely lacking critical reflections on the method, even though its weaknesses are becoming obvious in the results despite their high grade of generalization. English language of the manuscript is subject to abundant basic errors, some of which make it impossible to understand what sentences means. In summary, I find that the manuscript cannot be considered for publication owing to substantial issues in methods and over-interpretation of questionable results. I consider the work required to thoroughly tackle these issues to be way beyond the time frame for revisions, so that I unfortunately have to recommend rejection despite the interesting topic and general potential.

Response: We have made two major improvements in the revised manuscript. (1) Added the Evaluation of MODIS-derived grid (30km) SLA-EMS. (2) We have changed the temperature and precipitation data of meteorological stations into ERA5 reanalysis data, the correlation coefficients between the SLA-EMS, temperature, and precipitation during 2001 to 2016 are calculated on a grid-by-grid basis.

In addition, the English language will be further improved in the revised manuscript. The result data (MODIS-derived SLA-EMS in the 16 years) will be available online as the supplementary data related to this article, after it is accepted.

In the following are my comments on some of the major issues of this manuscript that might help the authors to improve the study for a future submission.

The methodological evaluation is not robust and a critical evaluation of the actual data quality is lacking: - MODIS data is presented as the 'most recent and advanced remote sensing snow product' (L76) and treated as this throughout the manuscript. The fact that there are much more recent missions providing more detailed data is ignored, the adverse effects of the extremely coarse resolution of 500 m is hardly considered, and studies clearly indicating that the quality of MODIS snow cover is less accurate for HMA (Rittger et al., 2013) is not mentioned.

Rittger, K., Painter, T. H. and Dozier, J.: Assessment of methods for mapping snow cover from MODIS, Advances in Water Resources, 51, 367–380, 2013.

Response: In this research, we mainly focus on using MODIS snow cover products to monitor the spatial and temporal patterns of the SLA-EMS in the whole of the HMA. This research is a practice without precedent, despite the coarse resolution of the SLA-EMS dataset (30km) and the data source (500m).

The spatial resolution of the remote sensing data source should vary with the spatial scale of the research object, not always the higher the better. For example, the applications of the Landsat data and other high resolution remote sensing images in the snowline monitoring are mostly limited to individual glacier or small areas (L76), due to the low temporal resolution and large cloud cover. But the spatiotemporal pattern of SLA-EMS from the whole of the HMA under climate change is poorly understood. Thus we experimented with the cloud-removed MODIS fractional snow cover product to investigate the spatiotemporal pattern of SLA-EMS in the HMA from the grid scale of 30km. In this study, we pay attention to the spatiotemporal change of SLA-EMS on the large scale, rather than the details on the local area (such as local slope and aspect). The coarse resolution of the 500m in MODIS can be tolerated in this study.

We have checked the study of Rittger et al. (2013). It is not true for Reviewer's comment of "the quality of MODIS snow cover is less accurate in HMA". Instead, the Rittger et al. (2013) showed that the MOD10A1 fractional snow cover product in HMA were more accurate than the other areas (the Table 3). The MOD10A1 fractional snow cover product is exactly what we used in this manuscript. We appreciate the Reviewer for the recommendation of this important reference, and we have added it in the revised manuscript.

6.1. Regional sensitivity

As presented in Section 5, the Himalaya region has the greatest errors in snow-covered area, while the three North American regions show similar results. In North America at the 15% threshold, all binary statistics exceed 0.9, whereas in the Himalaya *Recall* drops below 0.8 and the *F* statistic therefore also drops below the North American values (Table 2).

For the fractional methods (Table 3), the RMSE for MOD10A1 is actually better in the Himalaya than in North America (0.155 vs 0.229+). MODSCAG's RMSE in the Himalaya is slightly worse than

(Rittger et al., 2013)

Table 3
Summary of fractional statistics.

Region	Statistic	MOD10A1 fractional
Sierra Nevada	RMSE[a]	0.276
	Mean difference[b]	0.180
	Median difference	0.190
Upper Rio Grande	RMSE	0.229
	Mean difference	0.178
	Median difference	0.193
Cold Land Processes Experiment	RMSE	0.247
	Mean difference	0.186
	Median difference	0.190
Himalaya	RMSE	0.155
	Mean difference	−0.087
	Median difference	−0.085
All	RMSE	0.227
	Mean difference	0.114
	Median difference	0.122

[a] RMSE is defined in Eq. (11).
[b] Difference is defined as of $f_{SCA}^{MODIS} - f_{SCA}^{Landsat}$.

(Rittger et al., 2013)

In section 2.2.1. MODIS Fractional Snow Cover (FSC) Data

"…*Evaluation studies have proved a high accuracy (with a mean absolute error less than 0.1) of the MODIS FSC data (Hall and Riggs, 2007; Rittger et al., 2013; Salomonson and Appel, 2004; Tang et al., 2013).*"

We agree with the Reviewer that it is necessary to evaluate the quality of the MODIS-derived SLA-EMS. We have selected 5 grids to evaluate the MODIS-derived SLA-EMS, using Landsat images (TM, ETM+ and OLI) selected from melt seasons. And the discussion for the possible uncertainty and error sources of the method are added in the Section 5. (Discussion).

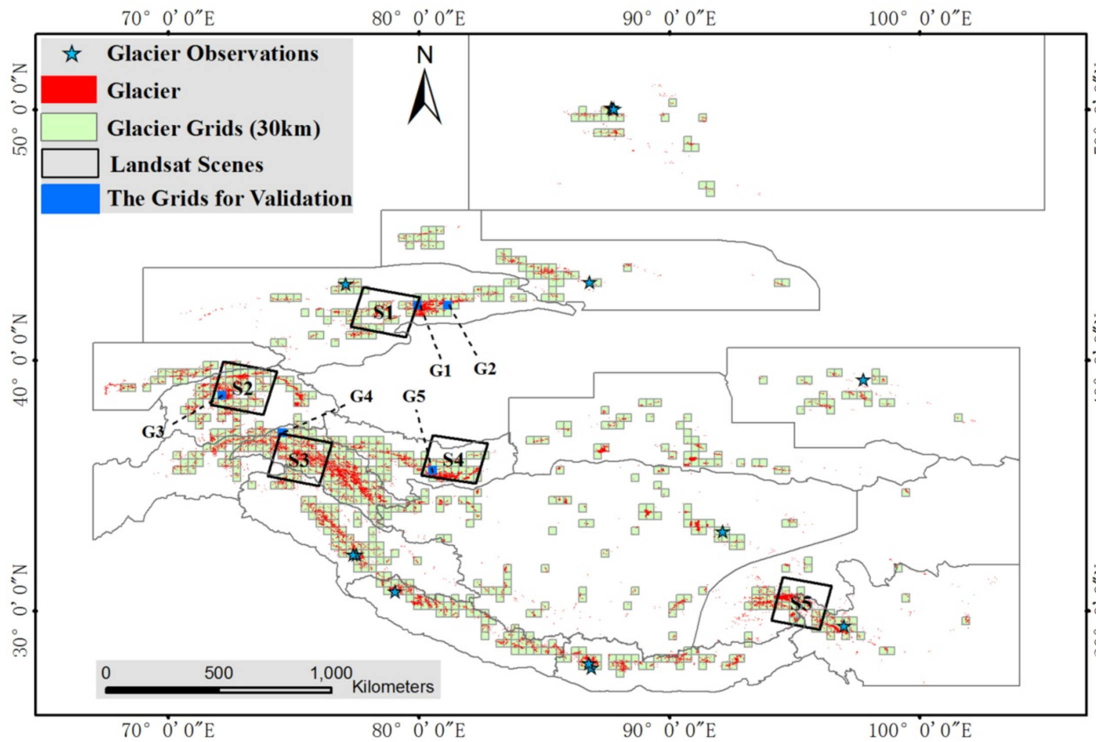

Figure 2. *…The 5 blue grids (G1-G5) indicate the site for SLA-EMS evaluation.*

Table 2. *Information about Landsat TM/ETM+/OLI images used in validation of MODIS-derived SLA-EMS.*

Year	*G1 and G2*	*G3*	*G4*	*G5*
	Path 147, Row 31	*Path 151, Row 33*	*Path 150, Row 34*	*Path 145, Row 35*
2001	*Aug 13*	*Jul 26*	*Jul 3, Aug 20, Sep 5*	*Aug 25, Sep 2*
2002	*Jul 1, Jul 17, Aug 18*	*Aug 30*	*Aug 7, Aug 23*	*Jul 3*
2003	*Jul 20*	*Jul 16, Sep 2*		*Jul 22*
2004	*Jul 22, Aug 7, Aug 23*	*Jul 2, Aug 3, Sep 4*	*Jul 11, Jul 27, Aug 12*	*Jul 8, Aug 25, Sep 10*
2005	*Jul 25, Aug 10, Aug 26*	*Jul 21, Aug 6, Sep 7*	*Jul 14, Aug 15, Aug 31*	*Jul 11, Aug 12, Sep 13*
2006	*Jul 28, Aug 13, Aug 29*	*Jul 24, Aug 25, Sep 10*	*Jul 17, Aug 2, Sep 3*	*Jul 30, Aug 15, Sep 31*
2007	*Aug 8, Aug 24, Sep 1*	*Jul 27, Aug 12, Aug 28*	*Jul 4, Jul 20, Aug 5*	*Aug 10, Aug 18, Sep 3*
2008	*Aug 2, Aug 10, Sep 3*	*Jul 29, Aug 14, Aug 30*	*Jul 6, Aug 7, Aug 23*	*Jul 3, Aug 4, Aug 5*
2009	*Jul 20, Aug 10, Aug 21*	*Jul 16, Aug 1, Aug 17*	*Jul 9, Jul 25, Aug 2*	*Jul 6, Jul 15, Aug 31*
2010	*Jul 15, Jul 23, Aug 16*	*Jul 19, Aug 20, Sep 5*	*Jul 12, Aug 21, Aug 29*	*Jul 9, Jul 17, Aug 26*
2011	*Jul 26, Aug 3, Aug 19*	*Jul 22, Aug 23, Sep 8*	*Jul 7, Aug 8, Aug 24*	*Jul 28, Aug 5, Aug 21*
2012	*Jul 28, Aug 29*	*Jul 9, Aug 25, Sep 10*	*Jul 17, Aug 2, Aug 18*	*Aug 31*
2013	*Jul 23, Jul 31, Sep 1*	*Jul 19, Jul 27, Aug 28*	*Jul 4, Jul 28, Sep 6*	*Jul 17, Aug 2, Aug 10*
2014	*Jul 10, Jul 26, Aug 11*	*Jul 14, Aug 7, Aug 31*	*Jul 15, Jul 23, Aug 1*	*Jul 28, Aug 13, Aug 21*
2015	*Aug 6, Aug 14, Aug 30*	*Jul 17, Aug 18, Sep 3*	*Aug 19, Aug 27, Sep 4*	*Jul 23, Aug 8, Sep 9*
2016	*Aug 8, Aug 24, Sep 1*	*Jul 27, Aug 4, Aug 28*	*Jul 20, Jul 28, Aug 13*	*Jul 2, Jul 17, Jul 25*
Total	*43*	*43*	*44*	*41*

In the secsion 4. Results

"*4.1 Evaluation of MODIS-derived grid (30km) SLA-EMS*

To evaluate our method, we compared SLA-EMS of 5 grids manually digitized from *high-resolution Landsat images (Table 2) with the automatic measured results from MODIS, during 2001-2016. To be consistent with the DEM data sources of the MODIS-derived SLA-EMS, the 90m SRTM DEM is also used to calculate the SLA-EMS derived from the manual delineation. For each grid and year, the highest snowline is manually digitized as the "truth-value" of SLA-EMS by combining several Landsat images of melt season. The mean absolute error, root mean square error and correlation coefficient are employed to evaluate the reliability of the MODIS-derived SLA-EMS (Table 3). In the 5 validation grids, the mean absolute error of MODIS-derived SLA-EMS compared with the manually-derived (Landsat) values is between 44.9 and 124.7 m, and the RMSE is between 52.3 and 133.4m. Despite these differences between the MODIS-derived SLA-EMS and that from manually-derived (Landsat), the correlation coefficients between them are high (between 0.63 and 0.87), and they are all significant at the 0.01 level. The significant correlations indicate that the proposed method can be used to accurately monitor the interannual variations of SLA-EMS. We believe that the MODIS-derived SLA-EMS with such accuracy in the 30km grids can be applied to investigating the spatiotemporal patterns of SLA-EMS in the HMA."*

Table 3. *Comparison of SLA-EMS derived from manual delineation of snowline (Landsat images) and automatic calculation from MODIS, during 2001 to 2016.*

Site	*Mean absolute error (m)*	*Root mean square error (m)*	*Correlation coefficient*
G1	*76.4*	*84.4*	*0.70***
G2	*124.7*	*133.4*	*0.65***
G3	*67.1*	*78.0*	*0.87***
G4	*50.6*	*62.2*	*0.76***
G5	*44.9*	*52.3*	*0.64***

*** indicate statistical significance at the 0.01 level.*

In the section 5. Discussion

…

"*Due to the coarse resolution (500m) of the MODIS data, the proposed method for SLA-EMS monitoring is limited to large scale areas, and it is also why the glacier grids are divided as big as 30km in this study. The uncertainty of the MODIS-derived SLA-EMS may come from different sources of errors: (1) errors occurred due to the pixel size of the remote sensing images, slope and aspect of the terrain, the accuracy of the georeferencing and the quality of the DEM (Rabatel et al., 2002, 2005, 2012); (2) the errors in MODIS snow mapping algorithm (Hall and Riggs, 2007; Rittger et al., 2013) and cloud removal method (Tang et al., 2013), although the MODIS SCD threshold is calibrated in this method.* "

MODIS FSC data treated with the 'cloud removal method' by Tang et al. (2016) are presented as having a 'high snow classification accuracy' (L94). However, a considerable part of the methods focuses on finding an empirical threshold to replace the number of days per year for perennial snow cover –which should clearly be 365– with a number that fits observations.

Response: Theoretically, the SLA-EMS can be determined by the MODIS derived snow covered days (SCD), that is, the boundary altitude of perennial snow cover (where the SCD⩾365d).

However, the SCD⩾365d is too strict and idealistic, due to the annual cumulated errors of MODIS snow mapping algorithm and cloud removal method. That is to say, for the cloud-removed MODIS snow cover images will fails to really identify perennial snow cover, as long as there is more than one error in the 365 days. Therefore, in order to accurately estimate the perennial snow cover (minimize the annual cumulated errors in MODIS snow mapping algorithm and cloud removal method), the MODIS SCD threshold was calibrated using both the glaciers annual mass balance observations and Landsat images.

It is generally stated that there is a 'significant linear relation' of the MODIS-derived SLA-EMS results with WGMS glacier mass balance measurements (L209f), but the presented data clearly shows this is not the case. Only for six out of twelve glaciers 95% critical values of sample correlation are reached. Conversely, data for Leviy Aktru is basically uncorrelated and R values for Chorabari as well as Pokalde are far off the thresholds. Also, RMSE and R_2 values are not considered at all.

Response: Many previous studies (Braithwaite, 1984; Barandun et al., 2018; Rabatel et al., 2005, 2008, 2012; Shea et al., 2013; Xie et al., 1996), which focused on the individual glacier or local areas have shown that glacier annual mass balance is highly correlated with the SLA-EMS. This is the reason why we used the glaciers annual mass balance observations to calibrate the MODIS SCD threshold, the highest negative correlations between annual mass balance and SLA-EMS indicate an optimal SCD threshold (Figure 4).

It is normal that the correlations between glaciers annual mass balances and the MODIS-derived 30km grid SLA-EMS are not all significant (95%), due to the individual glacier annual mass balance observation is difficult to represent the true value for the 30km grid regions. How accurately the MODIS-derived SLA-EMS predicts annual mass balance is not the objective at this stage of our research. The quantitative relationship between SLA-EMS and glacier annual mass balance at the grid scale (30km) needs to be further studied in the future work using adequate spatially resolved glacier annual mass balance data, for example using time series of DEMs derived from ASTER optical satellite stereo-images (Brun et al., 2017).

We modified the relevant text to make it more rigorous. For example, the "significant" has changed as "good", in L219.

- Using Landsat data to evaluate the MODIS snow cover results is a good idea. However, instead of simply checking whether the overall areas are equal I would consider it mandatory to investigate in how far the classifications match.

Response: We believe the "checking whether the overall areas are equal" is exactly a good indicator for "investigate in how far the classifications match". In the method, the altitude value of the SLA-EMS for each glacier grid (30km) is also measured by the perennial snow cover areas and the area-elevation distribution curve (Figure 7). Therefore, we focus on the comparisons of Landsat-derived perennial snow cover area and that of MODIS-derived (checking whether the overall areas are equal) in the calibration of MODIS SCD threshold using Landsat data (Figure 6).

SLAs are substantially influenced by local topography, particularly slope aspect. The 500 km input data is hardly capable of detecting these, the 30 km grid resolution pixels completely ignores such effects. Therefore, the relevance of the findings regarding (individual) glaciers is highly questionable.

Response: In this study, we pay attention to the spatiotemporal change of SLA-EMS on the large scale area, rather than the details on the local topography (such as local slope and aspect). And there are no relevant findings in this research to regarding individual glaciers. In Figure 4 and 5, we just used the glaciers annual mass balance observations to calibrate the MODIS SCD threshold, based on the findings of the previous studies (Braithwaite, 1984; Barandun et al., 2018; Rabatel et al., 2005, 2008, 2012; Shea et al., 2013; Xie et al., 1996) (they showed the glacier annual mass balance is highly correlated with the SLA-EMS).

It does not become clear how data from the meteorological stations is treated, i.e. how averages are calculated over space and time, and how these are related to the results. As visible in Fig. 1, meteorological stations are extremely scarce in glaciated regions. There are no data at all for the Karakoram and the W Kunlun and most of the other stations are far away from glaciers, typically in completely different climate regimes down in the valleys – this is obviously known to to the author's according to L410ff. So why not use more appropriate data, such as the freely available ERA5?

Response: We agree with the Reviewer. We have changed the temperature and precipitation data of meteorological stations into ERA5 reanalysis data. The product of "ERA5 monthly averaged data on single levels from 1979 to present" was downloaded from https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=ERA5. Horizontal resolution: 0.25° x 0.25°; temporal resolution: monthly.

For each grid, the correlation coefficients between the SLA-EMS, temperature and precipitation during 2001 to 2016 are calculated (Fig. 13). In Fig. 13, both of the climate variables are calculated from summer and hydrological year (from September of the previous year to August of the current year).

The relevant result analysis in this manuscript will be modified accordingly in the revised manuscript.

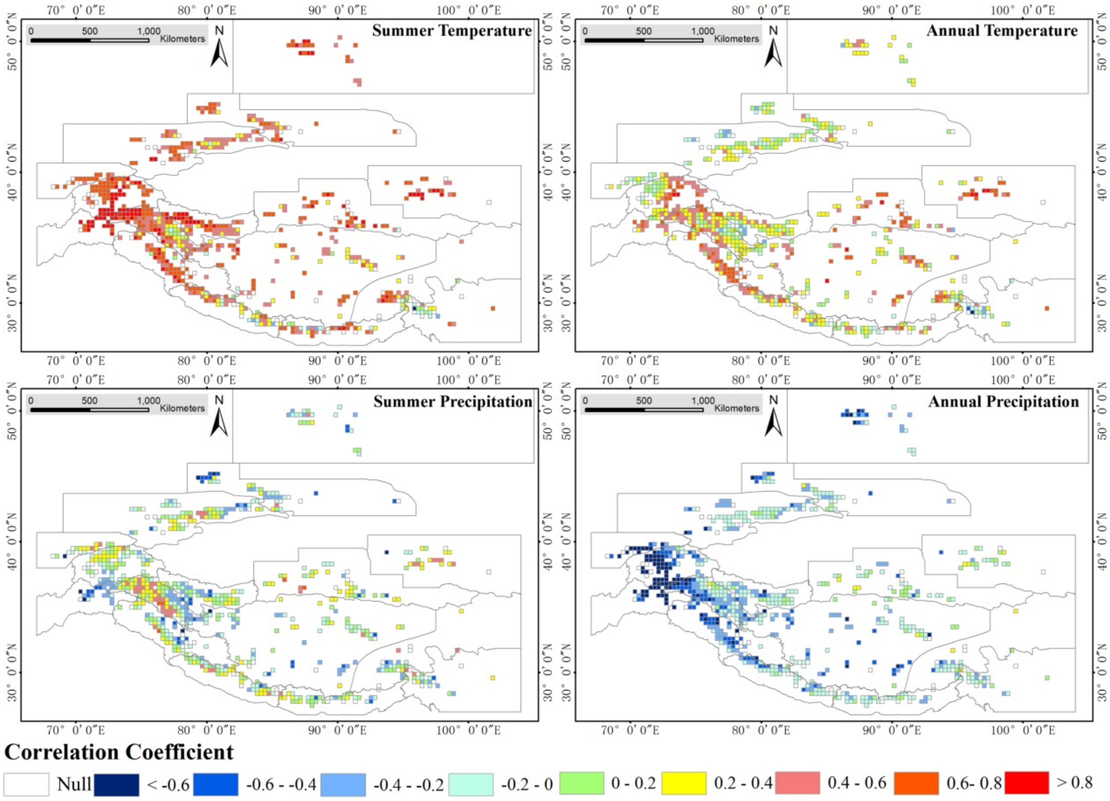

Figure 13. The correlation coefficients between the SLA-EMS, temperature, and precipitation during 2001 to 2016.

Table. The averages of Pearson correlation coefficients between the SLA-EMS, temperature, and precipitation for different subregions in the period of 2001-2016.

Regions	***Summer temperature***	***Annual temperature***	***Summer precipitation***	***Annual precipitation***
S and E Tibet	*0.55 **	*0.38*	*-0.05*	*-0.09*
Hengduan Shan	*0.13*	*0.01*	*0.06*	*0.01*
Qilian Shan	*0.75 ***	*0.61 **	*0.26*	*0.17*
Inner Tibet	*0.52 **	*0.36*	*-0.08*	*-0.19*
E Tien Shan	*0.58 **	*0.17*	*-0.18*	*-0.16*
W Tien Shan	*0.55 **	*0.11*	*0.05*	*-0.13*
E Himalaya	*0.46*	*0.23*	*0.03*	*0.01*
E Kun Lun	*0.64 ***	*0.48*	*0.15*	*0.14*
C Himalaya	*0.37*	*0.36*	*0.13*	*-0.16*
Pamir	*0.77 ***	*0.41*	*0.04*	*-0.53 **
W Himalaya	*0.64 ***	*0.52 **	*-0.02*	*-0.40*
Altay and Sayan	*0.67 ***	*0.30*	*-0.07*	*-0.32*
Hissar Alay	*0.67 ***	*0.13*	*0.15*	*-0.61 **
Hindu Kush	*0.86 ***	*0.46*	*-0.36*	*-0.68 ***
W KunLun	*0.63 ***	*0.22*	*-0.05*	*-0.08*
Karakoram	*0.57 **	*0.32*	*0.19*	*-0.28*

Honestly, I don’t understand why the manuscript focuses on the end-melting season. By this approach the greatest advantage of MODIS data, its high temporal resolution, is lost whereas the challenges regarding the quality of specific measurements are fully affecting the results.

Response: The reasons for why the manuscript focuses on the snowline altitude at the end-melting season (SLA-EMS) were clearly introduced in the introduction.

“The snowline altitude at the end of melting season (SLA-EMS) approximates the equilibrium line altitude (ELA), it can serves as a good proxy for ELA and therefore for the mass balance of glaciers (McFadden et al., 2011; Pandey et al., 2013; Rabatel et al., 2005, 2012; Tawde et al., 2016). Numerous studies (Braithwaite, 1984; Barandun et al., 2018; Rabatel et al., 2005, 2008, 2012; Shea et al., 2013; WGMS, 1991-2013; Xie et al., 1996) have shown that glacier annual mass balance is highly correlated with the ELA or SLA-EMS, and the SLA-EMS enables reconstruction of annual mass balance time series. The climate sensitivity of SLA-EMS has been generally emphasized as a supplement to current climate change indicator systems. A study of the spatial-temporal variations of the SLA-EMS can help in assessing the hydrologic cycle balance as well as to understand the regional and global cryosphere and climate changes.”

Large parts of the discussion do not present content supposed to be there. While interpretations of the results and evaluations of their implications against the literature are short and remain superficial, many paragraphs basically repeat statements regarding the relevance of such remote sensing studies as well as the general, subjective praise of the method.

Response: We will try to improve it in the revised manuscript.