Response to Anonymous Reviewer 1

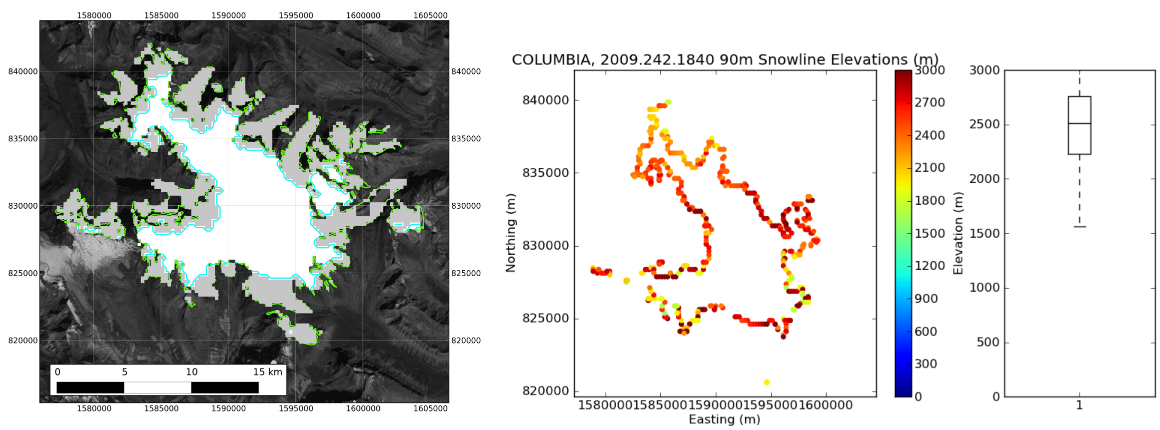
We thank Anonymous Reviewer #1 for the detailed comments and overall positive remarks on our manuscript. Below, we address the general and specific comments, and provide new text and information that will be included in the manuscript. Our responses are in bold.

General Comments

1. The use of "regional snowline","regional MODIS-derived ELA","regional ELAs", etc., and even the use of "snowlin" appear to be abusive. The authors use the method they present based on MODIS images to extract not even the snowline, but the 20th percentile of elevation of snow-covered pixels (ZS(20)), and they claim that this ZS(20) metric yield to the best correlation with the surface mass balance for the glaciers where field data are available. In other words, they consider that this ZS(20) metric is representative of the snowline/equilibrium line. The studied glaciers are located in the midlatitudes and must be temperate, so that we can assume that the end-of-summer snowline can be representative of the equilibrium line altitude, but what about the ZS(20) metric? However, because the authors have of all the necessary data, they can easily demonstrate this point. For the eight glaciers used for validation, I would be interested to see: - the scatter-plot between the snowline altitude computed from MODIS for each year and the ELA calculated from field data for the corresponding year. - the scatter-plot between the ZS(20) metric computed from MODIS for each year and the ELA calculated from field data for the corresponding year. Furthermore, I would be interested to understand why the authors use this ZS(20) metric instead of the ice/snow limit. Is it to avoid any confusion between the snowline and the firn line? In any case, further explanations have to be given. Also, using the ice/snow limit would avoid the problems of glacier delineation errors, bare rock pixels in the accumulation zone, cloud-covered pixels and so on.

   Response: These are valid points, and we regret the confusion caused by our use of these terms. In the revised manuscript, we will incorporate some definitions in the introduction and consolidate their usage throughout the manuscript:

   "The distinct boundary that separates snow-covered and snow-free zones on a



(a) (b)

Figure 1: a) Landsat 5 scene of the Columbia Icefield, DOY 242, 2009, with MOD02QKM clusters and delineated snowline (blue) and b) snowline elevations extrated from the constructed shapefile and 90 m DEM (not projected) and boxplot of extracted elevations for the same date.

> glacier varies both spatially and temporally. During the melt season, this boundary is defined as the ’transient snowline’ (Østrem, 1975), and over a large region thsi can be qualified as the ’regional transient snowline’. We assume in this study that the maximum elevation of the regional transient snowline observed over a melt season is representative of the regional equilibrium line altitude (ELA). ”

Our initial approach was to map the snowline (the ice/snow limit) as a point shapefile and use this to extract elevations from a DEM (Figure 1). The mean elevation of the extracted elevations was assumed to provide a measure of the regional transient snowline. However, the extracted snowline elevations showed substantial variation , which we believe is due to a number of factors. These factors include (1) the spatially variable nature of snowline elevations over large icefields, (2) geolocational errors, (3) misclassification errors, and (4) cloud cover. “Inliers” (patches of ice that occur above the transient snowline) and “outliers” (patches of snow that occur below the transient snowline) will also affect the calculation of a mean regional snowline elevation (Cogley, 2011).

As suggested, we have also plotted the ELA calculated from field data (the observed ELA), versus (1) our regional ELA proxy, the maximum elevation of $Z_{S(20}$ (Figure 2), and (2) the maximum snow/ice limit (Figure 3). Agreement is better between field-derived observations of ELA and the $Z_{S(20)}$ metric we have chose. Sample sizes are smaller than those for net balance, as the ELAs that are based on field data occasionally go unreported.

2. The authors mention that their methodology is an extension of Rabatel et al. (2005) approach,

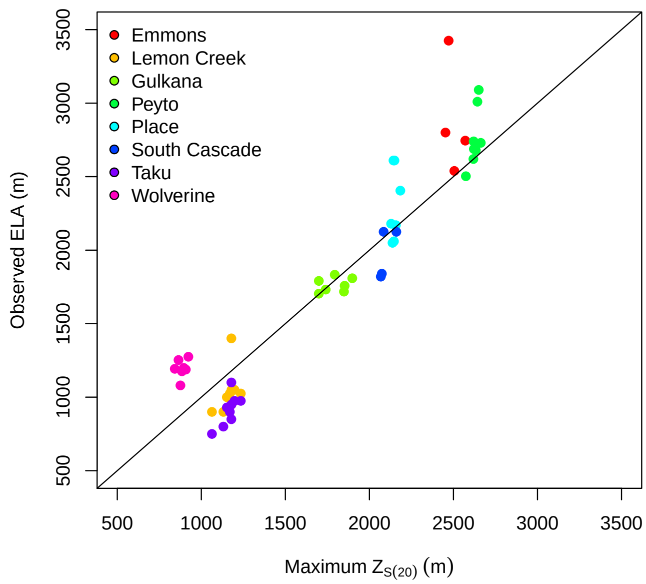


Figure 2: Index glacier ELAs observed from field data versus maximum regional $Z_{S(20)}$, 2000-2009.

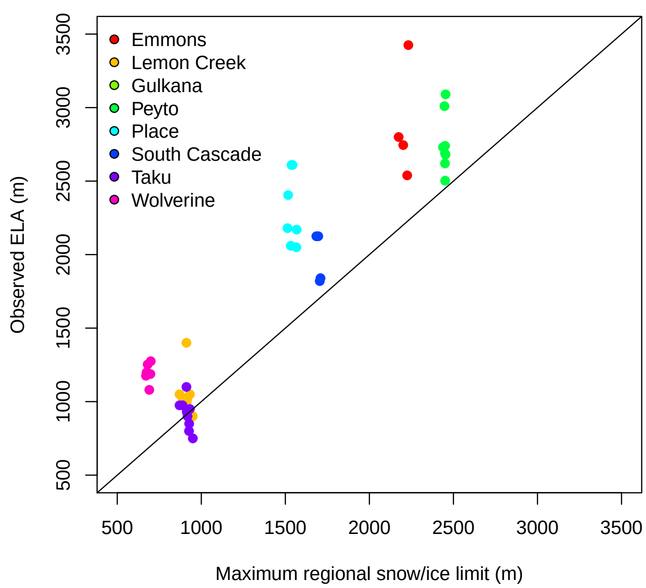


Figure 3: Index glacier ELAs observed from field data versus maximum regional snow/ice limit, 2000-2009

but it has almost nothing to see. Here, the authors compute the mass balance using a proxy of the ELA (the Zs(20) metric) and mass balance gradients for the accumulation and ablation zones. However, Rabatel et al. (2005, and see also, Rabatel et al., 2008, J. Glaciol. 54, 185, 307-314) compute the annual mass balance using the geoditic balance over a study period and the difference between the snowline altitude for each year of the study period with the altitude of the ELA0 (representative of a steady state of the glacier over the same period), this difference being multyplied by the mass balance gradient at the level of the ELA0. One question is: because the authors have the geodetic mass balance for many glaciers, computed by the difference between SRTM and SPOT5 DEMs, why don't them simply apply Rabatel et al. (2005, 2008) method? They can also apply their equation 1 in parallel and compare the results of the two approaches. And finally compare both approaches with annual mass balance computed from field data.

Response: While we do feel that our contribution is an extension of the Rabatel et al. (2005) approach, there are two important distinctions. First, our approach is intended for large icefields, as opposed to individual glaciers. Second, we do not have mass balance data computed from field data at our geodetic sites to make the suggested comparison. Given the sparseness of mass balance data for western Canada, we needed to rely on the use of historical mass balance gradient data obtained from a single index glacier. In some cases, (e.g. Lillooet Icefield) the mass balance data was collected 15 years before the first MODIS scene was available.

3. The authors mention time-series of "ZS(20) metric used as a proxy of ELA" and time-series of mass balance. They even comment the observed trends for some of the studied glaciers, but where are the data?? A table with the time-series and a graph presenting the temporal evolution have to be presented.

   Response: This is a good suggestion - we will add Figure 4 (below) to the revised manuscript. This figure quantifies the trends at each site and distinguishes between those that are significant (Wolverine, Peyto) and those that are not.

4. About the geodetic method to compute volume changes by differencing DEMs, what is the impact of the different resolution between SRTM and SPOT5? Did you consider the penetration of radar signal which may biased the results? See see Gardelle et al., 2012, J. Glaciol., 58, 419-422.

   Response: Using the methods of Gardelle et al. (2012), we have recalculated our estimates of geodetic mass change for the icefields in this study, as suggested by the reviewer. In doing so, we have also discovered a significant DEM shift that was previously uncorrected in the Lillooet Icefield calculations. Unfortunately, for the Lillooet icefield the SRTM X-band was unavailable, so corrections for radar penetration could not be performed.

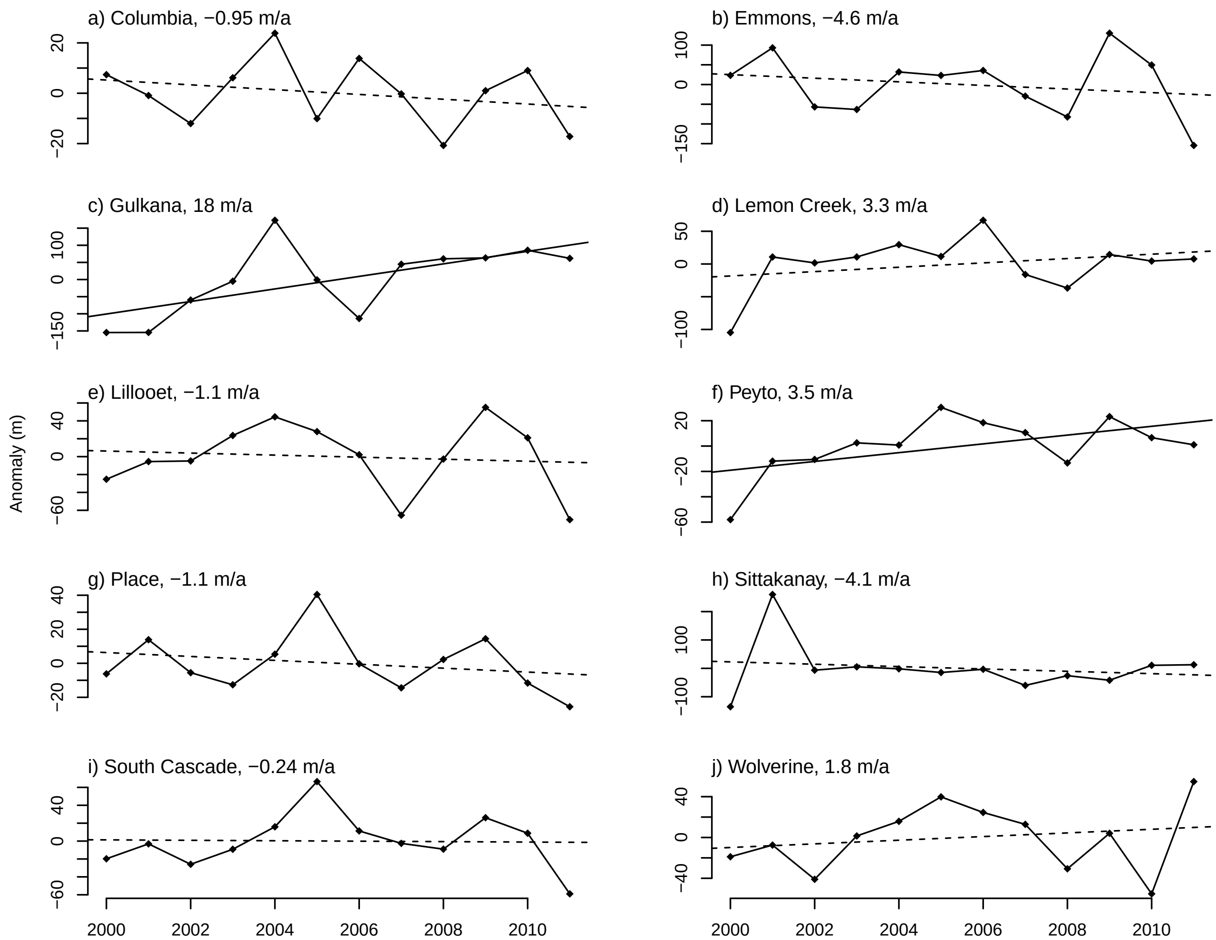


Figure 4: Time series of regional ELA anomalies derived from MOD02QKM imagery. Least-squares regression lines are plotted to illustrate the magnitude of a linear trend in the time series. Trend magnitude is given in the figure caption, and solid trend lines are statistically signficant at $\alpha = 0.1$.

Original and revised geodetic estimates are given below in Table 1. Consideration of this point also led us to recalculate the geodetic balance at Lillooet Icefield after removal of the ablation areas of lake-terminating glaciers. Original and recalculated geodetic balances are shown in Table 1.

Table 1: Original and revised estimates of geodetic mass change for Columbia, Lillooet, and Sittakanay Icefields. DEM shifts were previously calculated for Columbia and Sittakanay Icefields.

	Mass change (Gt)		
Estimate	Columbia	Lillooet	Sittakanay
Original	-0.65 ± 0.10	-3.31 ± 0.57	-2.26 ± 0.11
DEM shift, resolution and penetration corrections	-0.62 ± 0.11	-1.28 ± 0.26	-2.10 ± 0.57
Without lake-terminating ice	NA	-1.11 ± 0.26	NA

5. In a general way, more details have to be given about - the satellite data (dates used to finally compute the "Zs(20) metric used as a proxy of ELA" for the different glaciers. This can be given in a table). - the field data: a table giving for each glacier the monitoring period, number of ablation and accumulation measurements, ... - the error analysis for the computation of the "Zs(20) metric used as a proxy of ELA". With a pixel size of the images of 250 m, a DEM resolution of 90 m and considering the slope of the glacier at the level of the ELA, what is the error? - the accuracy of the method for the smallest glaciers for which the wide must be contained within two pixels of a MODIS image?

   Response: As discussed in the manuscript, we do not calculate snowline elevations for single glaciers, but for a much larger glacierized region or entire icefield. The reviewer correctly points out that the 250 m resolution is not suitable for snowline estimation on a glacier that is only 500 m (2 pixels) wide. However our results indicate that ELAs derived for entire regions are strong predictors of individual glacier mass balances, and can be used to estimate regional glacier mass change. In our response to Reviewer #2 and the revised manuscript we provide specific information about the number of MODIS scenes used for each site and season.

Specific Comments

- The title is not appropriate because the authors do not provide a "regional estimate of glacier mass chang". They present a method to compute the mass balance for single glaciers/ice caps, and validate the method. Thus, it has to be changed.

Response: Our revised title is: ″An approach to derive regional snowlines and glacier mass change from MODIS imagery, western North America".

- Abstract: As mentionned in the general comments, the use of "regional snowline", "regional MODIS-derived ELAs" is abusive and these terminologies have to be removed. This is the case for the whole paper.

  Response: As indicated above, we will address the definitions in the introduction and refer only to "regional transient snowlines" and "regional ELAs".

- P. 3758, L. 1. The method described does not allow to automatically extract the ELA but a proxy of the ELA.

  Response: Fixed.

- P. 3758, L. 25. How much represents ″a handful of mass balance record″? A reference has to be cited here.

  Response: Good point made by both referees here. We have changed ′handful′ to ′18 glacier mass balance records longer than 10 years′, and the following text will be added to the manuscript: "Between 2000 and 2009, we find 24 sites where net mass balance is reported for western North America (M. Zemp, personal communication 2012). Of these, 14 glaciers are less than 2 km^2 in area, and 15 are clustered in the North Cascades (Pelto and Riedel, 2001). However, mass balance gradient (db/dZ) information is available for only three sites from 2000 to 2009: Place Glacier, Peyto Glacier, and Lemon Creek Glacier (two years only)."

- P. 3760, L. 12. Why do you use, here and everywhere in the draft the terminology: "index glacier site" or "index glacier mass balance sites"?? Also, you mention here seven glaciers, but then eight are presented (for example on the same page L. 25, in Fig. 6, ...)

  Response: We use the word ′index′ here to denote that these are sites where ground observations of glacier mass balance are collected. This term was also used by Kaser and Georges (1999) and Chinn et al. (2005), and is similar to ′benchmark glacier′.

- Some bibliographical references are missing in this section: - Demuth and Pietroniro, 1999. Geogr. Ann., 81A(4), 521-540. - Jiskoot et al., 2009. Ann. Glaciol., 50, 133-143. - Pelto, 2011, The Cryosphere, 5, 1127-1133.

  Response: As indicated in our response to M. Pelto, we will be adding the Jiskoot et al. (2010) and Pelto (2011) references. Thank you for pointing out the work of Demuth and Pietroniro (1999), we will be including this in the revised manuscript.

- P. 3761, L. 5-10. Are these data used to compute the mass balance gradient? Why don't you use more rencent values?

Response: Our study is based on the availability of both geodetic and surface mass balance observations. We acknowledge that the age of the mass balance data used to calculate gradients may be a source of error in our estimates of mass change (P3765 L20), but there are no concurrent mass balance observations for the sites where we have the geodetic change observations.

- P. 3761, L. 9, L. 15. BC, HEG have to be defined.

  Response: We will define these terms in the revised manuscript.

- P. 3761, L. 12-23. Finally, how many images have been used? In total, for each year?

  Response: Please see our response to reviewer #2, who had a similar query. We will add a table to the revised mansucript which lists the number of scenes used at each site and year.

- P. 3761, L. 25. What is the "seasonnal ELA for a given glacierized region"?

  Response: This is the regional ELA - sentence will be adjusted to reflect the new terminology.

- P. 3762, L. 3. GTED, SRTM have to be defined.

  Response: We will define these terms in the revised manuscript.

- P. 3762, L. 20. In equation 1, - b0 is finally the "ZS(20) metric used as a proxy of ELA" and so could be mention as "ZS(20)". - b1 and b2 are respectively the mass balance gradient for the ablation and accumulation zone and could be mentionned as db/dzabl, and db/dzacc - Zj < b0 represents the ablation zone and, Zj > b0 represents the accumulation zone, why don't you just say that?

  Response: We will mention that b_0 is also the $Z_{S(20)}$ metric, and will adjust the equation in the revised manuscript to indicate ablation and accumulation zones.

- P. 3764, L. 4-8. As mentionned in the "General comments", a Table with the time series and a graph would be welcomed. P. 3764, L. 8. The word "exist" should be removed.

  Response: These will be included in the revised paper, and the word 'exist' will be removed.

- P. 3764, L. 9. Table 3 should be Table 2 and conversely, Table 2 becomes Table 3 because the current Table 3 is cited before Table 2.

  Response: Good catch - we will double-check the table numbering and revise.

- P. 3764, L. 16-17. Why do you consider the values for Emmons Glacier and Place Glacier, because you say on the same page L. 2-3 and you show it on Fig. 6, that for these two glaciers, the "ZS(20) metric used as a proxy of ELA" is not correlated with the mass balance?

  Response: We feel that it is important to show the limitations of our approach as well. At Place and Emmons glaciers, the regional ELA is not strongly correlated with the observed net mass balance, and we discuss possible reasons for why this might occur.

- P. 3766, L. 11-13. About SRTM data, see Gardelle et al., 2012, J. Glaciol., 58, 419-422, about the impact of resolution and radar penetration on glacier elevation changes computed from DEM differencing. Indeed, due to radar penetration, the SRTM DEM may map a surface which is below the real surface, especially in accumulation areas, leading to biased estimate of glacier elevation changes.

  Response: We thank the reviewer for pointing out this reference, and will discuss this potential source of error in the estimates of geodetic balance.

- Table 1 = For Lillooet site, mention the SPOT5 DEM of the 20 of August before the one of the 29.

  Response: Switched.

- Table 2, which should be Table 3 = Use the same units than in the text P. 3765, for coherency.

  Response: Units will be consistent.

- Table 3 should be Table 2

  Response: Fixed.

- Figure 6 = Include the r2 for each regression line.

  Response: We will include the r2 value for each regression line.

References

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