Response to Short Comment - M. Pelto

We thank Dr. Pelto for his detailed comments and interest in our work. Below, we first provide answers to the three issues he raised in his comments. Our replies to his detailed comments appear in bold font.

1. At present the research is not well informed by a careful enough reading of the existing applications of similar methods.

   Response: We acknowledge that our manuscript would be improved with additional references.

2. The reporting on the following are insufficient: the specific amount and dates of MODIS imagery utilized, sources of balance gradient information, snowline identification error analysis, and identification of what simple regional ELAs represent.

   Response: Our manuscript does not identify the specific MODIS imagery used because we analysed between two and four MOD02QKM scenes per day between 15 August and 15 October, over 10 years (n $\approx$ 1830). Mass balance data were obtained from the World Glacier Monitoring Service (M. Zemp, pers. comm.) and supplemented with internal reports from the National Hydrological Research Institute (Mokievsky-Zubok et al., 1985) and BC Hydro (Mokievsky-Zubok, 1990, 1991, 1992). Although our acknowledgement section recognized the contribution of all agencies and individuals for the surface mass balance data we used, we will identify all individual contributors in the revised manuscript. Errors in snowline/ELA identification are identified on P3766, and we will include new text that discusses what the regional ELAs represent.

3. Validation of the balance gradients and ELA data derived needs to be expanded. There are several fairly simple techniques that have been previously applied that could be applied here. There is limited discussion of the relative increase in error due to low resolution for the smaller alpine glaciers in the study.

   Response: Unfortunately the mass balance gradients we calculate cannot be validated since they arise from the use of observation data and our use of a piecewise spline. As noted in the manuscript (P3766-L8), we re-iterate that regional ELAs obtained from

MODIS imagery will not correspond to ELAs obtained using the glaciologic method at index glacier sites (P3766-L8), a point which was first demonstrated by Østrem (1975).

Specific Points

- It is inaccurate to identify only a handful of annual mass balance records for estern North America. There are 20 such glaciers that have submitted data to the WGMS for the last 20 years and 24 glaciers for shorter periods (WGMS, 2011).

  Response: We regret our wording since there are indeed more than a handful of mass balance records in western North America. There are, however, only a small number of sites for which mass balance data by elevation are publically available. We have used these records in our calculation of mass balance gradients.

- 3759-20: Cogley et al (2011), is not the appropriate reference. Either Ostrem (1975) or Williams et al (1991) would be more appropriate.

  Response: We thank the reviewer for this suggestion, and will include references to (Østrem, 1975) and Williams et al. (1991) here.

- 3760-11: The use of MODIS for ELA-TSL observation is not a new technique in this region and reference to this fact needs to be made. Pelto (2011) utilized both Landsat and MODIS to identify the TSL and ELA on Taku Glacier.

  Response: We thank the referee for drawing our attention to the work of Pelto (2011). Our use of MOD02QKM imagery for automated snowline delineation, however, is unique for the region. In our reading of Pelto (2011), that work appears to use MOD10 binary snow cover data at 500 m resolution. Figures 2 and 3 in the original manuscript demonstrate that the MOD10 data set may not be suitable for discriminating between snow and glacier ice, as suggested by Hall and Riggs (2007).

- 3761-5: Why use data from Bridge and Andrei Glacier as part of the validation when the records are both short and do not overlap with the study period? Given the changes in area of glaciers in the region noted in several studies the balance gradient from the previous time period may not be particularly accurate for the last decade. There are certainly other glaciers that could be used.

  Response: One of the main objectives of this study was to develop regional estimates of mass change for large icefields. Mass balance data from Bridge and Andrei glacier were used as these sites are close to large icefields where we have geodetic balance information, and mass balance data by elevation band are also given for these sites. We were furthermore able to locate additional data for both Bridge and Andrei glaciers from BC

Hydro and National Hydrological Research Institute reports (P3761-9). At long-term mass balance sites (Peyto and Place), we do not find any significant trends in fitted mass balance gradients (Figure 1) which suggests that historical gradients calculated for Bridge and Andrei may be appropriate.

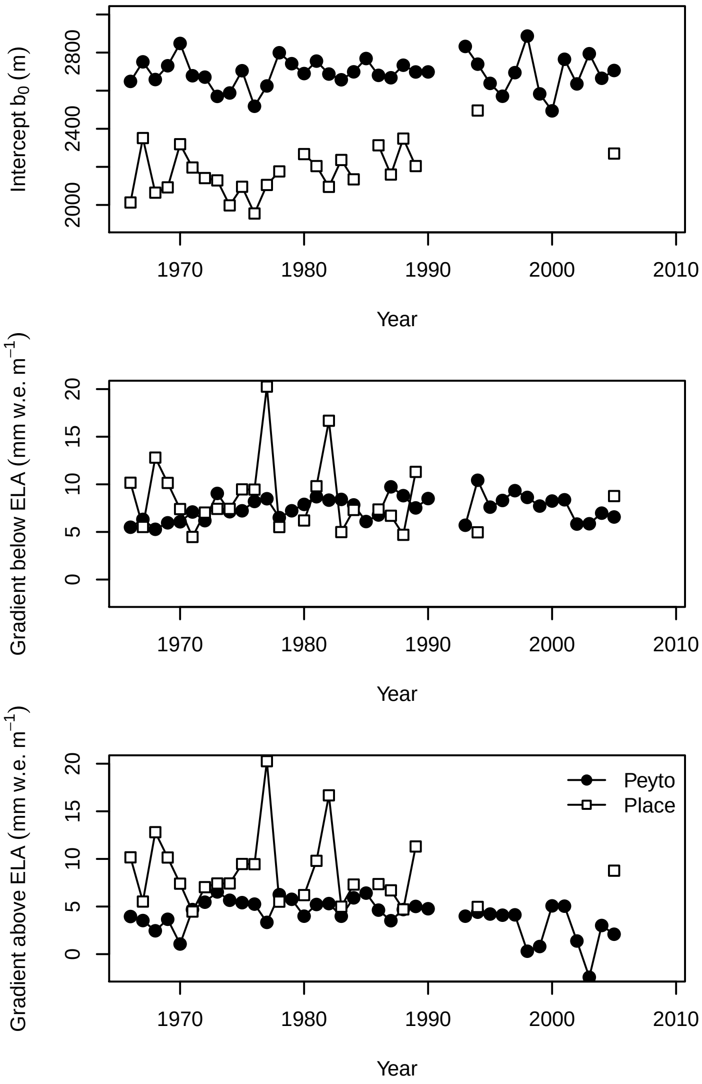

Figure 1: Time series of mass balance coefficients fitted with a piecewise spline (see manuscript Eq. 1 for details.)

- 3761-26: What data was used in the time series of snowline variation?

  Response: MOD02QKM. We will clarify this in the text.

- 3762-11: What imagery is used in this process just MODIS, if so from when how many dates at the various locations?

Response: All MOD02 tiles covering western North America between 15 August and 15 October, 2000 - 2009, were analysed (P3761-11).

- 3762-23: The method of transfer of data from specific to regional glaciers is not carefully described or defended. Some reference to Kuhn et al (2009) or Huss et al (in press) should be made, even if their method is not utilized. Jiskoot et al (2009) also test several methods of ELA assessment and transference to glaciers with various levels of ground truth in the same study area.

  Response: We only transfer mass balance gradients from index glaciers to the icefields where we have independent geodetic estimates of glacier mass change. This is described on P3762, though we agree with the Dr. Pelto that this section could be expanded. A table describing the mean and standard deviation of the calculated mass balance gradients will be added (Table 1), and new text will discuss how not adjusting the balance profiles may introduce errors:

  > "Balance profiles are not adjusted for median elevation differences as suggested by Kuhn et al. (2009), and this assumption may introduce errors in our analysis. However, differences in median elevation between the index glaciers and the regional icefields examined in the study range between -201 and +46 m (Table 1)."

Table 1: Median elevations (Z_{med}, in m a.s.l.) for index mass balance sites and regional glacierized areas, and mean ($\overline{x}$) and standard deviation (σ) of fitted mass balance gradients, in mm w.e. m^{-1}. Standard deviation is also shown as a percentage of the mean in brackets.

Site/Icefield	Glacier Z_{med}	Regional Z_{med}	$\overline{x}_{b1}$	$\overline{x}_{b2}$	σ_{b1} (%)	σ_{b2} (%)
Andrei/Sittakanay	1589	1388	5.48	2.09	0.74 (13.5)	0.77 (36.5)
Bridge/Lillooet	2272	2318	6.62	3.53	1.46 (22.0)	0.74 (20.9)
Peyto/Columbia	2644	2689	7.48	4.01	1.27 (17.1)	1.87 (46.7)

- 3763-23: What is the source of the balance gradient information for each glacier, how long is the record? What is the robustness from year to year?

  Response: Sources of balance gradient information are given on P3761. These include M. Zemp (personal communication, 2012), Mokievsky-Zubok et al. (1985); Mokievsky-Zubok (1990, 1991, 1992) and Dyurgerov (2002). Standard deviations of mass balance gradients calculated for Peyto Glacier were given on P3765-L23, but we now provide these for all three sites in Table 1. Standard deviations of calculated mass balance gradients (Table 1) indicate that ablation zone gradients (b_1) have lower variability than accumulation zone

gradients (b_2), and that the variability in b_2 is greatest at Peyto Glacier. Time-series (Figure 1) and boxplots of calculated gradients (Figure 2, below) demonstrate the overall robustness of mass balance gradients, and the distinct climatic regimes of each glacier.

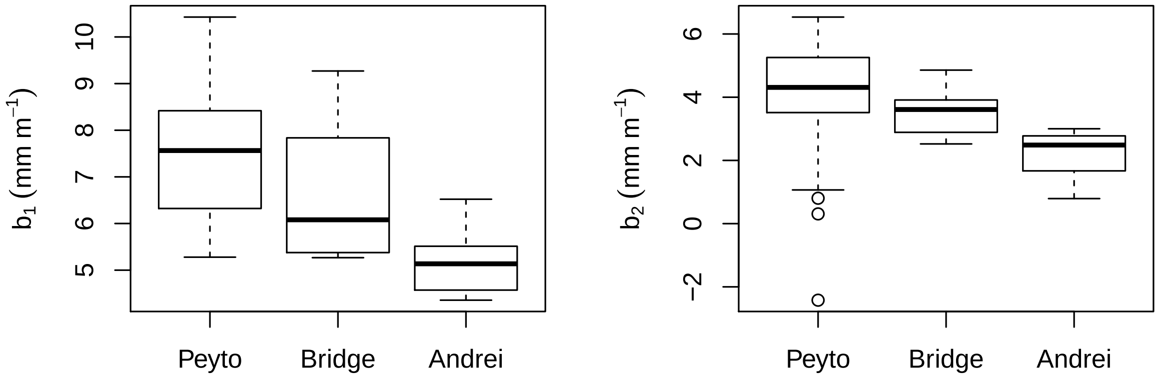

Figure 2: Boxplots of calculated mass balance gradients below (b_1) and above (b_2) the ELA.

- 3764-3: There are difficulties given the 250 resolution in using MODIS for small glaciers to derive snowlines. How reliable can the results be on South Cascade Glacier and Place Glacier where the glacier width in many areas is only two pixels? Pelto and Brown (2012) were unable to utilize MODIS to aid in snowline mapping on Mount Baker, North Cascades, due to poor resolution.

  Response: As Dr. Pelto points out, 250 m resolution imagery is indeed insufficient for identifying snowlines on individual glaciers. Thus, for each index glacier mass balance site, we select a regional sample of glaciers/icefields that are used for the daily MOD02QKM classification and subsequent snowline delineation. Throughout the manuscript we refer to 'regional snowline', but this term will be clarified in the revised manuscript.

- 3764-9: Juneau is noted in Table 3. I assume this is the Juneau Icefield, what is utilized for the icefield ELA, is it the Taku and Lemon Cree, all glaciers or just the Alaskan side?

  Response: We compare both the Taku and Lemon Creek net mass balance to the regional snowline (Figure 6), determined from the southern half of the Juneau Icefield.

- 3764-8: Some comparison with the observations of Jiskoot et al (2009) who also comment on changes in the ELA on Peyto Glacier is essential.

Response: We thank Dr. Pelto for pointing out this important reference. Jiskoot et al. (2010) assess the change in ELA using geomorphic information, and their estimate of a 100-200 m rise in ELA from the Little Ice Age to present puts our estimate in perspective. We have added the following text to the manuscript:

> ″For the Clemenceau Icefield region, Jiskoot et al. (2010) find a 100-200 m increase in ELA from the Little Ice Age (LIA) to 2001, based on geomorphic parameters. If we assume a LIA maximum at ca. 1850 (Luckman, 2000), this represents an average ELA rise between +0.7 and +1.3 m a^{-1}, versus our estimate of +2.9 m a^{-1} over the period 2000 - 2009 for the Peyto Glacier region. ″

- 3764-23: What dates are utilized for MODIS imagery? There is no listing of the number of dates for which MODIS was analysed and TSL derived for any of the glaciers. How did the TSL change during a melt season as observed on a glacier? Is the changing snow cover area fraction utilized (Huss et al, in press)?

  Response: We have addressed this comment above, and as we were concerned primarily with the elevation of the end of summer snowline, we did not obtain or analyse MOD02QKM imagery for the entire melt season. An example of the change in TSL over an entire region between 15 August and 15 October is given in Figure 4 of the original manuscript. We were unable to locate the Huss reference, but we do not use the changing snow cover area fraction, our estimate of snowline is based on the 20th percentile of snow-covered pixel elevations.

- 3765-11: Where is this constructed time series? Table 3 has overall data as does Figure 6 but I do not see a time series presented.

  Response: Please refer to Figure 4 in the original manuscript, which provides an example of transient snowline elevations and derived ELA for a single season.

- 3765-20: Three issues are noted by the authors that could be addressed with a bit of further examination of the data in hand, and have been contemplated by previous research. (1) improperly specified mass balance gradients. In this case the rise of the TSL with time on glaciers where the mass balance is measured also allows validation of the balance gradient derived from TSL observations compared to actual surface mass balance. Given the automated methods this would be a particularly valuable outcome. Hock et al (2007), Pelto (2011) and Huss et al (in press) applied this methodology. Pelto (2011) examined the balance gradient for one of the same glaciers, Taku Glacier, comparing the MODIS-Landsat observed ELA and the field observed balance gradient. I suggest the authors utilize both the Taku Glacier work and extend this analysis to at least one other glacier, such as Peyto Glacier, since it is smaller and in a different climate setting. The combination would provide an essential validation of the balance gradient. (2) errors in MODIS-derived ELAs. This can be examined by comparison of same date imagery with Landsat or field assessment. Pelto (2011) did this for a single date, which is clearly insufficient. This is particularly important on smaller glaciers. (3) differences in the dates of geodetic image acquisition and our calculation. If the mean rate of TSL change observed at the end of the melt season is identified, this can be either applied directly to adjust for the number of days between TLS observation and the end of the melt season (Hock et al, 2007; Pelto, 2011) or the rate of TSL rise late in the melt season identified in the MODIS imagery could be used in conjunction with temperature data to use a simple positive degree day model to make this adjustment.

Response:

1. **We recognize the possibility that our mass balance gradients may be improperly specified (P3765-20), and recommend distributed mass balance modelling as a way of deriving synthetic mass balance gradients for use in regions with no data (P3766-25). We opted to validate our approach by comparing mass change estimates derived from mass balance gradients and regional ELAs with geodetic imagery.**
2. **In Figures 2 and 3 of the original manuscript we provide examples of how the MOD02QKM surface classification compares with both the MOD10 product and Landsat imagery. We have done similar comparisons at all sites, and are thus confident in the results, but chose to include only two examples for brevity. Additional examples can be provided as supplementary online material.**
3. **We do not feel that such an adjustment is appropriate for our study. First, the end of the melt season will vary from location to location and from year to year. Applying a correction to an arbitrary date (e.g. 30 September) may introduce additional errors. Second, rates of TSL change, particularly towards the end of the melt season, are subject to rapid fluctuations due to snowfall events (see Figure 4, original manuscript). Our approach attempts to capture the maximum elevation of the snowline, regardless of what date it occurs on.**

- 3766-28: An ELA is only useful for determining mass balance if it used to derive either the AAR or the snow covered area fraction, the elevation alone is not (Huss et al., 2012; WGMS, 2011). How in this method is the ELA transitioned to represent the mass balance, just using the hypsometry?

  Response: Relations between ELA/AAR and net mass balance are equally strong. We chose to use the MODIS-derived regional ELA as it exhibits lower variability than MODIS-derived regional AARs (Table 2). Our approach assumes that net mass balance gradients

are different between accumulation and ablation zones. From our equation [1] in the original manuscript, we insert the regional MODIS-derived ELAs and calculate annual mass loss or gain based on icefield hyspometry.

Table 2: Mean regional ELA and mean regional AAR derived from MOD02QKM, and associated mean standard errors derived from loess fits. Mean standard errors are also expressed as a percentage of the mean (in brackets). All sites and years are included in this calculation.

$\overline{x}_{\mathrm{ELA}}$ (m)	$\overline{x}_{\mathrm{AAR}}$	$\overline{\sigma}_{\mathrm{ELA}}(m)$	$\overline{\sigma}_{\mathrm{AAR}}$
1893	0.43	22 (1.14%)	0.03 (7.0%)

- Figure 6: For these glaciers the actual ELA is also reported to the WGMS, how does MODIS compare to that?

  Response: MODIS-derived regional ELAs are positively correlated with observed index glacier ELAs at all sites except Emmons Glacier (which has a sample size of four). In absolute terms, the regional ELA can be both higher and lower than the observed ELA, and given the effects of wind loading, topographic shading, and terrain influences on glacier geometry, we would not expect the index glacier ELA to correspond directly to a regional ELA (Figure 3 below).

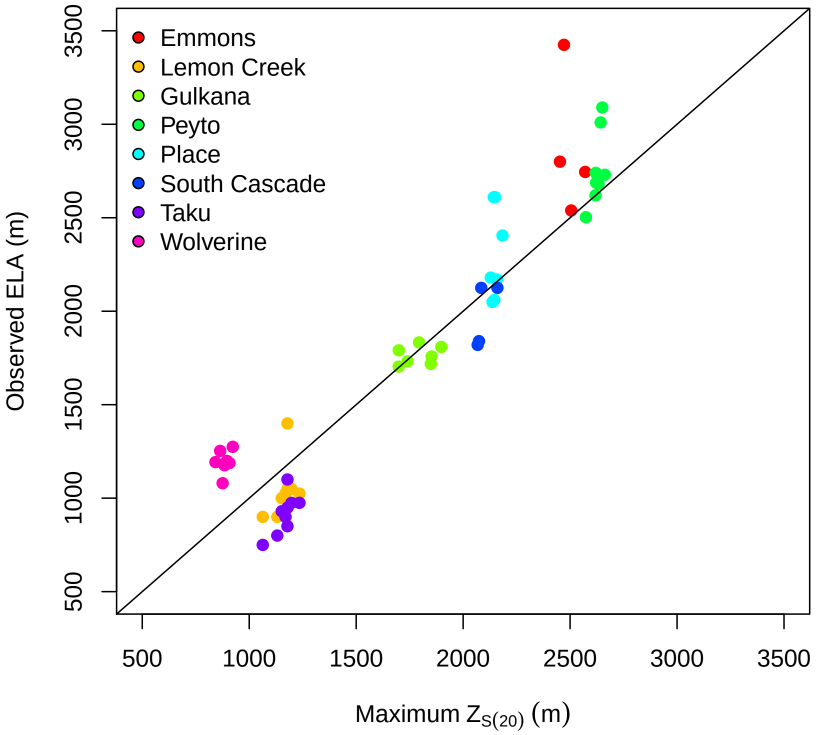

Figure 3: Observed ELA at index glacier mass balance sites versus regional ELA proxy (maximum elevation of $Z_{S(20)}$).

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