Response to Anonymous Reviewer 2

We thank Anonymous Reviewer #2 for the detailed comments and overall positive remarks on our manuscript. Below, we address the reviewer's specific comments, and provide new text and information that will be included in the manuscript. Our responses are in bold.

Specific Comments

1. Title

- Title - The title should be changed since true ELAs are not actually determined

  Response: As both reviewers have recommended changes to the title, we have amended the title to: "An approach to derive regional snowlines and glacier mass change from MODIS imagery, western North America".

2. Abstract

- Abstract- P. 3758, L.4: The authors should be careful about using "MODIS-derived ELAs" to describe ZS(20). Also, the authors need to develop a consistent terminology throughout the rest of the paper.

  Response: We have addressed this comment in our response to Reviewer 1, and added clarifiying text in our introduction. We describe the $Z_{S(20)}$ metric as a proxy for regional ELA.

- P. 3758, L.9: The worst estimate of mass change (+32%) is not within 30% of traditional geodetic approaches.

  Response: Good catch - after addressing comments of Reviewer 1 (SRTM radar penetration in snow) and finding an additional DEM shift for the Lillooet site, our estimates of mass change have changed. Please see Table 1 in our response to Reviewer 1. Text in the abstract will be changed.

- P. 3758, L.9-10: Is this study really "revealing" continued mass change? I think another word, such as "corroborates", might be more appropriate.

Response: Changed.

3. Introduction

- P. 3758, L.17: Instead of using "substantial", please provide a range from the literature.

  Response: New text and references reflect estimates of 21st century sea-level rise from glaciers and icecaps between 0.51 and 0.124 m (Raper and Braithwaite, 2006; Radić and Hock, 2011)

- P. 3758, L.23-24: Be more specific about how "glacier mass change affects surface runoff in glacierized basins."

  Response: Changed, and new text will be added: "Glacier mass change supplements streamflow in years with lower snowpacks or summer precipitation totals, but long-term declines in glacier area will lead to reductions in annual streamflow volume."

- P. 3758, L.25: Use a number instead of the word "handful."

  Response: We have addressed this in our response to Reviewer 1, and find that there are 18 long-term mass balance records (greater than 10 years) in western North America, but that only three records give balance gradients over the period 2000-2009.

- P. 3759, L.18-19: "...closely mirrors the equilibrium line altitude (ELA)." Please provide a few references to support this claim. Some examples: (Klein and Isacks, 1999; Williams et al., 1991; Winther et al., 1999)

  Response: We have added references to Klein and Isacks (1999); Williams et al. (1991); Winther et al. (1999), thank you for pointing them out.

- P. 3759, L.23-24: What was the availability of Landsat imagery? Approximately how many scenes were available during the ablation period of each year?

  Response: For the Alaskan sites, there are very few available Landsat scenes images - between 2000 and 2009 we could only find 2 cloud-free ablation season scenes for the Kenai Peninsula (Wolverine Glacier) and the Alaska Range (Gulkana Glacier). For the southern sites (Peyto, Place, South Cascade glaciers) there are more cloud-free ablation scenes available, but given the two-week acquisition interval there are not enough to construct time-series of snowline elevations.

4.Data Methods

- P. 3761, L.15: define HEG acronym

  Response: Defined.

- P. 3761, L.18: Mention GLIMS here.

  Response: Done.

- P. 3761, L.18-20: This portion of the methodology requires more detail. If this method is to be applied at other locations then the reader will need more detail to carry out the same procedure. What program was used to perform the cluster analysis? A brief discussion of k-means cluster analysis would also be helpful. Did topographic shading or atmospheric variability affect clustering?

  Response: We will expand this portion in the revised manuscript with the following text: "The `kmeans2` module in Python (Scipy) was used to perform the unsupervised k-means cluster analysis, which minimizes the euclidean distance between cluster means. Errors due to topographic shading were minimized by analysing scenes that were obtained between 10 am and 3 pm local time, though shading on north-facing slopes will result in misclassifications. The effects of atmospheric variability (smoke, haze) on the cluster analysis results are unknown, but are not likely to be large."

- P. 3761, L.22: If possible, please include a Table showing the total number of scenes that met these criteria for each site.

  Response: Table 1 will be included in the revised manuscript.

Table 1: Number of MOD02QKM scenes that meet criteria for time of acquisition, cloud cover, and snow extent thresholds for each index glacier/icefield region and year.

Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Totals
Columbia	18	26	15	17	18	14	41	15	21	21	206
Emmons	34	46	46	18	40	32	55	38	31	38	378
Gulkana	8	17	12	13	17	13	11	13	3	13	120
Lemon Creek/Taku	3	6	5	12	21	8	10	11	4	14	94
Lillooet	27	24	39	11	21	16	44	21	25	28	256
Peyto	17	25	12	17	13	14	40	15	17	24	194
Place	25	27	33	12	27	17	47	22	25	29	264
Sittakanay	1	9	8	14	14	8	8	12	6	12	92
S. Cascade	28	32	35	16	31	28	51	25	22	41	309
Wolverine	19	8	18	19	36	9	15	19	7	17	167

- P. 3762, L.3: Define acronyms GTED and SRTM

  Response: Defined.

- P. 3762, L.4: What program was used for resampling?

  Response: The Geospatial Data Abstraction Library (GDAL) - this has been defined in the text.

- P. 3762, L.6: If possible use a number instead of "most."

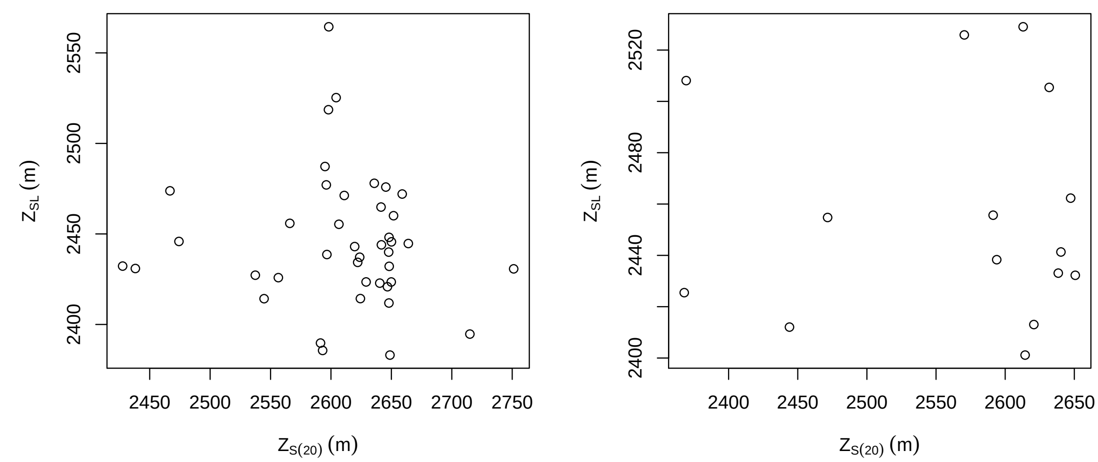
  Response: In light of this comment, we have re-examined the relations between the $Z_{S(10)}$, $Z_{S(20)}$, and the AAR snowline metrics. Overall values of r^2 are greater for $Z_{S(20)}$, but relations between maximum $Z_{S(10)}$ and observed B_n are significant (p=0.10) at 6 of 8 sites, whereas only 4 of 8 are significant with $Z_{S(20)}$. The minimum observed AAR provides significant fits at 5 of 8 sites (see Table 2 below).

Table 2: Sample size (n), coefficient of determination (r^2) and significance (p) for linear regressions of observed net mass balance versus snowline metrics maximum $Z_{S(10)}$, maximum $Z_{S(20)}$, minimum AAR, and maximum Z_{SL} by site.

		$Z_{S(10)}$		$Z_{S(20)}$		AAR	
Site	n	r^2	p	r^2	p	r^2	p
Emmons	4	0.016	0.875	0.059	0.756	0.010	0.902
Lemon Creek	9	0.340	0.099	0.252	0.169	0.290	0.135
Gulkana	10	0.363	0.065	0.438	0.037	0.610	0.008
Peyto	9	0.465	0.043	0.642	0.009	0.592	0.015
Place	9	0.101	0.405	0.141	0.405	0.882	0.000
South Cascade	8	0.517	0.044	0.525	0.042	0.271	0.186
Taku	9	0.380	0.077	0.307	0.122	0.318	0.114
Wolverine	10	0.464	0.030	0.466	0.030	0.618	0.007
	Mean:	0.331	0.205	0.353	0.185	0.449	0.171

- P. 3762, L.6-9: The metric ZS(20) should represent the ELA and not "the elevation of the local transient snow-line." This point should be moved to the results section. I would be interested to see how ZS(10), ZS(20), and ZS(30) correlated to observedsurface mass balance at each site. How does the actual, averaged snow-line correlatewith surface mass balance? I'd like to see a comparison for one or two years showing ZS(20) versus the actual, averaged elevation of the snow-line extracted from theMODIS classification.

  Response: Good suggestion - we have moved the text to the results section. Figure 1 below provides examples of the comparison between mean daily snowline elevation and $Z_{S(20)}$ at the Columbia Icefield. At all sites, there appears to be no relation between these two metrics.



(a) 2006

(b) 2007

Figure 1: Scatterplots of daily 20th percentile elevation of snow covered pixels ($Z_{S(20)}$) and the icefield/region-averaged snowline elevation, for the 2006 and 2007 ablation seasons, Columbia Icefield.

- P.3763, L.1: I realize that the methods are described elsewhere, but I think a brief description of DEM co-registration is important.

  Response: New text outlining the DEM co-registration and differencing will be added to the revised manuscript: "For each icefield, we reprojected the SPOT and SRTM DEMs to the same projection (BC Albers) and resampled them to a 90 m resolution. We differenced the DEMs and analyzed elevation change on stable areas free of ice and vegetation. Using the stable areas, we checked for co-registration by plotting elevation change normalized by the tangent of the slope versus aspect (Nuth and Kääb, 2011). If the DEMs are co-registered, there should be no bias in this plot. The Columbia and Lillooet icefield DEMs showed no significant bias. There was a bias between the Sittakanay Icefield DEMs, which was modeled and removed using the methods for co-registration similar to Nuth and Kääb (2011)."

- P. 3763, L.6: GLIMS acronym has not been defined yet.

  Response: Fixed.

- P. 3763, L.6-9: Which standard error value is used? Is it the standard error associated with the MODIS-derived ELA or the average standard error calculated for the entire lowess curve? Also, please explain the choice of "an assumed error ... of 10%."

Response: The standard error is extracted from the lowess curve fit at the point of the maximum value of the snowline metric. Our choice of an assumed error of 10% for mass balance gradients is arbitrary, and attempts to reflect the possible errors in misspecified mass balance gradients.

5.Results

- P. 3763, L.14: How favorably do the glacier surface types derived from MODIS compare with Landsat-derived surface types? In order to make a quantitative evaluation, I would recommend hand-digitizing the snow and ice facies in a few Landsat scenes and then resampling the resulting classes to 250 m. In this way, the "accuracy" of the MODIS classification could be determined using some simple quantitative statistics.

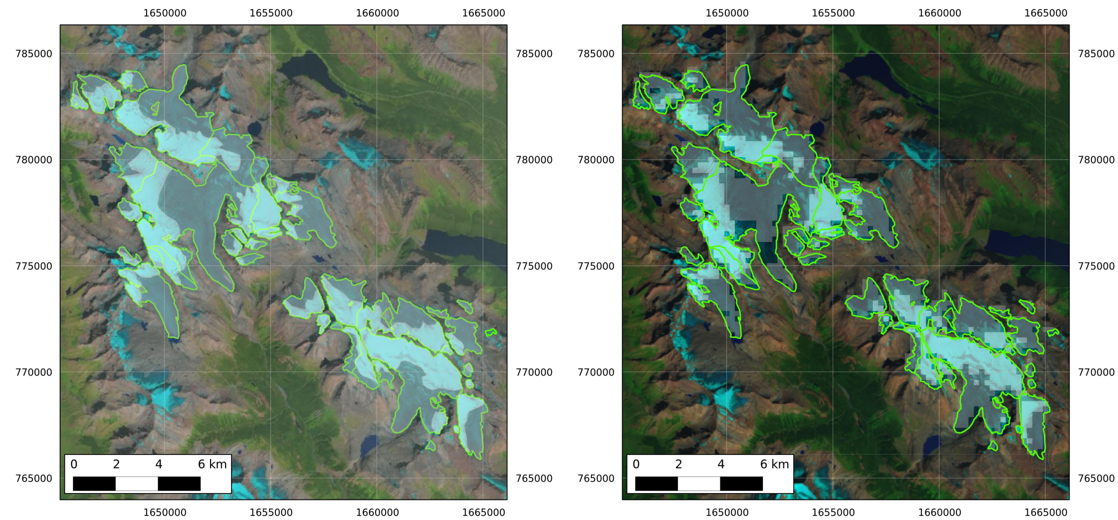
  Response: As suggested by the reviewer, we have conducted a manual classification of snow and ice classes for two Landsat scenes (Figures 2 and 3), and will incorporate the results in a revised manuscript. Snowline metrics ($Z_{S(10)}$,$Z_{S(20)}$,AAR, Z_{SL}) were calculated for both the manual and automated classifications using a 90m SRTM DEM (Table 3). Despite differences in the delineated snowlines (the automated procedure, for example, misclassifies heavily shaded slopes as ice), the general snowline patterns and derived snowline metrics are similar. Our preferred snowline metric, $Z_{S(20)}$ derived from MOD02QKM imagery, is very similar to that derived from a manual classification of a contemporary Landsat scene.

Table 3: Comparison of snowline metrics derived from manual delineation of snow and ice classes (Landsat scene) and automated classification from MOD02QKM cluster analysis.

	Wapta/Waputik, 20 August 2009		Lillooet, 04 October 2001	
Metric	Manual	Automatic	Manual	Automatic
$Z_{S(10)}$ (m)	2631	2624	2102	2132
$Z_{S(20)}$ (m)	2656	2655	2203	2245
AAR	0.47	0.34	0.73	0.52
Z_{SL} (m)	2671	2408	2089	2050

- P. 3764, L.3: There is no mention of the trend associated with South Cascade glacier. The linear regression coefficients and statistics could be shown in a table.

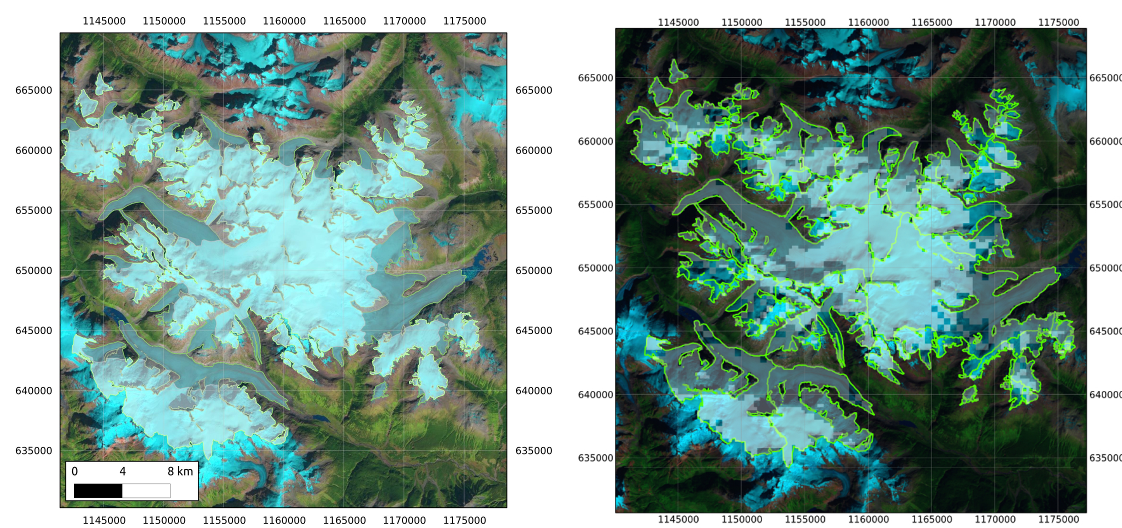
  Response: In response to Reviewer 1, we have added the trends and significance to a Figure which shows time series of of the ELA proxy. Reference to the South Cascade site will be made explicit in the text.



(a) Manual snow/ice classification

(b) Automated MOD02QKM classification

Figure 2: Landsat 5 scene of the Wapta/Waputik Icefield and Peyto Glacier, 20 August 2009, with (a) manual classification, and (b) MOD02QKM automated classification of snow (white) and ice (gray).



(a) Manual snow/ice classification

(b) Automated MOD02QKM classification

Figure 3: Landsat 5 scene of the Lillooet Icefield and Bridge Glacier, 04 October, with (a) manual classification, and (b) MOD02QKM automated classification of snow (white) and ice (gray).

- P. 3764, L.4-8: This paragraph requires more discussion. Presumably, most of the other index glaciers that do not show significant ELA trends lost area from 2000-2011. So what does this mean if the ELA proxy isn't changing, but glacier area is declining? Are changes undetectable because of the relatively small time interval and moderate spatial resolution? How did the actual ELAs change during the same time? Instead of Figure 3 from the supplement reply to Dr. Pelto, I'd like to see individual linear regressions (actual ELA vs. ZS(20)) for each index glacier. This will be telling for whether ZS(20) is actually a good proxy for ELA.

  Response: While the length of the ELA proxy time series is generally too short for trend detection, these are interesting results. If there is no trend in the ELA proxy and glacier area is declining, this would suggest that the glacier is in disequilibrium with the current climate. There may also be errors in the detection of the maximum value of $Z_{S(20}$ due to cloud cover or misclassification, which would affect the calculation ELA trends. Individual plots of reported ELA versus ZS(20), which we can include in the revised manuscript, are shown below (Figure 4). Significant relations are observed at Peyto and Taku Glaciers, and positive relations with outliers are found at Lemon Creek, South Cascade, and Place Glaciers.

- P. 3764, L.9: Table 3 and Table 2 need to be switched based on the order that they are mentioned.

  Response: Table numbering will be fixed.

- P.3765, L.1-2: How were estimates of volume change in mm w.e. converted to estimates of volume change in m i.e.? I did not see any mention of this in the Methods section.

  Response: This section will change given our new geodetic and ELA-derived estimates of mass change. Volume changes are given in m w.e. for both geodetic and ELA proxy approaches, and converted to gigatons (1 km^3 w.e. = 1 GT).

- P. 3765, L.6: I believe "Andrei" should be switched to Sittakanay.

  Response: Schiefer et al. (2007) report mass change rates for the Andrei Icefield, which is located east of the Sittakanay Icefield, so the original text is correct.

- P. 3765, L.9: It would be helpful to put the mass loss in context by comparing estimates from this study with those from other regions of the world.

  Response: Good suggestion - the following text will be added to the discussion: "Rates of mass loss found in this study are slightly lower than those observed in other regions. Average losses between 1989 and 2009 at an icecap in northern Norway were -0.90 m w.e. a^{-1} (Andreassen et al., 2012), while an overall thinning rate of -1.0 m w.e. a^{-1} was estimated for the Patagonian Icefield (Rignot et al., 2003). At South Cascade Glacier, Krimmel (1999) found geodetic balances ranging from -1.90 to -0.24 m w.e. a-1 between 1985 and 1997."

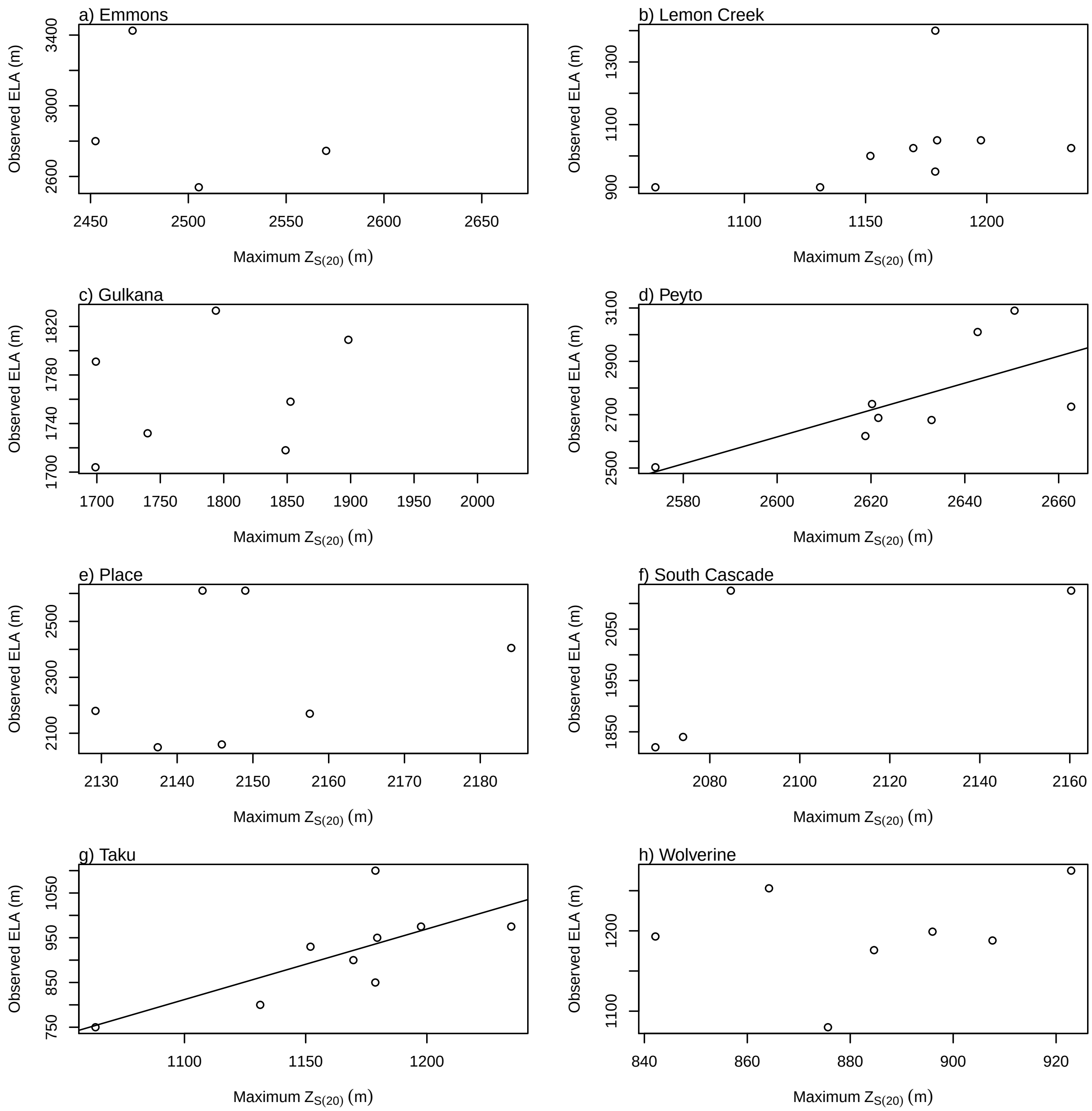


Figure 4: Individual plots of observed index glacier ELAs and maximum regional $Z_{S(20)}$, 2000 - 2009. Significant relations (p<0.10) are shown with a solid regression line.

6.Discussion

- P. 3765, L.11-18: This paragraph should be moved to the Conclusions section.

  Response: Moved.

- P. 3765, L.17: "within 30%" is not correct since the highest difference was +32%.

Response: This has changed given our new results.

- P. 3765, L.24: Are there temporal trends associated with the mass balance gradients from other sites?

  Response: We are unable to calculate trends in mass balance gradients for other sites as either the data are unreported, or the series is too short.

- P. 3766, L.7-9: The actual ELA and ELA proxy may not match exactly, but the trend in ELA should be about the same.

  Response: Good point. We have adjusted the manuscript to reflect this.

- P. 3766, L.24: How prevalent is debris-cover for these sites? Also, where should this methodology be applied next?

  Response: Debris cover is significant at the Gulkana site (Alaska Range, see Figure 5 which will be added to the revised manuscript), moderate at the Columbia site (See Figure 6, which will be added to the revised manuscript), and not really a factor at any of the other sites. The method should be applied next on glaciers in different regions (e.g. Arctic, European Alps, Himalayas).

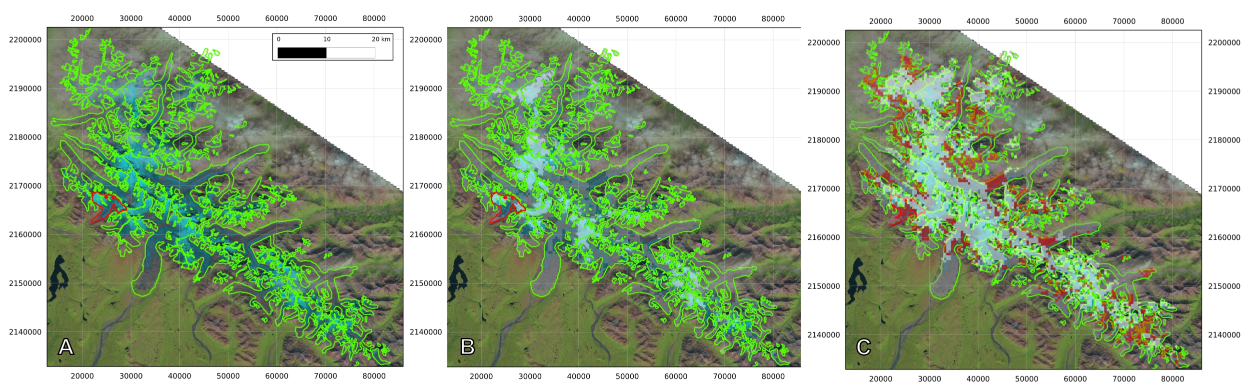


Figure 5: A) Landsat 5 scene of the eastern Alaska Ranges, 15 August 2004, with (B) 22 August 2004 MOD02 snow (white) and ice (gray) clusters, and (C) 22 August 2004 MOD10 snow cover product. Cloud-obscured pixels in (C) are shown in red. Gulkana Glacier is highlighted in red.

7.Conclusion

- P. 3767, L.8: The only "marked improvements" are shown visually in two figures. While I agree that the improvements do appear to be significant, the authors need to quantify this improvement in order to make this claim.

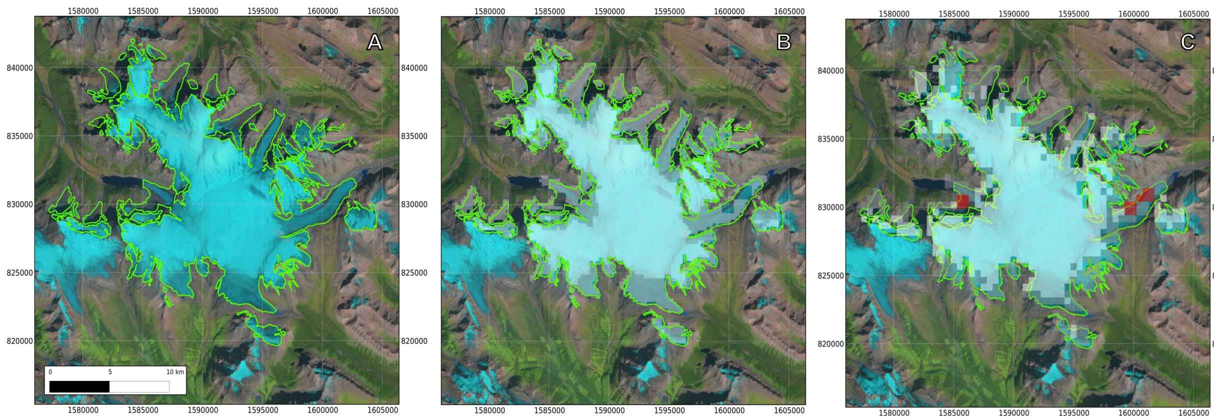


Figure 6: A) Landsat 5 scene of Columbia Icefield, 29 August 2009, with (B) corresponding MOD02 snow (white) and ice (gray) clusters, and (C) MOD10 snow cover product. Cloud-obscured pixels in (C) are shown in red.

Response: We have manually digitized snowlines from two Landsat scenes (Figures 2 and 3 above) and compared derived snowline metrics with those obtained from the automated procedure. Additional figures (Figures 5 and 6 above) in the revised manuscript will help reinforce our conclusion that a cluster analysis of MOD02QKM imagery will provide improved estimates of snowline elevation on glaciers and icefields versus the MOD10 product.

- P. 3767, L.11: Again, fix 30%.

  Response: Fixed.

8. Tables

- Include a Table summarizing the GLIMS glacier area, elevation range, and number of MODIS pixels corresponding to each index glacier and icefield.

  Response: See Table 4 below, which will be included in the revised manuscript.

- Table 2 and 3 should be switched.

  Response: Switched.

9. Figures

- Figure 1: I would suggest changing the color of the symbols associated with the ice-fields. Also, there are no units on the scale bar. Some additional detail, such as an underlying DEM, would improve this map as well.

Table 4: Area, glacier elevation range, and number of MOD02QKM pixels (N) MOD02QKM) of regional icefields/glacierized regions analysed in this study. Index glacier mass balance sites included in parentheses. Area and elevation range based on GLIMS glacier outlines (Armstrong et al., 2012) and GMTED 200 m digital elevation model.

Region (index mass balance site)	Area (km^2)	Z range (m)	N
Eastern Alaska Range (Gulkana)	1298	760-2885	18814
Southern Juneau Icefield (Lemon Creek, Taku)	1451	5-2003	22371
Columbia Icefield	216	1721-3624	3436
Wapta/Waputik (Peyto)	86	2078-3203	1363
North Kenai (Wolverine)	569	66-1730	8927
Southern Coast Mountains (Place)	50	1675-2545	805
Rainier (Emmons)	92	1163-4367	1475
South Cascades (S. Cascade)	19	1533-2604	304
Sittakanay Icefield	399	64-2173	6403
Lillooet Icefield	490	911-2958	7845

Response: Good suggestions - we have revised Figure 1, added digital elevation data, switched the colors, and added scale bars. See Figure 7 below.

- Figures 2 and 3: These figures are well done. To be consistent with Figure 1, please make sure the units of the map labels are in degrees. Also, indicate the band combination (it looks like 5,4,3). For Figure 3, indicate the location of the Bridge glacier. In Figure 2a, it appears that either the Columbia Icefield includes a few debris-covered glaciers or that the GLIMS outlines are not correct for a few glaciers. Does the presence of debris or exposed bedrock in the lower portion of the outline affect clustering?

  Response: Thanks! We've kept the map labels in BC Albers though, as these are in equal area projections. Debris-covered portions of the Columbia Icefield appear to be classified as snow-free. The clustering analysis is currently set to produce only two surface types, and the lower reflectivity of the debris cover causes it to be classed with the snow-free ice surface, which also posesses a low reflectivity. So we do not feel that the presence of debris or exposed bedrock will affect the clustering results.

- Figure 5: Show r2 values for each portion of the piecewise linear fit. The y-axis range should be the same for each subplot.

  Response: All plots now have the same y-axis, and the same elevation range on the x-axis (see revised Figure 8 below). As this is a piecewise regression, we can not report r^2 values for each portion of the fit. Additionally, we have found some discrepancies

between the WGMS dataset and the original soft copies of mass balance data. These additions and corrections are reflected in Figure 8, though the impact on estimated mass change is modest (less than (20%).

- Figure 6: Show the r2 for each regression line.

  Response: r^2 values are given in the new table (Table 2 above).

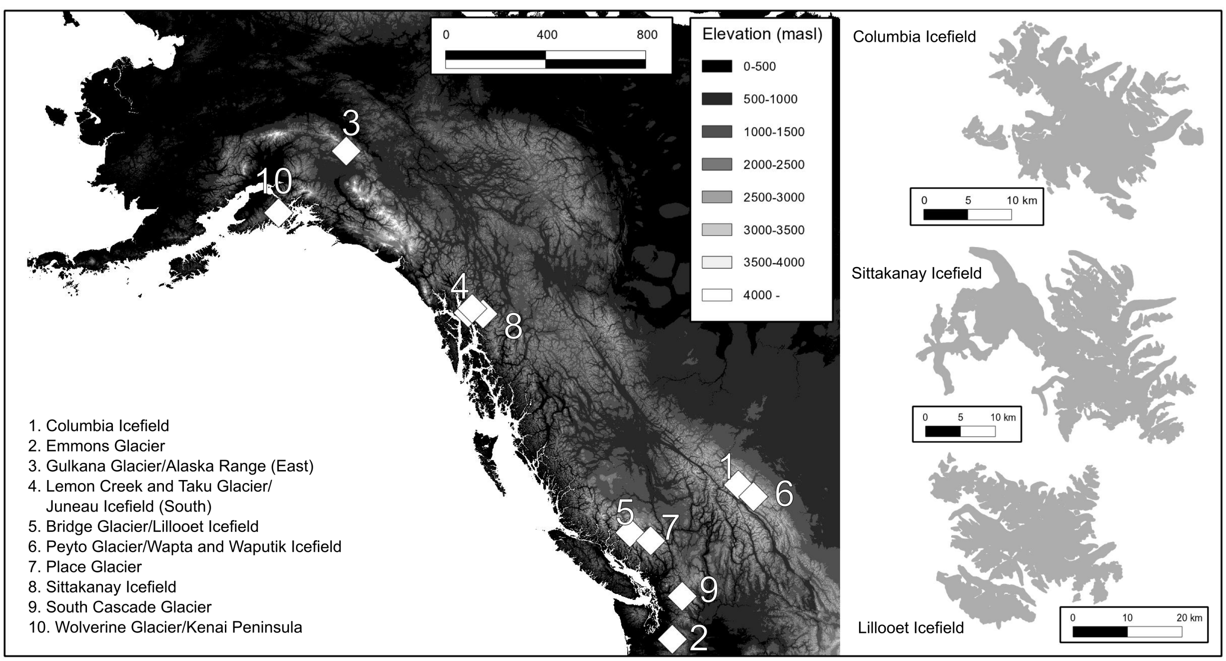


Figure 7: Revised study area figure.

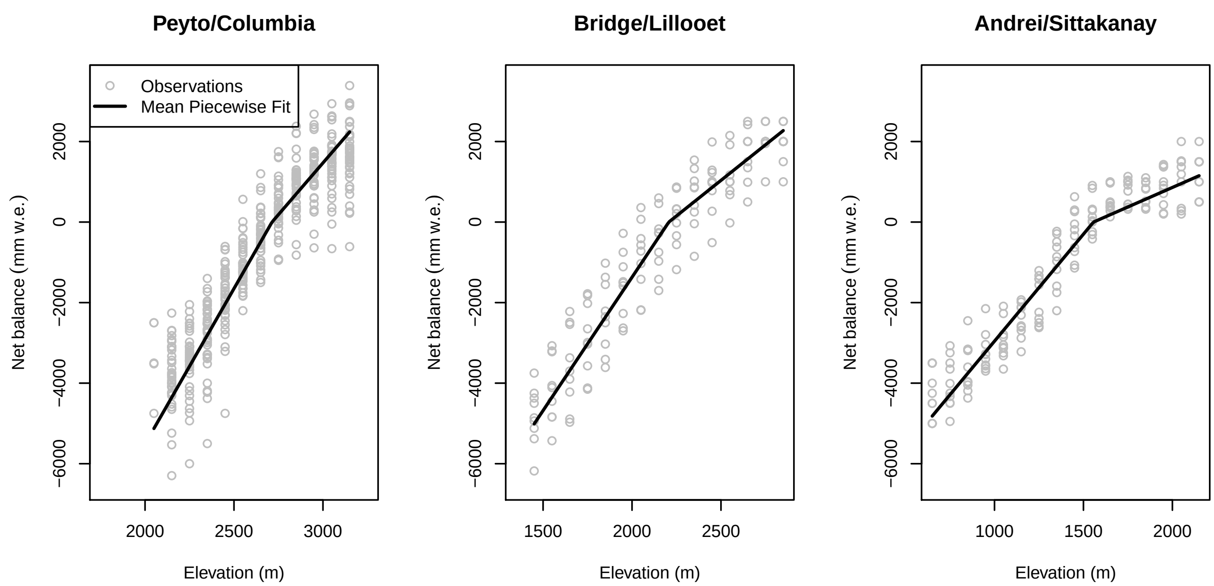


Figure 8: Revised Figure 5.

References

Andreassen, L. M., Kjøllmoen, B., Rasmussen, A., Melvold, K., Nordli, Ø., 2012. Langfjordjøkelen, a rapidly shrinking glacier in northern Norway. Journal of Glaciology 58, 581–593.

Armstrong, R., Raup, B., Khalsa, S., Barry, R., Kargel, J., Helm, C., Kieffer, H., 2012. GLIMS glacier database. Digital Media, National Snow and Ice Data Center, Boulder, Colorado, USA.

Klein, A., Isacks, B., 1999. Spectral mixture analysis of Landsat thematic mapper images applied to the detection of the transient snowline on tropical Andean glaciers. Global and Planetary Change 22 (1), 139–154.

Krimmel, R., 1999. Analysis of difference between direct and geodetic mass balance measurements at South Cascade Glacier, Washington. Geografiska Annaler. Series A. Physical Geography, 653–658.

Nuth, C., Kääb, A., 2011. Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change. The Cryosphere 5, 271–290.

Radić, V., Hock, R., 2011. Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. Nature Geoscience 4, 91–94.

Raper, S. C. B., Braithwaite, R. J., 2006. Low sea level rise projections from mountain glaciers and icecaps under global warming. Nature 439, 311–313.

Rignot, E., Rivera, A., Casassa, G., 2003. Contribution of the Patagonia Icefields of South America to sea level rise. Science 302 (5644), 434–437.

Schiefer, E., Menounos, B., Wheate, R., 2007. Recent volume loss of British Columbian Glaciers, Canada. Geophysical Research Letters 34, 16503.

Williams, R., Hall, D., Benson, C., 1991. Analysis of glacier facies using satellite techniques. Journal of Glaciology 37 (125), 120–128.

Winther, J., Gerland, S., Ørbæk, J., Ivanov, B., Blanco, A., Boike, J., 1999. Spectral reflectance of melting snow in a high arctic watershed on svalbard: some implications for optical satellite remote sensing studies. Hydrological Processes 13 (12-13), 2033–2049.