August 29, 2015

Dr. Andreas Vieli,
Associate Editor
The Cryosphere

Re: Manuscript TCD-9-2915-2015, “The relative contributions of calving and surface ablation to ice loss at a lake-terminating glacier”

Dear Dr. Vieli,

We wish to thank the reviewers for their comprehensive reviews and very useful comments that will greatly improve our manuscript. We have undertaken significant effort to substantially revise this manuscript to address the reviewers' concerns on four main points: 1) correct grammatical and definitional errors, 2) restructure the manuscript and reduce length by eliminating redundant text, 3) focus on improved clarity in our methods and provide a stronger, clearer justification for our study design and assumptions, and 4) re-focus our Discussion section to provide a more comprehensive discussion of the transferability of our findings to other studies and lake-calving glaciers worldwide.

We have accepted and amended the text to address all editorial suggestions provided by the two reviewers, and thank them for taking the time to make these suggested changes. Below we summarize our primary changes and respond to specific reviewers' comments and critiques on the paper content in a point-by-point fashion.

We hope you will find our revised manuscript has adequately addressed all of the concerns of the reviewers, and is significantly improved.

We appreciate the opportunity to revise our manuscript, and we look forward to any additional feedback that you or the reviewers are willing to provide.

Sincerely,

Matthew Chernos, Michele Koppes, and R. D. Moore

RESPONSE TO REVIEWS

Original in **bold**, response in *italics*

Reviewer #1, Roman Motyka

1. There is a woeful lack of referencing recent publications, and also older ones, that are really pertinent to their work. A list of these references plus others is provided at the end of my comments. In particular, the authors would find Trüssel et al. 2013 and Trüssel et al 2015 instructive. It is surprising that at least the 2013 paper wasn't referenced because it fits precisely within their stated desire to put Bridge Glacier into a "contextual" framework. For additional "contextualizing", see papers on Patagonia lake calving glaciers: Sakakibara et al 2013, Sakakibara and Sugiyama 2014, Warren et al 2001. You should also look at Larsen et al 2007 for additional information on lake calving glaciers in SE Alaska.

We have added references to more recent papers to the Introduction (see text comments below), as well as changed wording on framing previous research. We also highlight that we are comparing Bridge Glacier to other freshwater calving glaciers where not only calving but also mass balance or surface ablation have been measured.

2. Perhaps the most egregious lapse in this paper is the use of terminology. The authors should avail themselves of the Glossary of Mass Balance and Related Terms, (2011) available online and acquaint themselves with the basic definitions concerning mass balance. All too often the authors use the term "ice loss" to mean summer surface melt below the ELA in a given year. This occurs in the title of the paper itself! In the context of mass balance, ice loss implies thinning and shrinking of the glacier, i.e., a net mass loss over time. If a glacier is in quasi-equilibrium, then ice lost in the ablation area is replenished by ice flux from the accumulation area. Even with negative mass balance, the summer melt is not equivalent to glacier ice loss, it is just summer the summer melt. Understanding the differences is important because other publications they cite compare calving losses to glacier mass balance and not summer melt. The entire paper needs to be rewritten to emphasize these distinctions.

We thank the reviewer for this comment; it has helped us clarify our manuscript. We have rewritten the paper to reflect that we are focusing on net ablation of the ice, through calving and surface melt. We now define the term ablation in the Introduction at lines 65-67, and distinguish it as ice loss that is a separate entity from annual snow and firn losses. Furthermore, we would like to stress that we are only looking at ablation of glacial ice. As such, we can consider calving to be 'frontal ablation', while surface melt is equal to the net surface ablation below the snowline (ELA).

3. DEMs: the authors need to state the date of the Lidar survey that they are using for hypsometry. Is it 2013? If so, is the glacier outline, particularly the terminus, from this Lidar survey? If not, what is outline based on? A graphic displaying the hypsometry would be useful.

We note that the glacier outline is from Sept. 2013 (now noted in Figure 1), and the Lidar DEM is from 2006. The AAR of Bridge Glacier, based on the average 1984-2012 ELA (~2100 m), is 71%, and this has been added to the study area description (Lines 82-83).

4. But what about other DEMs? Isn't there one from the original map for this region? And also the SRTM data from 2000? Can't you compare the Lidar DEM to these older DEMs to get a handle on the actual amount of drawdown Bridge Glacier has experienced? Perhaps do a geodetic determination of mass balance? Perhaps someone has already done this?

DEM data are also available from TRIM data for 2000. However, these data are in a coarser resolution (25 m), and have several digital artifacts (such as an unrealistic 'reverse slope' of 50 m in the lower reaches of the glacier). These artifacts, combined with the relatively small period of time between DEMs, and that the Lidar DEM was obtained with snowcover (estimated at 2-5 m), we did not feel confident that any DEM comparison would yield reliable information on thinning rates. However, this question could be more fully explored in future research.

5. Another egregious error is hind-casting their melt model without consideration of the so-called Bodvarsson effect: *Bodvarsson G (1955) On the flow of ice-sheets and glaciers. Jo¨kull,5, 1–8.* Thinning due to a negative surface mass balance can cause the ice surface elevation to lower and expose the ice to warmer climate conditions. Progressively larger areas of the glacier then lie below the equilibrium-line altitude (ELA). This effect becomes even more pronounced if the ELA rises to higher elevations due to changing climate.

While we agree that thinning can drive velocity changes (i.e. the Bodvarsson effect), for Bridge glacier we note that the elevation difference between the 1970 and 2013 terminus positions was <100 m. Moreover, the change in ELA during this period was less than 200 m (see Figure 7c). Hence, we conclude that thinning and lowering of the surface elevation below the ELA is likely would only have a minor effect on modelling results, and its error would be difficult to quantify.

6. When you are hind-casting, what climate conditions are you assuming in order to drive your melt model? Or are you just assuming same as 2013? If so, that is quite an assumption!

To hind-cast the melt model we are using piece-wise linear mass balance model with measured ELAs from Landsat imagery (see lines 310).

7. Firn line vs. snowline: if ELA rises high enough, then firn from previous years will be exposed to melting. Are you ignoring this in your analysis?

In our melt model, firn is treated as snow (i.e. it is omitted from ice loss calculations). Moreover, ELAs are measured using end of summer Landsat imagery, from which we could detect the snow-firn transition, and used this to define the ELA and the extent of ice melt.

8. Regional climate indices: Why would Vancouver be representative of this mountainous region, which you previously said was under a mixture of climate influences? You need to defend your choice or find a closer index. Perhaps the mean annual flow anomaly is a better proxy but I am not sure since you don't state the size of the basin the gauge samples and the influence of rainfall.

During summer, air temperature exhibits a high level of regional coherence due to the spatial scale of the synoptic-scale features that dominate the weather – especially anticyclonic systems, which produce widespread fine, warm weather that is conducive to surface melt. The weather station at Vancouver Airport is free of signals associated with local land use change and we consider it a good broad-scale climate proxy for the Bridge Glacier area because it is well correlated with discharge from the gauge at the outlet of Bridge Lake. We also compared the discharge record with the climate record at Whistler, BC, which is only ~50 km to the south; however, we found that the relation was weaker (R^2 of 0.59 vs. 0.65 for Vancouver Airport).

The Bridge River streamflow gauge is located just downstream of the outlet of Bridge Lake, about 1 km east of the edge of our map in Figure 1. The gauge captures the outlet of the lake basin, of which 60% of the watershed is filled with the glacier; hence, other precipitation inputs are considered negligible. We have updated our description of the study area at lines 93-105 to better explain this.

9. Terminus retreat: you need to be consistent when providing data. In the methods, you state terminus change was determined by comparing successive Landsat images and measuring the area of change. Yet Figure 3e and later in the text, you use m per yr, not area! How did you convert area to linear retreat?? There are now standardized methods for doing so to get an average rate of retreat. In Fig. 3e, did you plot all Landsat data or just one from each year? It appears that the terminus advanced in some years. Not unusual, as we see calving of floating tongues in lake systems to be quite episodic, on the scale of years sometimes, see Trussel et al 2013.

Retreat rate (m/yr) was found by averaging the surface area lost (in m^2) by the terminus width (in m). Negative 'retreat rates' would correspond to advances, the most recent of which occurred in 2007. In Figure 3e, we plotted end-of-season terminus positions for each year (between Sept and Oct. of each year).

10. Velocity data: please show all of your velocity results somewhere, either as vectors on the map or in a table with reference to position. This is important for a reader to assess the validity of your ice flux calculations.

Thank you for your comment. We now include velocity vectors measured across the glacier in Figure 5.

11. Lapse rate: what do you mean "standard lapse rate"? Need a reference.

We have clarified that the lapse rate was derived by Stahl et al. (2008) (see lines 263).

12. Section 7.2: comparing summer surface melt that takes place below the ELA to calving losses seems to be the crux of your paper. I am having much trouble understanding the data in this section and much more explanation is needed. Furthermore, I do not understand how you arrived at your 85 day retreat area. I also have problems with water depth, flotation and ice thickness. a. b. c. First of all, you should show all of your velocity results somewhere, either as vectors on the map or in a table with reference to position.2cd, just how did you determine the 65 m terminus retreat over the 85 day period? Is this an average? Or can you show schematically the area of retreat? 3rd, what width did you use to get an area of -0.297 km^2 for the retreat?? You would have to have a width of 4.6 km for a retreat of 65 m in order to get your answer of - 0.297 km^2! If I use the width you used for calculating ice flux, 1.055 km, and a retreat of 65 m, that gives me an area of 0.068 km^2, not -0.297 km^2. Or was this a typo and you meant -0.0297 km^2? That would fit withe a terminus width of ~ 0.5 km.

a) As mentioned above, the spatial distribution of surface velocities is now included in Figure 5.

We are grateful for these comments, for they have helped us clarify our description of the methods we used. We have reworded this section and now state: "Over the 85-day study period in 2013, a change in terminus area (dA_T) of -0.297km^2 was measured from repeat terminus delineations. The average velocity at the terminus (U) was 139 m/yr, across a terminus width (W) of 1055 m, yielding a calving flux of 0.00342 km^2.

13. OK, now for ice flux area. a. So where was the velocity = 139 m/yr (0.38 m/d) measured?? Are you assuming plug flow? What about drag from the valley walls? What does the cross-valley velocity profile look like? b. Where is your "flux gate", i.e., where on the glacier are you measuring this flux? You state a width of ~ 1 km, so that would put it about a km from the terminus? Please show it on one of your figures!

a) Velocities were measured from Nunatak TLC (see above), and along the floating tongue (Terminus TLC). We believe that plug flow is a reasonable assumption in this case. The terminus region (see Figure 1,5,6) is not constricted by valley side-walls. The cross-valley velocity profile at Nunatak TLC does show measurable lateral drag (see above), although velocities along the centre flow-line are very close to measured velocities along the floating terminus.

b) Thank you for the comment - we now show the flux-gate in Figures 1 and 5. (Study Area, Bathymetry/Velocity)

Now for ice thickness: Why are you measuring water depth 500 m from the June 2013 terminus to calculate flotation thickness in 2013?? Aren't the appropriate data the soundings right next to the terminus?? Using 109 m is wrong! From your Fig. 6, maximum depth is about 90 m at the terminus and much shallower on either side of the lobe, so perhaps an average of 80 m or so?

The median depth of 109 m is a typo (this is the estimated ice thickness). If we assume *a water depth of 91 m, and an H_b of 10 m, the ice-height is ~109 m. We believe that the median water depth is an appropriate estimate for the terminus given the steep bathymetry on either side, and the relatively flat 'U-shaped' bathymetric cross-section anticipated at the flux-gate. We have re-written: "The median depth was 91 m, corresponding to a height above buoyancy of 9.9 m, and an estimated ice thickness of 109 m"*

15. Speaking of ice thicknesses of floating tongue: why use equation 13 when you have a highly accurate Lidar DEM? If it is really floating then just use the freeboard to estimate ice thickness. You also have your TLC data to give you floating tongue freeboard. Judging from Fig. 5 photo you may be overestimating the ice thickness. For floating tongues, ice thickness is primarily controlled by the thickness at the grounding line. At Yakutat Glacier, the lake depth was 325 m but ice thickness was about 175 m.

We clarified the text at lines 290-297 to indicate that we did use the freeboard to estimate the ice thickness

16. Figure 10 and 11. Again the terminology is really confusing. What you are measuring is summer melt below ELA, specifically for 2013, not surface melt, not glacier mass balance. To be accurate, surface melt would include all melting, including snow above the ELA. The confusion comes from thinking in terms of glacier mass balance, where net ice loss (or gain) has a specific meaning, i.e., net accumulation minus net ablation.

As mentioned above, we have rewritten the text to reflect that we are modelling ablation (i.e. only glacial ice losses). All terms are defined in the last paragraph of new Introduction.

17. Figure 11: is never cited in text. I presume it was to be keyed to section 7.3? What are the shaded envelopes? Some sort of estimate of uncertainty? If so, it needs discussion and explaining.

Calculated uncertainty is discussed in the Results Section. We have now updated the figure caption to include this.

Figure 12: these sorts of figures were in vogue a couple of decades ago when researchers were first trying to understand the drivers of calving. I am not sure how useful they are anymore, particularly for floating tongues. Although these figures do point out the difference in calving rates for marine vs. lacustrine glaciers, water depth is clearly not the reason why.

We thank the reviewer for the comment. We think that this figure helps position Bridge Glacier within the broader context of worldwide calving glaciers. In particular, we find it helpful to quickly position both the magnitude of calving and the size/depth of the lake relative to study sites across the world.

Redundancies: the discussions sections contained so much of what was already said, it was hard for me to read through it. Filled with too many generalities.

We thank the reviewer for this comment, and have re-written the Discussion section to be more concise and streamlined.

Uncertainties: a section on propagation of all of the uncertainties should be included in Methods.

Uncertainty estimates/calculations have been re-organized to follow results for each section.

Text Comments:

Title: This title is confusing to me because I think of ice loss in the context of glacier mass balance. Here, you are not looking at overall mass loss or gain (positive or negative mass balance) (accumulation - ablation) but instead simply comparing summer surface melt below ELA to frontal ablation (calving losses).

We re-titled paper as "Ablation from calving and surface melt at lake-terminating Bridge Glacier, British Columbia, 1984-2013" to attempt to minimize confusion and improve clarity.

P1

L 7: "surface melt": This implies across entire glacier, whereas you are only measuring below ELA?

We now use the term surface melt below the snowline - see comments above. We have re-written the text throughout to improve clarity.

L11: What do you mean by summer balance? You do not have info on accumulation to make a glacier wide assessment.

Here we use the term summer balance to define net annual surface ablation below the ELA. We assume that below the ELA, the local net balance is equal to the ice loss because there is no net change in snow storage on an annual basis. We redefine these terms at lines 65-71.

L 23: Include more modern references: Shepperd et al. 2013, Radic and Hock 2011, Also see Clarke et al. 2012.

We have added Radic and Hock 2011 as well as Gardner et al. 2013 and Zemp et al. 2015.

P2L 4: Include Radic and Hock 2011, Shepard et al 2013 L 18: see also Larsen et al 2007

We have added Radic and Hock 2011, Gardner et al. 2013

L 23- 25: Again ignoring more recent work of Japanese in Patagonia on Upsala and other glaciers. See ref. list for Sakakibara et al 2013 and 2014 and also Warren et al 2001 for Glaciar Nef in Chile. Also for Alaska, see Larsen et al 2007, Truessel et al 2013 and 2015.

We apologize for not including more recent work in Alaska and Patagonia as part of our review of relevant literature. We have now rewritten the introduction to include other freshwater calving glaciers where both calving dynamics and glacier mass balance (or ablation) have been quantified, including Yakutat Glacier (Truessel et al 2013.) and Upsala (Sakakibara 2013).

P4

L 13-15: rewrite this confusing sentence.

"Calving rates and retreat from Bridge Glacier are then compared with findings from other lacustrine calving glaciers in Alaska, New Zealand and Patagonia. Commonalities in the nature and timing of calving fluxes and summer ice ablation allow for a broad understanding of the temporal pattern of ice loss during the transient calving phase of a retreating alpine glacier."

L 19: Cite Fig. 1 here.

Included

P5

L 7: 1972? Fig. 2 starts with 1985.

This section has been re-written and moved to lines 86-90. We chose 1985 as the earliest Landsat image in Figure 2 because the image is visually of much higher quality than those from the 1970s.

L 13, Fig. 3e: How is terminus position defined? Is an average? How measured? Advanced in some years??

See comment above.

L 15: Why would Vancouver be representative of this mountainous region, which you previously said was under a mixture of climate influences? You need to defend or find a closer index.

See comment above.

L 17 -20: Rewrite, too confusing.

We now state:

"However, this period of elevated melt conditions did not continue into the 21st century as retreat continued to accelerate." (Note: this section has been moved to Results (line

320-340)).

L 22-23: OK, once again mixing apples and oranges. Your study is not measuring surface mass balance so you don't really know what the annual ice loss is!

See comment above. We are measuring ice loss only below the ELA, where the net balance is equal to ice loss.

L 26: reference the model being used.

The model is a combination of methods described in MacDougall and Flowers (2011), Hock (2005), Hock and Holmgren (2008), and Shea et al. (2010). Relevant citations are made within the model methods.

P6L 10 – 14: To really check the model, you need ablation measurements at higher altitudes too.

Thank you, this is a valid point. While we agree that melt near or above the ELA would be necessary to fully constrain our model, we were constrained by logistics and timing and were unable to install ablation stakes in the upper reaches of the glacier this season (this will be the focus of future efforts). However, we stress that the error is partially constrained by our application of an observed snowline to the data, which restricts the potential for 'runaway' melt in the higher reaches of the glacier (i.e. further from our measured ablation points)

L 19 – 20: This is confusing. Were 74 pts measured or interpolated between measurements?

We have re-written this section to now say:

"Due to the presence of large, unstable icebergs throughout the lake, depth measurements were taken at 893 discrete points in an irregular grid. Access to the terminus and the middle part of the lake was hindered by the presence of icebergs, necessitating the inclusion of additional 74 points that were added by linear interpolation using known depths along east-west transects to improve coverage. "

L 23-24: OK but in results, you state 65 m retreat not area.

Re-written. See comment #12

L 26: ?? what rgeos?

rgeos is package function in the R statistical software language. The function we used was gArea().

L 28: TLC 1.5 km east: Location not shown in Fig.1.

Thank you for the comment, Figure 1 has been amended to now show the location of both TLCs used in the study.

P7

L2: References on how this is done? E.g., Krimmel or Harrison? See ref. list.

We have re-written to add clarity: "following Harrison et al. (1992) and Eiken and Sund (2012) (see Chernos 2014, Chapter 4 for further details) "

L 10 – 11: These velocity vectors should be plotted on one of your maps along with magnitude. This should be part of your results! Also, what is ice surface elevation of both your ablation stakes and your velocity markers? Please state somewhere!

Velocity vectors have been added to Figure 5. The elevations of the stakes have also been included in the text (line 120).

L 13 – 15: What is the date of the Lidar?? Reference here and in Fig. 1. Lidar is usually very accurate so you should know surface elevations quite well.

The Lidar survey was conducted in winter 2006. This has been added to Figure 1 caption.

L 15 – 20: You are ignoring the Bodvarsson effect.

Please see comment #5

L 16 – 18: Sentence as written is confusing.

We have re-written this sentence to clarify the text, and now state:

"Annual terminus positions and equilibrium line altitudes (ELAs) were reconstructed from Landsat images from 1984 to 2012. All Landsat data images taken between September 12 and October 24 to represent end-of-season snowlines and terminus positions."

P8

L 10 - 14: This is totally confusing. Snow is ice! Total ice loss during summer implies melt from above snowline too! Basically what you are measuring is specific balances on exposed ice below the snowline.

We have now defined our use of the term 'ice loss' in the Introduction (see comment above), and have re-written to clarify:

"As our purpose was to calculate total ablation during the summer melt season, we only consider ice melt and not snowmelt, and hence the model was only applied to exposed glacial ice below the snowline at each time step."

P12

L 2: Reference for lapse rate. How do you know whether it applies to Bridge?

We now cite Stahl et al. (2008), who determined a lapse rate of 6 degC/km by calibrating a model applied to Bridge River's catchment for simulating both glacier mass balance and streamflow.

P13

L 19: Why are you using this equation? If you know ice surface elevation above lake and you believe it is floating, then way not use free board estimate??

Given there have been several observations from the time-lapse cameras of tabular calving events that show some movement across the lake immediately following calving, combined with an estimate of height above the waterline and measured bathymetry, we feel confident that the terminus is near or above the threshold for flotation. We confirm this calculation using the freeboard estimate.

P14

L 1- 2: I would be really dubious about this assertion. Ice thickness of floating tongue is more likely established at grounding line.

See comment above.

L 2: There are two red arrows in the Fig. 5. Which is which?

Figure 5 has been replaced with a new figure in hopes of better illustrating the location of the inflection point marking the transition to flotation and approximate grounding line of Bridge Glacier.

L 8: Is this average speed, max speed or what? What is the gradient across glacier? Makes a difference when computing fluxes.

Here we are estimating the average speed, which is now explicitly stated

L 21-22: Poor coverage ?? Not according to your Fig. 6.

The bathymetric coverage was increased for areas that were covered by icebergs using linear interpolation. As such, we have less confidence in the bathymetry in this small region relative to the rest of the lake, where depth measurements were more closely spaced.

L 24: ?? You are not measuring mass balance are you? So how do you know about long-term mass loss?

Estimates of historical annual ablation rates are derived using ELA observations and a fitted mass balance gradient derived from several glaciers in the region (Shea 2013).

L 26: What makes you think summer specific balance is linear with altitude?

We arrived at this assumption from the work of Shea (2013), which is based on mass balance observations from several glaciers in the region (including Bridge Glacier). We *now include this in the text.*

L 26: What are the terms in the equation? Define them! Is this a specific mass balance measurement?

We have re-written this line "Below the snowline, the net balance (b_n) at a point is equal to the summer balance (b_s)…"

L 27: This again mixes apples and oranges. It may be equal to summer ablation but not glacier ice loss.

This point has been corrected for clarity (see above comments)

L 27: Is hypsometry from Lidar?

The hypsometry is derived from the 2006 winter lidar survey, shown in Figure 8.

P15**L 9 – 10: ?? Why not use elevation from Lidar?**

It was not possible to derive elevations for the lower reaches of the glacier that had calved before 2006.

L 10 - 16: How do you know hypsometry for prior years? What about Bodvarsson effect? Also, you are measuring seasonal melt not overall ice loss. The latter is mass balance. This gets really confusing!

We are assuming that hypsometry pre-2006 (date of Lidar survey) is similar, with the expectation of the loss/gain of glacier coverage in Bridge Lake (which we assume is approximately equal to the elevation of current terminus). See previous comment(s) on the Bodvarsson effect.

L 19 – 22: I think it would be good to have a table of hypsometry vs. ice loss. Reminder, you are modeling specific balances. Also, by definition, shouldn't your summer specific balance at the ELA be zero?

Figure 6 shows the net balance to be 0 at ELA. It also plots net balance against glacier elevation. We believe this is better means of visually representing the change in melt over elevation than could be seen in a hypsometric plot or table.

P16

L 1-8: What are the elevations of your stakes? From your figure, they all appear to be clustered at between 1500 and 1600 m. How far apart are they? Also, that's great that it works at your terminus ablation stakes but you have no upglacier control. Also, I believe you said earlier that stakes were 3 m long? But you are measuring ablation on the order of 4 - 5 m?

The location of stakes was constrained by logistics/timing. However, the error is partially constrained by having applied an observed snowline to the data, which restricts the potential for excessive melt in the higher reaches (i.e. further from measured ablation *points).*

While our drill only allowed for stakes to be at most 3 m long, the stakes were re-drilled in mid-July (see Field Methods): "The stakes were installed on June 18, and were resurveyed and re-drilled on July 19 and September 13, 2013." Hence we were able to capture up to 5 m of melt over the entire season.

L 9 – 16: Where did you measure this width? First of all, you should show your velocity results somewhere, either as vectors on the map or in a table with reference to position. 2cd, just how did you determine the change in terminus area over the 85 day period? 3rd, what width did you use to get -0.297 km2?? You would have to have a width of 4.6 km to get your answer! If I use your width of 1.055 km and a retreat of 65 m, that gives me an area of 0.068 km2. You need to show where on the glacier is your flux gate and also show just how you computed the 85 day loss in terminus area. Finally, I don't understand why you are using a position 500 m downstream of the terminus!

see comment #12

Sect 7.3: Totally ignores changes in surface elevation (Bodvarsson effect). P18

see comment #5

L 1-2: Hmm! This is all very obvious, does it need stating?

Have edited Discussion section extensively to reduce redundancy and remove generic statements.

L 13-14: ?? How did water depths increase? Did the lake level rise somehow? L 16: ??? Water depth at terminus looks deeper to me during 2004-2012.

Thank you for your comment. We have extensively re-written the Discussion section to be more focused on the general findings from Bridge Glacier, their agreement with findings from other lake-calving glaciers, and the transferability of our findings towards a more comprehensive "life-cycle" of a calving glacier. In particular, please see Lines 423-437.

L 19 -22: What's this all about? How do you get thinning rates from Landsat images? Where is this data published??

Please see above comment. In particular, this section has been re-focused in Lines 454-465.

P19

L 1: Why would glacier thicken? Positive net balance? Floating tongue thickness probably set at grounding line.

Please see above comment. We have re-written this section, see Lines 454-465 and Lines 501-512.

L 8-11: !!! Again, you need to be clear on what is being compared! Annual ice loss (or gain) usually refers to glacier-wide mass balance. Here, you mean summer ablation below ELA!

Thank you, we have re-written for clarity:

"…to a flux responsible for between 20-45% of the annual ice loss"

P24

L 28: published in 2002 not 2003.

Thank you - apologies for the oversight. This has been corrected.

Figures.

We have amended all figures as suggested.

Anonymous Referee #2

General

This manuscript deals with recent calving and mass balance changes taking place on Bridge Glacier, Canada. This issue is relevant for the journal, and can be of interest for a wide community of people working on calving glaciers. The number of measure- ments done by the authors is very extensive and I think they are describing important processes taking place in the area. But, I consider that the introduction is not well based on recent literature and that presentation of the data, methods and study area are not well organized. I think there are several concept confusions that need to be ad- dressed and improved before discussing and obtaining conclusions. I'm giving below several detailed comments/critics/questions. I'm afraid it was difficult to follow the text, for example when conclusions are presented in the study area before discussing how the data used to reach these conclusions were collected. I recommend re-writing the first sections before presenting results, discussion and conclusions.

We thank the reviewer for these supportive comments. They have helped us to restructure and significantly improve the text.

Detailed comments

Title:

I think the word "relative" is misleading. Is the manuscript dealing with water pro-duction? Surface ablation is important for quantifying how much water is leaving the glacier, but if they are interested in the mass balance, they must incorporate accumula- tion and see if the glacier is in balance, is gaining mass or is losing mass. The relative in this sense is not clear to me

Thank you for your comment. We have revised the title to better reflect this lack of clarity.

"Ablation from calving and surface melt at lake-terminating Bridge Glacier, British Columbia, 1984-2013"

Abstract:

1) I suggest changing the first phrase to: Bridge Glacier is a freshwater calving glacier located in the Coast Mountains of British Columbia, Canada, which has retreated over 3.55 km since 1972. The majority of this retreat occurred since 1991.

We have re-written: "Bridge Glacier is a lake-terminating glacier in the Coast Mountains of British Columbia, which has retreated over 3.55 km since 1972. The majority of this retreat occurred since 1991."

2) I suggest revising the use of two significant figures (3.55 for example), in order to be consistent with the accuracy in determining frontal changes or any other parameter.

We have re-ordered and significantly revised all Figures in the text, in particular Figures 1,3e, 4 and 5, to more clearly highlight the frontal and surface changes we observed.

3) I think the asseveration that the retreat is "out of proportion to surface melt" is confusing two different processes. The retreat is a response to mass balance changes and calving. Mass balance is a result of ablation and accumulation. The glacier can have a huge amount of ablation (and calving by the way), but its front can be stable or even advance, depending on the relationship with accumulation and therefore, with the total mass balance. Surface melt is certainly an important process for understanding glacier changes, but the consequences are not directly converted into frontal changes.

We now more clearly define the processes we are investigating, namely the contributions to total ablation and ice loss from surface melt and from calving, in the Introduction and Discussion sections. We also re-worded this statement for better clarity, and now state:

"This retreat is substantially greater than what has been inferred from regional climate indices, suggesting that retreat rates have been driven primarily by calving as the terminus retreated across an over-deepened, water-filled basin."

4) "Calving is responsible of 23% of mass loss". I don't understand this asseveration. Mass loss includes ice thinning? Did the authors estimate the mass balance of the whole glacier during this period, in order to reach this conclusion? Maybe they are only talking about frontal changes during the melt season.

We have re-worded to emphasize that the study considers only ice loss due to ablation (frontal and surface ice ablation, and not snow/firn loss) below the ELA over the melt season.

5) Then they talk about summer balance in relation to calving. Again, mass balance (even if only during the summer season) is not equal to surface melt.

Thank you. We have re-written to clarify that we only consider surface melt below the ELA, and therefore only concern glacial ice.

6) ". . .expected to diminish as the terminus recedes into shallower waters" Do they have any estimation of ice thickness upstream the present front? I can expect this trend if I have some data about the thickness, otherwise is just speculation.

Our ability to estimate ice thickness is admittedly coarse, but is based on the lake bathymetry, which gives an indication of ice thickness at the terminus, and of the thickness where the glacier becomes grounded. We estimate the ice thickness at the grounding line in 2013 is ~110 m. See text at lines 300-305 and Figure 4.

<u>Introduction</u>

1) I suggest that in the introduction they quote more recent and more closely related to the study area papers when giving examples.

Thank you for the comment. We agree with both reviewers and have added more recent and relevant references, including: Radic and Hock, 2011, Gardner et al. 2013, Zemp et al. 2015; Sakakibara et al., 2013 and Truessel et al, 2013.

2) The authors stated that few lake- calving glaciers have been studied worldwide. I'm afraid they need to have a better literature review including many more papers about this type of glaciers. Only in Patagonia (mentioned by the authors) there are studies on freshwater calving glaciers Upsala, Spegazzini, O'Higgins, Nef, Leones, Grey and Tyndall, among many others.

Thank you for the comment, please see above. We have added references to several more relevant studies to the Introduction and Table 1. Several Patagonian glaciers, including Upsala and Nef, are now listed in Table 1 in the Discussion, and we have changed some the language to reflect the diversity in Patagonian glacier studies. We would again like to emphasize that we are focusing on lake-calving glaciers where both calving dynamics (and/or retreat) as well as mass balance (and/or ablation) have been observed over the same time periods. While many of these studies have investigated calving fluxes and retreat rates, only a few (those in Table 1) contextualize those frontal changes with ice losses from surface ablation.

3) The last paragraph of the introduction is almost a repetition of the text previously presented. Maybe they can delete this part.

This section (lines 65-75) has been re-written to define the terms we are using and to emphasize that ablation from surface melt and from calving will be directly compared.

<u>Study area and retreat history</u>

1) I think a better Location Figure is needed. The Figure Number 1 has not enough information for a reader not well familiarized with the study area.

The inset map of Figure 1 has been updated to more clearly show the location and context for Bridge Glacier, including southwestern BC elevation data.

2) I think this chapter is mixing results with a description of the study area. For example; how did you estimate ELA since the 1970's? No methods, no reference etc. This must be moved to results. The frontal changes are not quoted; therefore I understand that these results were obtained by this manuscript. If this is correct, I suggest moving all of this to results. Before that, you need to discuss in methods how you measured these changes, the estimated errors, the used databases, etc. Figure 2 also needs to be moved and improved (add co-ordinates, scale, North etc. Figure 3 also needs to be moved to results

Thank you for your comment, the reviewer is quite correct. We have now moved all of our 'results', including Figure 3, to the appropriate sections in Results.

We have also added a North arrow and scale bar to the Landsat images in Figure 2.

3) They talk about over deepened basin. Again, this is a result of this manuscript? Did they measure bathymetry? Or is a result that needs to be quoted from a different paper?

Bathymetry was measured in study, and our description of this has been moved to Results. However, we stress that the over-deepening can be inferred without bathymetry; based simply on the shape of the lake and the size of the icebergs currently visible in the lake.

4) In Page 5 line 14 and 15, says: ". . .cannot be fully explained by regional climate. . .". This is a strong conclusion and must be moved out of "study area". This entire paragraph (lines 14-21) includes conclusions and must be justified by quoting a paper from the specialised literature.

Has been re-written:

"This retreat is substantially greater than what has been inferred from regional climate indices" (Note: this finding is echoed in Stahl (2008) - which has now been cited with this sentence).

<u>**Field methods**</u>

1) I suggest separating AWS, from Bathymetry, from mass balance, from satellite images, ice dynamics, etc., using subtitles.

We appreciate this suggestion, and have re-structured our Methods chapter to separate the individual field and modelling components, with appropriate subtitles.

2) The location and use of AWS needs to be better justified. Maybe you didn't have access to other locations or there is a hypothesis underlying this location. The same about the bathymetry. How were designed the tracks?

This section has been re-written to clarify the locations and methods chosen.

3) Figure 1 can be improved and quoted here to show the location of cameras and AWS. For example, in line 28, page 6, you mention TLC, and 1.5 km east. I needed to look very carefully and calculate distances in order to locate the cameras.

Figure 1 has been revised, and TLC "1.5 km east" is now added to the map as 'Lake TLC'. Additionally, Figure 5 (which shows the lake bathymetry) now also contains the TLC locations (and velocity vectors derived from the TLCs).

4) In page 6 line 28 you talk about "Floating terminus". This asseveration needs to be better justified. I presume you concluded this, but in this case you must describe in results how you did it. In the study area section you mentioned large calving events as explanation. Again, this is a result of your work of investigated by somebody else? I think you must give more attention to the explanation of both issues (tabular icebergs and floating tongue) in discussions after describing

your own results.

Thank you for this comment. We have re-written and added a new photo in Figure 4 that we hope more clearly shows the inflection point on the glacier surface which we argue indicates flotation. We also added the following text for clarity:

"During the melt season, large tabular icebergs calved and showed limited mobility, suggesting that the glacier is at or near the boundary criterion for flotation. There is a notable inflection point (Figure 4) roughly 500 m from the end-of-season terminus, where the surface slope becomes flat or slightly reclined, which has remained stationary since 2012, and where we assume that the terminus transitions from grounded to floating.

<u>Modelling Surface melt</u>

1) In this section you are mixing different methods, some of them partially described in the previous section (use of Landsat images for example). I think you need to reorganize this and the previous section.

Thank you for your points on organization. We have re-organized this section extensively - see comments above.

2) In Point 4.1 you again mix method descriptions with results (we estimate that ice loss is less than 10%...)

See comments above.

3) I think you are confusing here the term "ice loss" with ablation, which is not the same and need to be changed everywhere in this manuscript.

Thank you. For clarity we have re-worded ice loss as ablation, and now define all terms in the final paragraph of the Introduction.

4) In Point 4.2 Net radiation. I don't see if you calculated direct short wave radiation per pixel per day. I presume you considered declination angles and change the zenith angles day by day during the melt season.

Incoming Shortwave radiation was calculated considering declination, shading, etc. following Oke (1987). Full details are found in Chernos (2014). We felt that including these details in the manuscript would be redundant and/or cumbersome given that they are commonly applied calculations in energy balance models.

5) Did you calculate distributed albedo or you only use albedo from the AWS? This is clearly a limitation in the model. Did you use the photographs from the fixed cameras to estimate distributed albedo? This is something you can try.

Albedo was estimated from the on-glacier AWS, and was held constant for each day. Although this limits the model's representativeness over the whole glacier, given the model is only applied over bare ice, simplifying the albedo in this way is not expected to have an appreciable impact on the modelled volume of ice melt.

6) There is a problem when using LWR from outside the glacier and apply this to the glacier. Humidity is not the same out and on top of the ice. At least you must discuss this limitation.

Although incoming longwave radiation is expected to vary on- and off-glacier, the relatively small difference in humidity between the Glacier and Lake AWS (approximately 10% higher humidity on-glacier), we expect that any difference in incoming longwave radiation between the two sites is relatively small. Much more comprehensive studies by Shea 2010 (PhD Thesis) found "no systematic difference... over all sky conditions".

7) In page 10 line 24, you assume that terrain T° is equal to air T°, but later on you assume that the ice is at melting point.

By "terrain temperature" we are considering only non-ice terrain (i.e., rock, vegetation). Terrain temperature is only used to calculate incoming LWR from surrounding terrain (1-skyviewfactor).

8) In page 11, line 7 and 9 you say that the glacier is at melting pressure point, then you are dealing with a temperate ice. If this is correct, I have serious doubts on the asseveration that the lower tongue is floating. Normally, when temperate glaciers approaching flotation are collapsing due to the presence of water and crevasses within the lower tongues. This is something you must at least discuss and address.

While floating temperate ice tongues have been shown to be unstable, often leading to disintegration and dramatic retreat, the possibility of a floating termini made up of temperate ice remaining intact is not unprecedented in both freshwater and tidewater glacier systems. Some of the most prominent examples include glaciers that these authors and reviewer Roman Motyka have worked on: Yakutat and Bering glaciers in Alaska, Tyndall and Upsala glaciers in Patagonia. Boyce (2007) documents Mendenhall Glacier's calving rates, where an unstable floating terminus remained intact for approximately 2 years. Similarly, temperate lake-calving Yakutat Glacier (also Alaska) sustained a floating ~3 km terminus for over a decade (see Trussel 2013).

While we are aware of the more recent calving models that invoke the propagation of water-filled crevasses to the waterline or along the full ice thickness to the bed as one mechanism for generating longitudinal stresses and inducing calving (see Benn et al., 2007; Nick et al, 2010; Todd et al, 2014), these models require the presence of many open crevasses close to the ice front in order to cause 'collapse'. If, as at Bridge or Yakutat or Tyndall, the surface slopes decrease in the lower reaches and there is not an ice fall close to the terminus that would cause extensional strain, then many of the crevasses created up glacier will anneal, and will not generate a locus for calving.

Many examples of temperate floating tongues, where the height above buoyancy criterion has not been met but the calving front has not collapsed, and can be seen wherever large tabular bergs are found in lakes and fjords.

9) In line 11, page 11, you mentioned the use of 2.5 mm for ice, but you don't give a justification. This parameter is critical and must be well supported. What about sublimation?

The value was taken from Munro (1989,2006) and Pellicciotti (2005), and is within the range of "a couple of mm" suggested by Hock (2005) over glacial ice. If a glacier surface is melting, the vapour loss is evaporation and not sublimation, because the loss occurs from the water film coating the ice surface or snow grains, not the solid ice surfaces. We do not believe the air is dry enough in the region for significant rates of sublimation.

10) Line 12, page 12. What do you men for "standard temperature lapse rate". I mean, this number (-6 $^{\circ}$C/km) is not standard. Depends on the region, and hopefully you can calculate this by measuring at different altitudes. What is happening when precipitation is solid and air T$^{\circ}$ is <0°C? Are you using a threshold?

Thank you for this comment. The lapse rate is from Stahl et al. (2008), based on calibrating a model to predict both glacier mass balance and streamflow for the Bridge River catchment. The sentence has been re-written to reflect this.

During the study period no precipitation occurred at T < 0C (on-glacier temperatures were only below 2C for 3 hours, and never below the melting point).

11) In line 22 page 12. Please describe the used method. Clausius - Clapeyron?

Have added:
"Saturation vapour pressure was calculated using Teten's formula (Murray 1967)". More information about the methods can be found in Chernos (2014)

12) 4.4 Melt contribution. Please quote a proper paper for the use of this equation and parameters. Did you use an altitudinal gradient for precipitation or is constant?

We cite Hock (2005), where the equation and parameters are discussed in full. We used a constant precipitation gradient. With our two rain-gauges, we did not find a significant altitudinal or E-W gradient during the field season.

<u>Modelling calving flux</u>

1) The Calving flux as stated assumes that the ice is floating, but the equation in fact assume that the ice is near flotation, not necessarily floating. I already asked before for the temperate condition of a floating tongue, so again, this is something you must address more carefully.

Given there have been several observations from the time-lapse cameras of tabular calving events that show some movement across the lake immediately following calving, combined with our estimate of height of freeboard (above the waterline) and the *measured bathymetry, we feel confident that the terminus is near or above the threshold for flotation.*

2) Page 14. Notable inflection point (Fig. 5). To say the true I don't see this notable point in the figure. Improve the photo or explain better.

See above comments. We now include a new photo in figure 4 which we hope better illustrates the change in slope where we are asserting floatation and the grounding line.

3) I have serious doubts on the floating condition issue and the statement "it is clear that the terminus became ungrounded. . ." How did you estimate this from the images? This is again conclusion and not methods, and I'm afraid this is not well justified.

We have re-written: see our response to the comment in Field Methods #4

4) The height of the ice wall in Fig 5 shows in places that the ice is clearly grounded. This is ratified by the bathymetric map (Figure 6), where the water depths near the front are quite shallow (even less than 20 m water depth). There is only one section with a bit more than 100 m water depth, that seems to me is located at the large crevasse indicated in Figure 5.

The measured median water depth from our transect near the terminus is 91 m. We feel the median water depth is an appropriate estimate for terminus given the steep bathymetry on either side, and the relatively flat 'U-shaped' bathymetric cross-section anticipated at the flux-gate.

5) I don't understand the phrase in lines 13-14 in page 14 and the conclusion about calving rates prior 1991. The ungrounded condition has been permanent since 1991? How much changed the ice elevation in this period? How did you include ice elevation in the calving fluxes since 1991? Only assuming that was floating? These questions arise from the lack of proper description of results and proper discussion. We are supposed to be in methods and modelling.

Thank you, please see previous comments. We have re-written our methods, and have re-organzied to improve clarity.

<u>**Historical surface melt**</u>

1) I presume DEBM is distributed energy balance model. If yes, say so.

Yes. Amended in text (lines 7 - abstract).

2) I think there is a problem with the units here. Shea et al 2013 is talking about values of 5.17 to 7.25 mm w.eq./m, and you are talking about b1= 6.62 m w.eq./m . With your gradient the mass balance is amazingly out of any possible range. By the way, the data in Figure 7 seems to have an exponential and not lineal trend. Discuss this.

Correct. This was/is a typo; it should read "mm (w.eq.)/m"
Regarding the exponential trend we observed, given we have no way to verify whether other years followed this same exponential pattern and that the linear rates derived from Shea 2013 have proven successful at modelling summer balance, we feel the best way to account for this uncertainty is to include it in our estimate of the uncertainty in the ELA (which we set at 22%/, or 75 m). (pg 2929, line 15-16).

3) Page 15 lines 9-11. ELA determination. This is a good example of the organization problems in this manuscript. Several pages before you gave the results of ELA changes (Figure 3), and only now you describe how you measured this.

Thank you for your comment - we have extensively re-organized our Methods, and moved much of this section to the appropriate sections in Results. Please see above comments.

<u>**Results, Discussion and Conclusions**</u>

After all the above comments, I think the authors must re-write most of the previous text, especially by re-organizing these sections, otherwise the following parts will not be very clearly understood. A new version is needed before going into more details that need to be presented in the following chapters.

We are grateful for all the suggestions made to date, and thank the reviewer for their perseverance through our structurally challenging manuscript. We have amended and re-organized the entire paper as suggested, and hope that the new organization has significantly improved the paper.

We look forward to any recommendations that you would be willing to provide for the remainder of the text.

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~~The relative contributions of~~ Ablation from calving and surface ~~ablation to ice loss~~ melt at ~~a~~ lake-terminating ~~glacier~~Bridge Glacier, British Columbia, 1984-2013

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Abstract

Bridge Glacier is a ~~lake-terminating~~ lake-calving glacier in the Coast Mountains of British Columbia and has retreated over 3.55 ~~km since 1972, with the majority of the retreat having~~ km since 1972. The majority of this retreat has occurred since 1991. This retreat is ~~out of proportion to surface melt~~ substantially greater than what has been inferred from regional climate indices, suggesting that it has been driven primarily by calving as the glacier retreated across an over-deepened basin. In order to better understand the primary drivers of ~~mass balance, the relative importance of~~ glacial ice loss, surface melt and calving ~~is investigated~~ are quantified during the 2013 melt season using a distributed energy balance model (DEBM) and time-lapse imagery. Calving is responsible for 23 ~~% of the mass loss~~ % during the 2013 melt season, and is limited by modest flow speeds and a small terminus cross-section. Calving and ~~summer balance estimates over the last 30 years~~ surface melt estimates from 1984-2013 suggest that calving is consistently a smaller contributor of ~~mass~~ ice loss relative to surface melt. Although calving is estimated to be responsible for up to 49 ~~% of ice loss~~ % for individual seasons, averaged over multiple summers it typically accounts for 10 to 25 %. Calving has been driven primarily by buoyancy and water depths, and fluxes were greatest between 2005 and 2010 as the glacier retreated over the deepest part of Bridge Lake. ~~These losses are~~ The recent rapid rate of calving is part of a transient stage in the glacier's retreat, and ~~are~~ is expected to diminish within the decade as the terminus recedes into shallower water ~~.~~ at the proximal end of the lake. These findings are in line with observations from other lake-calving glacier studies across the globe, and suggest a common large-scale pattern in calving-induced retreat in lake-terminating alpine glaciers. Surface melt is the primary driver of ice loss at Bridge Glacier, and ~~future mass loss and retreat is dependent on governing climatic conditions~~ projections of future retreat should be closely tied to climate.

1 Introduction

Since the end of the Little Ice Age, glaciers across the globe have been shrinking at an accelerated rate ~~(e.g. ?Dyurgerov and Meier, 2005)~~(e.g. Dyurgerov and Meier, 2005; Radić and Hock, 2011; Gardner Although this retreat has been irregular, a ~~–~~general trend of ~~20th~~ 20^{th} century retreat is pervasive, and well correlated with an increase in global mean temperatures (Oerlemans, 2005). The reduction in ice cover in mountainous regions has raised concern about potential changes in the timing, volume, and duration of summer streamflow ~~(e.g. Marshall et al., 2011; Stahl et al., 2008)~~(e.g. Stahl et al., 2008; Marshall et al., 2011). These changes have major implications for hydroelectric projects, agriculture, aquatic habitat, water quality, and eustatic sea level rise ~~(Barry, 2006)~~(Barry, 2006; Radić and Hock, 2011; Gardner et al., 2013). While recent glacier retreat is well documented (e.g. Kaser et al., 2006), the projection of future retreat is critical to the management of water resources and understanding the evolution of riparian and aquatic habitats (Milner and Bailey, 1989; Cowie et al., 2014).

Due to their sensitivity to air temperatures and precipitation, glaciers serve as important high altitude climate stations (Oerlemans, 2005; Kaser et al., 2006). However, glaciers that terminate in bodies of water have been shown to respond at least partially independent of climate on decadal timescales (Warren and Kirkbride, 2003; Post et al., 2011). This blurring of the climate-glacier signal is due to calving, which can be an important additional source of ice loss (Benn et al., 2007a). While the climatic signal from a ~~–~~calving glacier is more complex than one from glaciers that terminate on land ~~(Van der Veen, 2002; Motyka et al., 2003)~~(Van der Veen, 2002; Motyka et al., 2002), their inherent instability suggests that they have the potential to contribute disproportionately to eustatic sea level rise (Meier and Post, 1987; Dyurgerov and Meier, 2005), highlighting their important role in glacier response to climate.

~~Although understanding the dynamics of lake-terminating glaciers is of critical importance for better watershed management and for unravelling the climatic signal in calving glaciers~~

~~, few lake-calving glaciers have been studied worldwide. Work~~ Recently, there has been an increase in the number of studies examining the response of freshwater-calving glaciers to climate change. Most of the research exploring the dynamics of lake-calving glacier systems has focused on ~~Mendenhall Glacier in Alaska (Motyka et al., 2003; Boyce et al., 2007)~~a few major regions: Alaskan glaciers Mendenhall and Yakutat (Motyka et al., 2002; Boyce et al., 2007; Trüssel et al., 2013), Tasman Glacier in ~~New Zealand (Warren and Kirkbride, 2003; Dykes et al., 2011; Dykes and Brook, 2010), and Perito Mereno Glacier in Patagonia (Warren and Sugden, 1993; Warren and Aniya, 1999; Stuefer et al., 2007)~~the Southern Alps of New Zealand (Warren and Kirkbride, 2003; Dykes and Brook, 2010; Dykes et al., 20 and several glaciers along the Patagonian Hielo Sur, most notably Perito Mereno, Nef, and Upsala Glaciers (Warren et al., 2001; Stuefer et al., 2007; Sakakibara et al., 2013). Here we present new data from Bridge Glacier, a ~~-~~lake-terminating outlet glacier of the Lillooet Icefield in the Coast Mountains of British Columbia, Canada. Bridge Glacier presents another valuable study site to supplement this worldwide database.

~~Few studies have compared mass losses from calving and surface ablation in order to assess the relative importance of calving on the mass balance of a lake-terminating glacier. A better understanding of the glaciological, lacustrine, and climatological conditions related to calving is needed to assess the drivers that promote ice loss. Furthermore, these data will help elucidate the broad commonalities between calving glaciers worldwide, allowing for a more universal understanding of calvingin freshwater glacier-lake systems~~In calving systems, the long-term retreat of the glacier has been found to follow a step-like pattern, where periods of stability are followed by a dramatic retreat, often coinciding with terminus flotation (Warren and Kirkbride, 2003; Boyce et al., 2007; Dykes et al., 2011). In many cases, terminus flotation is achieved through thinning near the terminus due to successive years of high melt rates. At Mendenhall Glacier (Motyka et al., 2002), climate induced thinning led to increased instability and propensity to calve, and eventually to the collapse of the terminus and retreat into shallower waters (Boyce et al., 2007). Similar findings have been made at Tasman Glacier in New Zealand (Warren and Kirkbride, 2003; Dykes and Brook, 2010), and in Patagonia (Warren and Sugden, 1993; Warren and Aniya, 1999; Skvarca et al., 2002), suggesting that retreat due to climatic warming may enhance calving rates over decadal time scales. Additionally, flotation can cause thinning due to an increase in terminus flow speeds (Rivera et al., 2012; Sakakibara et al., 2013), creating a positive feedback loop enhancing calving, and accelerating retreat rates.

This study investigates ~~the relative importance of current and historical~~ ice loss due to calving and surface melt at lake-terminating Bridge Glacier. ~~Ice lossfrom surface melt and calving~~ Here we define ‘ice loss’ as ablation of glacier ice from calving and surface melt (Cogley et al., 2011), and do not include snow and firn losses. Surface melt and the calving flux are estimated for the 2013 melt season from field measurements and a distributed energy balance ~~and~~ model. These results are then used to calibrate a mass balance model and calving model, which are applied to reconstruct calving ~~models, and are compared to calving~~ fluxes and surface melt ~~rates~~ from 1984 to ~~present. This study contextualizes calving rates~~ 2013. Calving rates and retreat from Bridge Glacier ~~using~~ are then compared with findings from other lacustrine calving glaciers in Alaska, New Zealand and Patagonia~~to highlight how the relative importance of calving~~ . Commonalities in the nature and timing of the calving flux and surface melt ~~change~~ allow for a broad understanding of the temporal pattern of ice loss over the transient calving phase of a retreating alpine lake-terminating glacier.

2 Study ~~area and retreat history~~Area

Bridge Glacier (50°48~~′~~'11~~″~~"N, 123°38~~′~~'40~~″~~"W), an outlet of the Lillooet Icefield, is located in the Pacific Ranges of the Coast Mountains of southwestern British Columbia, Canada, roughly 175 km north of Vancouver (see Figure 1). The glacier had an area of 83 ~~as of the end of the~~ km^2 as of September 2013~~melt season~~, extending from an elevation of over 2900 m at Bridge Peak, to 1390 m, where it terminates in a proglacial lake, locally known as Bridge Lake~~(see Fig. 1). The lake has grown from under 2 in 1972 to over 6 in 2013 as the glacierretreated across an overdeepened basin. The glacier has experienced large tabular calving events since the early 1990s, indicative of a floating terminus. The far (east) end of the lake traps numerous~~

~~large (several hundred) icebergs which are pressed along a submerged terminal moraine by persistent katabatic winds, and have been present, in most cases, for several years.~~

. 71% of the glacier's area is located above 2100 m, which is approximately the average end-of-season snowline. Bridge Glacier lies on the ~~divide between~~ lee side of the humid coastal Pacific Ranges and terminates in a valley in the drier interior Chilcotin Ranges. Synoptic air flow is predominantly from the west, generating heavy snowfall on the highest elevation, most westerly areas, while the eastern flank of the glacier is drier, with a mean May 1 SWE of 600 mm (BC Ministry of Environment, 2014).

~~The annual retreat of Bridge Glacier, derived from delineations of the terminus using repeat Landsat imagery since~~

Bridge Lake has grown from under 2 km^2 in 1972 ~~(Fig. 2), is comprised of several stages. Retreat was slow prior to 1991, characterized by small calving events along the shallow proglacial lake margin. The average rate of retreat between 1972 and 1991 was 21 , but accelerated to 144 after 1991, punctuated by high annual retreat rates followed by years of relative terminus stability, and the appearance of large tabular icebergs~~ to over 6 km^2 in ~~the lake. The rate of retreat accelerated again after 2009 to ∼ 400 (Fig. 7e)~~ 2013 as the glacier retreated across an overdeepened basin (see Figure 2). The distal (east) end of the lake traps numerous large (several hundred m^2) tabular icebergs which are pressed along a submerged terminal moraine by persistent katabatic winds, and have been present, in most cases, for several years.

~~The substantial retreat that Bridge Glacierhas undergone since 1991 cannot be fully explained by regional climate indicies (Fig. 7). For instance, from 1988 to 1998, summer temperatures, equilibrium line altitudes, and discharge from Bridge Lake were all above the 30 year average (Fig. 7a–d) , suggesting above average melting of the glacier surface. This period of elevated conditions for melt did not continue into the 21st century, however, retreat continued to accelerate. Since the mid-1990s, it appears that retreat was decoupled from climate . While it is clear the acceleration of retreat as of 1991 is largely due to accelerated rates of calving, it remains unclear to what extent calving contributed to the total volume of ice loss from Bridge Glacier over the past 30~~

Daily streamflow is measured by the Water Survey of Canada site "Bridge River (South Branch) Below Bridge Glacier" (Water Survey of Canada, 2015), and is available from 1978 to present. The hydrometric site is located less than 2 km downstream of the distal (east) end of Bridge Lake, and 60% of its catchment area (144 km^2) is occupied by Bridge Glacier. Temperature and precipitation for the region are obtained from Environment Canada climate station Vancouver International Airport, BC (49°12’ N 123°11’ W, elevation = 4 m, ID #1108447) (Environment Canada, 2015). Air temperature at the Vancouver climate station is a significant predictor of both mean annual flow at the Bridge River gauge and of Bridge Glacier ELAs, suggesting it is an adequate broad-scale climatic proxy.

3 Field ~~methods~~Methods

3.1 Weather Data

Three automatic weather stations (AWS) collected data from ~~20 June to~~ June 20 to September 12~~ September~~, 2013, to provide input data for a distributed energy balance melt model (see ~~Fig.~~ Figure 1). One weather station was installed on-glacier (Glacier AWS) and collected air temperature, humidity, wind speed and direction, and reflected shortwave radiation at 10 ~~min~~ minute intervals. A second weather station (Ridge AWS), installed on a ~~ridge ∼ 250~~ ridge ∼250 m above the glacier toe and hence shielded from strong, persistent katabatic flow, collected ambient temperature and solar radiation. A third weather station, located along the shore of Bridge Lake (Lake AWS) approximately 3 km from the terminus, on a partially submerged end moraine, measured incoming longwave radiation, air temperature, humidity, wind speed, and rainfall. Rainfall was also measured at an exposed nunatak north of the main arm of the glacier (Nunatak TLC), to estimate the precipitation gradient over the glacier tongue. Incoming shortwave and longwave radiation was collected off-glacier due to our inability to ensure the sensor remained level at Glacier AWS.

In order to ground-truth surface melt derived from from melt modelling, ~~3 m-long~~ 3-m-long ablation stakes were installed at six locations in the ablation area between 1500 and 1600 m. Due to logistical challenges, and to obtain results that could also be used to ground-truth velocity estimates, the stakes were located within 2 km of the terminus (~~Fig.~~ Figure 1). The stakes were installed on ~~18 June ,~~ June 18, and were resurveyed and ~~resurveyed on 19 July and~~ re-drilled on July 19 and September 13~~ September~~ , 2013.

~~The bathymetry of Bridge Lake was~~

3.2 Bathymetry

Bathymetric data were collected using a Lowrance HDS Gen2 depthsounder, with a depth range of 500 m and horizontal GPS accuracy of ±5 ~~. Depth~~ m. Due to the presence of large, unstable icebergs throughout the lake, depth measurements were taken at 893 discrete points in an irregular grid. Access to the terminus and the middle part of the lake was hindered by the presence of icebergs~~. An~~ , necessitating the inclusion of an additional 74 points which were added by linear interpolation using known depths along east-west transects~~to improve coverage~~. The bathymetric data were processed using the gstat package in R ~~(R Core Team, 2013; Pebesma, 2004)~~(R Core Team, 2013; Pebesma, 2004), and interpolated onto a 10 m grid using inverse distance weighting. Water depth for the 2013 calving flux was estimated from a cross-section parallel to, and roughly 500 m from, the June 2013 terminus position.

~~The change in terminus area during the study period was computed from Landsat images on 23 June and 11 September 2013. Shapefiles for both scenes were generated by manually delineating the terminus in Google Earth. The change in area was then calculated using the rgeos package in R.~~

3.3 Flow Speed

The terminus flow velocity was measured by tracking features from two time-lapse cameras (at Nunatak TLC, and ~~1.5 east~~Lake TLC) set up to capture the floating terminus and the glacier surface roughly 1 km up-glacier. Points were tracked manually using Tracker video analysis and modelling tool (Brown, 2014). Raw pixel displacement was converted into distances using known camera angles and several ground control points following Harrison et al. (1992) and Eiken and Sund (2012) (see Chernos, 2014, Chapter 4 for further details). Eight points in close proximity on the glacier surface (~~< 200~~ < 200 m) were tracked from each camera throughout the study period using daily noon-time images. Filtering routines discarded roughly 10 ~~%~~ % of the tracked data points due to negative displacement ~~,~~ or loss of target. Daily surface velocities were generated by averaging the daily displacements for each tracked point, and the average summer velocity was calculated by averaging the total displacement for each tracked point throughout the study period. Study-period time-lapse velocity measurements were complemented with an end-of-summer survey of ablation stakes; results were found to agree within the error of our Garmin eTrex GPS (±5 ~~-~~m).

4 ~~Modelling surface melt~~

3.1 Satellite Imagery and Elevation Data

The change in terminus area during the 2013 study period was computed from Landsat images on June 23 and September 11, 2013. Shapefiles for both scenes were generated by manually delineating the terminus in Google Earth. The change in area was then calculated using the rgeos package in R (R Core Team, 2013). Annual terminus positions and equilibrium line altitudes (ELAs) from 1984 to 2012 were reconstructed from Landsat imagery. All Landsat images were taken between September 12 and October 24 to represent end-of-season snowlines. Annual terminus retreat rates (ma^{-1}) were calculated by measuring the areal retreat, averaging it by the terminus cross-section (width), and correcting for a full calendar year.

In order to impose the snowline elevation in the distributed energy balance model for the the 2013 melt season, observed snowline locations were reconstructed from nine Landsat images obtained from the LandsatLook Viewer (U.S. Geological Survey, 2014) between June 1 and September 19, 2013. Multiple measurements of snowline altitude across the glacier surface were taken for each image, and averaged to produce a basin-wide snowline elevation.

Elevation data for the glacier surface were obtained using a 25 m resolution LIDAR digital elevation model from 2006 (from C-CLEAR by M. Demuth, C. Hopkinson, and B. Menounos, see Acknowledgements). The DEM was resampled to 50 m to reduce computation time and digital artifacts in the data. ~~To obtain historical estimates of surface melt, annual terminus retreat and equilibrium line altitudes (ELAs) were reconstructed from satellite imagery, using Landsat images from 1984 to 2012. All Landsat data were taken from images between 12 September and 24 October to represent end-of-season snowlines.~~

~~The volume of ice lost by surface melt during the 2013 summer season was computed with a~~

4 Modelling Surface Melt

4.1 Approach

We applied a distributed energy balance model ~~using the~~ driven by data from the three AWS and ~~the~~ a digital elevation model of the glacier surface ~~.~~ from 2006. As our purpose was to calculate the total ice loss during the summer melt season, we only consider ice melt (not snow or firn melt), and hence we only modelled surface melt for the area of exposed glacial ice below the snowline at each time step. Temporal interpolation between snowline elevations from Landsat data (see Section 3.1) was achieved using the loess smoothing function in R.

Surface melt of ice (M), in ~~, was calculated as~~

$$\cancel{M = \frac{Q_\mathrm{M}}{L_\mathrm{f}\rho_\mathrm{i}}}$$

~~where Q_M~~ m (w.e.) d^{-1}, is calculated as

$$M = \frac{Q_M}{L_f \rho_i} \qquad (1)$$

where Q_M is the sum of available energy at the surface (~~), L_f~~ W m^{-2}), L_f is the latent heat of fusion (3.34×10^6 J kg^{-1}) , and ~~ρ_i~~ ρ_i is the density of ice (917 kg m^{-3}). Energy supplied to the glacier surface is positive, while energy flux away from the surface is negative. The available energy for melt ~~was calculated as~~

$$\cancel{Q_{\mathrm{M}} = Q^* + Q_{\mathrm{H}} + Q_{\mathrm{E}} + Q_{\mathrm{R}}}$$

~~where Q^*~~ is calculated as

$$Q_M = Q^* + Q_H + Q_E + Q_R \tag{2}$$

where Q^* is the net radiation, ~~Q_{H} and Q_{E}~~ Q_H and Q_E are the sensible and latent heat flux, and ~~Q_{R}~~ Q_R is sensible heat of rain. All energy fluxes are in Wm^{-2}. We assume that all energy fluxes occur at the ice surface (Oerlemans, 2010; Munro, 2006); subsurface and subglacial melt is neglected.

4.2 ~~Snowline retreat~~Net Radiation

~~As our purpose was to calculate the total ice loss during the melt season only, we only consider ice melt and not snowmelt, and hence the model was only applied to the glacier surface below the snowline at each time step. In order to calculate the volume of ice melt at each time step, snowline retreat over the course of the summer melt season was reconstructed from nine Landsat images obtained from the LandsatLook Viewer (U.S. Geological Survey, 2014) between 1 June and 19 September 2013. Multiple measurements of snowline altitude across the glacier surface were taken for each image, and averaged to produce a basin-wide snowline elevation. Temporal interpolation between snowline elevations was achieved using the loess smoothing function in R. The snowline was at the terminus until 15 June, and the ablation area had become snow-covered again before 20 September, suggesting our field instrumentation captured all but 12–15 days of melt in the 2013 season. We estimate that ice loss during this period is less than 10 % of the total surface ice loss during the study period.~~

4.3 ~~Net radiation~~

Net radiation (~~Q^*~~Q^*) is calculated as the sum of incoming (↓) and outgoing (↑) shortwave and longwave (L) radiation as follows:

$$Q^* = (S\downarrow + D\downarrow)(1-\alpha) + (L\downarrow - L\uparrow)$$

$$Q^* = (S\downarrow + D\downarrow)(1-\alpha) + (L\downarrow - L\uparrow) \tag{3}$$

where shortwave radiation (K) is separated into direct (S) and diffuse (D) components, and α is the albedo of ice.

Reflected shortwave radiation was measured on-glacier ~~and on~~ over bare ice in the ablation area, throughout the melt season. Incoming shortwave radiation was measured from the off-glacier Ridge AWS. Differences in shading between the two sites were found to be negligible. To minimize the effects of small discrepancies in shading, uneven cloud patterns, and low solar angle errors (Oerlemans, 2010), the daily ice albedo (α) is assumed constant throughout the day, and is calculated as

$$\alpha = \textstyle\int K\uparrow \mathrm{d}t / \int K\downarrow \mathrm{d}t$$

$$\alpha = \int K\uparrow dt / \int K\downarrow dt \tag{4}$$

where the integrals are over the period of daylight each day. Albedo was only estimated from Glacier AWS, and was kept constant across the glacier. Although this limits the model's representativeness over the whole glacier, given the model is only applied over exposed glacial ice, this simplification is not expected to have an appreciable impact on the volume of melt modelled.

Direct shortwave radiation ($\mathrm{W m^{-2}}$) for each gridpoint on the glacier surface is calculated as

$$\cancel{S\downarrow_{i,j} = S\downarrow \frac{K_{\mathrm{ex}_{i,j}}}{K_{\mathrm{ex}}}}$$

~~where $K_{\mathrm{ex}_{i,j}}$~~

$$S\downarrow_{i,j} = S\downarrow \frac{K_{ex_{i,j}}}{K_{ex}} \tag{5}$$

where $K_{ex_{i,j}}$ is the potential direct solar radiation at grid point (~~i,j) and K_{ex}~~ i,j) and K_{ex} is the potential direct solar radiation at Glacier AWS. Measured global radiation was separated into direct and diffuse components based on the ratio of observed to potential shortwave radiation following Collares-Pereira and Rabl (1979) and Hock and Holmgren (2005). Potential direct radiation was corrected for slope geometry and diffuse shortwave radiation is calculated for all cells when ~~$K_{\mathrm{ex}} > 0$ (Hock and Holmgren, 2005; MacDougall and Flowers, 2011) as~~

$$\cancel{D_{i,j} = D_{\mathrm{o}}\phi_{i,j} + \alpha_{\mathrm{terrain}} K\downarrow (1-\phi_{i,j})}$$

~~where D_{o}~~ $K_{ex} > 0$ (Hock and Holmgren, 2005; MacDougall and Flowers, 2011) as

$$D_{i,j} = D_{o}\phi_{i,j} + \alpha_{terrain} K\downarrow (1-\phi_{i,j}) \tag{6}$$

where D_o is the global diffuse radiation, ~~corrected using the sky view factor (ϕ) for each grid cell~~and $\phi_{i,j}$ is the skyview factor at each grid point (i,j).

Due to the complications and heterogeneity involved in measuring the albedo for the surrounding non-glaciated terrain (~~$\alpha_{\mathrm{terrain}}$~~$\alpha_{terrain}$), a constant value of 0.17 was assumed, which is ~~within the range for~~ typical of dark, rocky surfaces (Oke, 1988). Sky view factor was calculated using SAGA GIS software and a 25 m lidar DEM. The algorithm integrates the maximum horizon angles (H) for each grid cell, for each azimuth angle (1° interval). A ~~maximum $10\,\mathrm{km}\times 10$~~ maximum 10×10 km search window was implemented to reduce computation time.

In order to spatially distribute incoming shortwave radiation, each grid point is modelled as either shaded or sunlit. A ~~-~~shading algorithm was implemented that calculates the maximum horizon angle for each grid point within a ~~10 km × 10~~ 10×10 km window, using 10° azimuth bins. At each time step, if the horizon angle is greater than the elevation angle (Z), the grid point is shaded, and only receives diffuse radiation. For times when the horizon angle is smaller than elevation angle, the grid point receives both direct and diffuse radiation.

Incoming longwave radiation was measured directly at the Lake AWS~~. In order to distribute longwave radiation across the glacier, it is scaled by the sky view factor (ϕ) as~~

$$\cancel{L\downarrow_{i,j} = L\downarrow_{\text{aws}} \frac{\phi_{i,j}}{\phi_{\text{aws}}} + L_{\text{terrain}}(1-\phi_{i,j})}$$

~~where additional longwave input is supplied by the surrounding terrain (L_{terrain}). Terrain temperature is assumed to equal air temperature, and the Stefan–Boltzmann equation is used with an emissivity ($\varepsilon_{\text{terrain}}$) of 0.95 and an ice emissivity (ε)~~ , and was computed at each grid point as follows:

$$L\downarrow_{i,j} = L\downarrow_{aws} \frac{\phi_{i,j}}{\phi_{aws}} + L_{terrain}(1-\phi_{i,j}) \tag{7}$$

where $L_{terrain}$ is the longwave radiation emitted by surrounding terrain. Longwave radiation emitted by the terrain was computed using the Stefan-Boltzmann law with a terrain emissivity of 0.95 (Oke, 1988) and the assumption that terrain temperature is equal to air temperature. Although atmospheric longwave radiation over the glacier and at an off-glacier site could be expected to differ due to the effects of katabatic flow on near-surface air temperature and humidity, the difference in humidity between Glacier and Lake AWS was less than 10%, while air temperatures at Lake AWS are 1.6°C warmer. Also, Shea (2010) measured incident longwave at on-glacier and off-glacier sites at the same elevation at Place Glacier and found little systematic difference over all sky conditions.

Longwave radiation emitted by the ice surface was computed from the Stefan-Boltzmann law using an emissivity of 0.98 (Oke, 1988). The surface temperature was set to 273.15 K. This assumption of a continuously melting ice surface is reasonable considering that on-glacier air temperature was always above 0°C during the study period, and only below 2°C for 3 hours.

4.3 Turbulent ~~heat fluxes~~Heat Fluxes

Sensible and latent heat fluxes are calculated using the bulk transfer approach:

$$Q_{\mathrm{H}} = \rho_{\mathrm{air}} c_{\mathrm{a}} C u (T_{\mathrm{g}} - T_{\mathrm{s}})$$

$$Q_{\mathrm{E}} = \rho_{\mathrm{air}} L_{\mathrm{v}} C u \left(\frac{0.622(e_{\mathrm{g}} - e_{\mathrm{s}})}{P} \right)$$

~~where c_{air}~~

$$Q_H = \rho_{air} c_a C u (T_g - T_s) \tag{8}$$

$$Q_E = \rho_{air} L_v C u \left(\frac{0.622(e_g - e_s)}{P}\right) \tag{9}$$

where c_{air} is the specific heat capacity of air (1006 J kg^{-1}K^{-1}), u is the windspeed (~~), T_{g}~~ ms^{-1}), T_g is the on-glacier air temperature, ~~T_{s}~~ T_s is the glacier surface temperature (held constant at 273.15 ~~), L_{v}~~ K), L_v is the latent heat of vaporization (2.50 $\times 10^6$ ~~), e_{g} and e_{s}~~ J kg^{-1}), e_g and e_s are the vapour pressures (hPa) of air and glacier surface (held constant at 6.11 hPa, assuming the glacier surface is at the melting point), and P is the atmospheric pressure (hPa) at Glacier AWS. The turbulent transfer coefficient C (unitless) is calculated using bulk Richardson ~~Numbers~~numbers, using a roughness length for momentum of 2.5 ~~for ice (Munro, 1989)~~mm for ice (Munro, 1989, 2006; Pellicciotti et al., 2005), and calculating the roughness length for temperature and vapour following Hock (1998).

Air temperature was distributed over the glacier surface using the approach developed by Shea and Moore (2010), which accounts for the effects of katabatic flow. In this approach, the magnitude of katabatic forcing was modelled as a function of the temperature difference (ΔT) between the on-glacier Glacier AWS ($\cancel{T_{\mathrm{g}}}T_g$) and off-glacier Ridge AWS ($\cancel{T_{\mathrm{a}}}T_a$, outside the katabatic boundary layer). Temperature differences were separated into upslope (northeasterly) and downslope katabatic (southwesterly) flows, based on the wind directions of Glacier AWS. Linear regression against off-glacier temperature (~~T_{a}, Fig.~~ T_a, Figure 3) shows a positive linear increase in ΔT, indicating the magnitude of katabatic forcing increases with increasing off-glacier air temperatures. Conversely, ΔT does not significantly vary as a function of off-glacier temperatures during upslope flow, although temperatures above 10 ~~°~~°C during these episodes were rare. The elevations of both weather stations are within 100 m, and small corrections to potential temperature using a ~~$-6\,^{\circ}\mathrm{C}$~~ $-6°\mathrm{C\ km^{-1}}$ lapse rate did not produce a meaningful difference in the linear fit.

On-glacier air temperature for each grid point is modelled as a function of the katabatic temperature depression where

$$\cancel{T_{\mathrm{g}} = T_{\mathrm{a}} - (k_1 T_{\mathrm{a}} + \Delta T^*)}$$

~~and ΔT^*~~

$$T_g = T_a - (k_1 T_a + \Delta T^*) \tag{10}$$

and ΔT^* is the threshold temperature differential at which katabatic flow is observed. The magnitude of katabatic forcing for each point on the glacier, k_1, is calculated using statistical coefficients and glacier flow path lengths ~~(Shea, 2010; Chernos, 2014)~~(Shea, 2010; Chernos, 2014). Flow path lengths for the glacier were calculated using the Terrain Analysis ~~–~~ - Hydrology module of SAGA GIS (Quinn et al., 1991; SAGA Development Team, 2008). During periods when wind direction is upslope, temperatures are distributed using the on-glacier temperature, $\cancel{T_{\mathrm{g}}}T_g$, and a ~~standard~~ temperature lapse rate of ~~$-6\,^{\circ}\mathrm{C}$~~ $-6°\mathrm{C\ km^{-1}}$ (Stahl et al., 2008).

Wind speed across the glacier was distributed as a function of katabatic forcing and ambient temperatures, following Shea (2010). For situations when the measured on-glacier wind direction was downslope, wind speed increases linearly with increasing off-glacier air temperature, while upslope wind speeds show no significant change. When the measured on-glacier wind direction is upslope, wind speed is held constant, using measured wind speeds from Glacier AWS.

Vapour pressure is calculated from measured relative humidity and saturation vapour pressure (~~e_{sat})~~ e_{sat}) which was calculated using Teten's formula (Murray, 1967). Relative humidity, measured at Glacier AWS, is held spatially constant across the glacier for each timestep, and saturation vapour pressure is calculated from distributed on-glacier air temperatures.

4.4 Melt ~~contribution~~ Contribution from ~~rain~~Rain

Energy supplied to the surface due to rain was calculated ~~as~~

$$\cancel{Q_{\mathrm{R}} = \rho_{\mathrm{w}} c_{\mathrm{w}} R T_{\mathrm{R}}}$$

following Hock (2005):

$$Q_R = \rho_w c_w R T_R \tag{11}$$

where R is the rainfall rate ($\mathrm{ms^{-1}}$), measured at the Lake AWS (and missing values are filled with measured data from Nunatak TLC), and ~~ρ_{w} and c_{w}~~ ρ_w and c_w are the density (1000 $\mathrm{kgm^{-3}}$) and specific heat of water (4180 $\mathrm{J\ kg^{-1}K^{-1}}$). The temperature of rain, ~~T_{R}~~T_R, is assumed equal to the ambient off-glacier air temperature, and is corrected for elevation using a ~~standard~~ $-6°\mathrm{C\ km^{-1}}$ lapse rate. Since we found no significant elevational or east-west precipitation gradient, rainfall is held constant across the glacier.

5 Modelling ~~calving flux~~Calving Flux

Calving losses are calculated from measured retreat rates and flow speeds, as well as estimates of ice thickness derived from bathymetry. The volume of ice discharged through calving from the glacier terminus, ~~Q_{calving} (~~$Q_{calving}$ (m^{3}a^{-1}), i.e., the calving flux, ~~can be quantified as~~

$$\cancel{Q_{\mathrm{calving}} = \left(\frac{\mathrm{d}A_{\mathrm{T}}}{\mathrm{d}t} + UW\right) H_{\mathrm{I}}}$$

~~where $\frac{\mathrm{d}A_{\mathrm{T}}}{dt}$~~ is quantified as

$$Q_{calving} = \left(\frac{dA_T}{dt} + UW\right) H_I \tag{12}$$

where $\frac{dA_T}{dt}$ is the change in glacier surface area at the terminus (m^{2}a^{-1}), U is the terminus flow velocity (~~), H_{I} and~~ ma^{-1}), and H_I and W are the ice thickness (m) and glacier width (m) at the terminus. Subaqueous melt at the ice front is assumed to be negligible with respect to the magnitude of the calving flux.

The thickness of ice at the terminus was approximated by assuming that the terminus is ~~floating~~right at the threshold for flotation. Using the height above buoyancy criterion (Van der Veen, 1996; Benn et al., 2007b), the ice thickness (~~H_{I}~~H_I) can be calculated as

$$\cancel{H_{\mathrm{I}} = H_{\mathrm{b}} + \frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{i}}} D_{\mathrm{W}}}$$

~~where H_{b}~~

$$H_I = H_b + \frac{\rho_w}{\rho_i} D_W \tag{13}$$

where H_b is the height of ice above the waterline (m), ~~D_{W}~~ D_W is the water depth, while ~~ρ_{w} and ρ_{i}~~ ρ_w and ρ_i are the densities of water and ice. ~~The validity of this assumption is supported by the observation that~~ During the melt season, large tabular icebergs ~~that calved during the melt season~~ calved and showed limited mobility~~immediately after calving~~, suggesting that the glacier is ~~close to~~ at or near the boundary criterion for flotation. There is a notable inflection point (~~Fig. 4) , where it is assumed~~ Figure 4) roughly 500 m from the end-of-season terminus, where the surface slope becomes flat or slightly reclined, which has remained stationary since 2012, and where we assume that the terminus transitions from grounded to floating.

The calving flux between 1984 and 2012 was computed from historical terminus positions, average retreat area water depth, taken from lake bathymetry (~~Fig.~~ Figure 5), estimated ice thickness, and measured velocity from the 2013 field season. ~~Historical terminus velocities were assumed to be approximately equal to the 2013 summer flow speed (140), and annual calving rates are calculated with 70 (50 %) potential variability around the 2013 mean.~~

~~From the repeat Landsat imagery, it is clear that the terminus became ungrounded and achieved flotation around 1991. Given that terminus velocities are presumed to be a function of basal drag (Benn et al., 2007a), once the terminus achieved flotation it is likely that terminus flow speeds have not changed dramatically since then. However, we recognize that terminus velocities were likely slower when the calving front was grounded, and hence we are likely overestimating calving rates prior to 1991.~~

6 Historical Ablation

~~A 60 uncertainty in measuring the terminus cross-section (W) (equal to 2 Landsat pixels) is applied. The uncertainty of $\frac{\mathrm{d}A}{\mathrm{d}t}$ is estimated as 7200 ($2\,\mathrm{m} \times 60\,\mathrm{m} \times 60\,\mathrm{m}$). The ice thickness uncertainty is estimated as 5.6 % plus an additional 10 to account for changes in sedimentation and ice thickness relative to water depth. Before 1991, the terminus was not floating; therefore, an ice thickness uncertainty of 60 is estimated to account for a range of grounded terminus geometries. Between 1991 and 2004, bathymetry has poor data coverage, and a ice thickness uncertainty of 33 is estimated.~~

7 ~~Historical surface melt~~

~~In order to understand the long-term mass loss at Bridge Glacier, estimates of historical surface melt~~ Estimates of historical annual surface melt rates are derived using ELA observations and a ~~fitted~~ fitted piece-wise linear mass balance gradient derived using mass balance observations from several glaciers in the region, including Bridge Glacier (Shea et al., 2013). Below the snowline, the net balance (~~where $b_\mathrm{n} = b_\mathrm{w} + b_\mathrm{s}$)~~ b_n) at a point is equal to the ~~glacier ice loss~~surface melt of exposed glacier ice, and is estimated using ~~the 2013 glacier hypsometry, where~~

$$b_\mathrm{n}(z) = b_1(\mathrm{ELA} - z)$$

glacier hypsometry from the 2006 lidar DEM, where

$$b_n(z) = b_1(ELA - z) \tag{14}$$

and is calculated for the elevation of every point, z (m a.s.l.), below the ELA.

The coefficient value ($b_1 = 6.62$ mm (w.e.)/m) taken from Shea et al. (2013) underestimates the volume of ~~ice loss~~ glacial ice ablation during the 2013 melt season calculated from the distributed energy balance model. Coefficient b_1 is derived from the mass balance gradient from the DEBM (9.07 mm (w.e.)~~, Fig.~~/m, Figure 6), and is used for all years.

The glacier area is determined from the end-of-season calving margin. ~~Calved area is~~ Previously calved areas are given an elevation of 1400 m (a.s.l.) and are considered in ~~Eq. (14). Historical ELAs are measured from end-of-summer (mid-September to mid-October)Landsat images from 1984 to 2013.~~ Equation 14.

~~Errors in ELA-derived mass balance calculations are estimated by assuming a 75 uncertainty in measuring the ELA, due to timing of available Landsat images, or 22 % according to Shea et al. (2013), whichever is greater. The ELA uncertainty estimate is~~

7 Results

7.1 Climatic Indicators and Retreat

The annual retreat of Bridge Glacier is composed of several stages. Retreat was slow prior to 1991, characterized by small calving events along the shallow proglacial lake margin. The average rate of retreat between 1972 and 1991 was 21 ma^{-1}, but accelerated to 144 ma^{-1} after 1991, punctuated by high annual retreat rates followed by years of relative terminus stability, and the appearance of large tabular icebergs in the lake. The rate of retreat accelerated again after 2009 to ~~account for errors that cannot be adequately quantified without additional historical data, such as the linearity of the mass balance gradient~~ ∼400 ma^{-1} (Figure 7e). Since 1991, the glacier has retreated over 3.55 km, punctuated by the production of large tabular icebergs, indicative of a floating terminus.

The substantial retreat that Bridge Glacier has undergone since 1991 does not fully follow regional climatic trends (Figure 7). For instance, from 1988 to 1998, summer temperatures, equilibrium line altitudes, and mean annual flows from Bridge River were all above the 30-year average (Figure 7a-d), suggesting above average melt. However, this period of elevated melt conditions did not continue into the 21st century as retreat continued to accelerate. Since the mid-1990s, it appears that retreat was decoupled from climate (Stahl et al., 2008). While it is clear the acceleration of retreat as of 1991 is largely due to elevated rates of calving, it remains unclear to what extent calving contributed to the total volume of ice loss from Bridge Glacier over the past 30 years.

8 ~~Results~~

7.1 The 2013 ~~surface melt~~Surface Melt

From ~~20 June to~~ June 20 to September 12 ~~September~~ , 2013, our model predicted ~~1.0 of surface ice loss of near the ELA to~~ surface melt ranging from 5.9 ~~-~~m w.e. near the terminus to 0 at the ELA, yielding a ~~total mass~~ total ice loss of 0.124 ~~(Fig.~~ km^3 (Figure 8). Melt rates are greatest along the main tongue of the glacier, due to high sensible heat flux driven by persistent katabatic flow. The southernmost tributary glacier shows relatively low melt rates relative to its elevation, most likely due to the fact that it remained sheltered from high winds and its north-facing aspect allowed for substantial shading throughout the melt season.

7.1.1 Error Analysis

The snowline was at the terminus until June 15, and the ablation area had become snow-covered again before September 20, suggesting our field instrumentation captured all but 12-15 days of melt in the 2013 season. We estimate that ice loss during this period is less than 10% of the total surface ice loss during the study period.

Modelled melt agreed within ±0.2 ~~m~~ m w.e. for four of the five ablation stakes (~~Fig.~~ Figure 9), representing an error of less than 5 ~~%~~ % of the measured value. Measured melt at ablation stake D, located roughly 400 ~~m~~ m up-glacier (~~∼ 100~~ ∼100 m increase in elevation) from Glacier AWS and stake A, is up to 0.8 ~~m~~ m less than other nearby stakes (including stake E, which is ~~200~~ 100 m higher in elevation, and further up-glacier), suggesting that there may have been errors in measurement, or localized effects shielding the stake from higher melt rates observed elsewhere in the ablation area.

~~7.2 The 2013 calving flux~~

~~The terminus retreated 65 over 85 days~~

7.2 The 2013 Calving Flux

Over the 85-day study period in 2013, ~~with a~~ a change in terminus area ~~of −0.297~~ (dA_T) of -0.297 km^2 was measured from repeat terminus delineations. The average velocity at the terminus (U) was 139 ~~m~~ ma^{-1} (see Figure 5), across a ~~width~~ width (W) of 1055 ~~m~~ m, yielding an ~~additional~~ ice loss of 0.0342 ~~km^2~~ km^2 due to calving.

~~Water depth was estimated from a cross-section parallel to, and roughly 500 from, the June 2013 terminus position. The median depth was 109~~ The median water depth was 91 m, corresponding to a height above buoyancy of 9.9 ~~m~~ m, and an estimated ice thickness of 109 ~~m~~ m. Combining these measurements in ~~Eq. (12)~~ Equation 12 yields an estimated calving flux of 0.0362 ~~for the 85 day~~ km^3 for the study period.

Comparing the volume of ~~mass~~ ice lost through calving with ~~the volume of surface ice~~ surface melt during the same period yields a ~~total mass~~ total loss of 0.160 ~~of ice~~ km^3. For the 2013 melt season, calving accounts for 23 ~~% of the mass~~ % of the total ice loss, equivalent to an additional 1.3 m of surface melt over the entire ablation area.

7.3 ~~Historical ice loss~~

~~The volume of ice lost from surface melt over the past 30 was predominantly a function of the position of the ELA, and showed only a minor decrease over time.~~

7.2.1 Error Analysis

A 60 m uncertainty in measuring the terminus cross-section (W) (equal to 2 Landsat pixels) is applied. The uncertainty of $\frac{dA}{dt}$ is estimated as 7200 m^{2}a^{-1} (2 $\times$ 60 m $\times$ 60 m). Bathymetric error is calculated at 5.6%, and was found by differencing 2 bathymetric models produced using a randomly selected half of the collected water depth point-measurements. The ice thickness uncertainty is estimated as 5.6% plus an additional 10 m to account for changes in sedimentation and ice thickness relative to water depth. Before 1991, the terminus was not floating; therefore, an ice thickness uncertainty of 60 m is estimated to account for a range of grounded terminus geometries. Between 1991 and 2004, bathymetry has poor data coverage, and a ice thickness uncertainty of 33 m is estimated. Historical terminus velocities were assumed to be approximately equal to the average 2013 summer flow speed (140 ma^{-1}), and annual calving rates are calculated with 70 ma^{-1} (50%) potential variability around the 2013 mean.

7.3 Historical Ice Loss

Between 1984 and 2013, the ELA varied ~~from~~ between 1926 ~~to~~ m and 2202 m; however, in most years ~~the ELA~~ it was between 2050 m and 2150 m, resulting in a standard deviation in ~~volumetric~~ glacier ice loss of 0.018 ~~. The surface ablation~~ km^{3}a^{-1}. Surface melt in 2013 was above the ~~30 year~~ 30-year average, but within one standard deviation of the mean

(~~$\bar{x} = 0.107$~~ $\bar{x} = 0.107$ km^{3}a^{-1}). Surface melt showed a minor decrease over time, which can be attributed to the loss of surface area in the lowest reaches of the glacier due to calving and retreat.

Historical calving losses are characterized by several years of high flux, and periods of relative stability. The magnitude of the calving losses increased once the glacier achieved flotation in ~~1991. Calving losses~~ 1991, and are minimal before ~~1991, most likely due to the relative stability of a grounded terminus.~~ 1991. From 1992 to 1994, the calving flux increased to 0.020 ~~–0.029 (19–27 %~~ - 0.029 km^{3}a^{-1} (19 - 27% of the total annual ice loss), before a two year period of low flux (~~<0.015~~ $<$ 0.015 km^{3}a^{-1}). From 1997 to 2000, ~~calving losses~~ the calving flux increased again (0.023 ~~–0.052~~ - 0.052 km^{3}a^{-1}), before settling into another period of relative stability in ~~2001–2002~~2001-2002. The highest calving fluxes occurred between 2003 ~~to~~ and 2006 (0.030 ~~–0.084~~ - 0.084 km^{3}a^{-1}) and again from 2008 to 2011 (0.036 ~~–0.100~~ - 0.100 km^{3}a^{-1}) with a period of stability in ~~2006–2007~~2006-2007. As the calving flux increased ~~in the period from 2003–2011~~from 2003-2011, surface ablation rates decreased, resulting in the calving flux becoming a larger component of the total ice loss in the ~~21st~~ 21st century. The volume of ice loss due to calving was roughly equal to ~~the volume lost due to~~ surface melt in 2005, 2008 and 2010 (~~44–49 % of total volumetric ice losses~~44 - 49% of total ice loss).

7.3.1 Error Analysis

Although our historical melt model treats firn as ice, we expect the differences in surface melt volume to be smaller than our calculated error, and therefore do not expect this simplification to measurably effect the interpretation of inter-annual surface melt results. Errors in summer balance calculations are estimated assuming a 75 m uncertainty in measuring the ELA due to timing of available Landsat images, or 22% according to Shea et al. (2013), whichever is greater. The ELA uncertainty estimate is to account for errors that cannot be adequately quantified without additional historical data. For example, the linearity of the summer balance gradient appears to be strongly controlled by the date of snow disappearance, where the 2013 non-linear snowline retreat is mirrored in the non-linear summer melt gradient.

Glacier hypsometry is not adjusted during the 1984-2013 study period, and is based on a 2006 lidar survey. Although thinning invariably affects the elevation, and therefore air temperatures predicted from our lapse rate, the elevation difference between 1970 and current terminus position is estimated at less than 200 m. Moreover, ELA variability during the period is less than 300 m. Therefore (and given the relatively coarse nature of our summer balance estimates to begin with), thinning and lowering of the surface elevation likely would only have a minor effect on modelling results, and its error would be difficult to quantify. Estimated errors in the historical calving flux are covered in Section 7.2.1

8 Discussion

8.1 ~~Controls on calving~~

8.1 Controls on Calving

During the 2013 melt season, calving was a moderate contributor of ~~mass~~ ice loss relative to surface melt at Bridge Glacier. Calving losses in this system are controlled by glaciological and topographical controls that ultimately limit the magnitude of the calving flux. The glacier width at the ~~calving margin~~ flux gate was just over 1 km, which restricts the volume of ice that can reach the floating terminus, in turn limiting the size of calving events. In contrast, the ablation area in 2013 was ~~over~~ 27.6 km^2, allowing for surface melt processes to act over a much larger area and contribute a substantially larger volume of ice loss than possible from the calving front.

Relatively modest glacier flow speeds at the terminus also limit the volume of ice delivered to the terminus and calving. Flow velocity at Bridge Glacier is moderate due to gentle gradients in the lower reaches of the glacier, as well as ~~relatively narrow side-walls. A~~ a relatively narrow cross-sectional area. A gentle surface slope reduces the gravitational stresses, while narrow valley sidewalls ~~provide~~ constrict glacier flow by providing substantial lateral drag ~~(Benn et al., 2007a; Koppes et al., 2011)~~(Benn et al., 2007a; Koppes et al., 2011), both of which limit flow speeds. Near-terminus flow speeds at Bridge Glacier are one to two orders of magnitude smaller than those observed at larger tidewater calving glaciers in Patagonia and Alaska ~~(Rivera et al., 2012; Koppes et al., 2011; Meier and Post, 1987)~~(Rivera et al., 2012; Koppes et al., 201 and reflect a ~~-~~more stable character and configuration, similar to lake-terminating glaciers Mendenhall and Tasman (Boyce et al., 2007; Dykes et al., 2011).

~~Although water depths increased substantially during the highest rates of calving in the late 2000s, we do not expect major changes in terminus velocity since the terminus achieved floatation in 1991. The 2013 mean terminus water depth was within 15 of depths during the late 2000s, and was larger than the average water depth between 2004 and 2012. Given the relative consistency in water depths , and that the terminusis assumed to have remained floating throughout this most recent stage of retreat, we do not expect large changes in resisting stresses. Furthermore, a first order examination of thinning rates using Landsat images from the last two decades does not reveal major year to year changes, suggesting that basal shear stresses, and hence velocities, have not varied significantly during this time. However, maximum water depths peaked in the mid-2000s, meaning that is is possible that velocities could have been higher during this period (Van der Veen, 1996), making our calving fluxes underestimates. Conversely, it is likely that pre-1991 velocities were substantially smaller than what was measured in 2013. As such, it is unlikely that calving losses could equal the upper bounds of our estimate during this pre-floatation period.~~

~~The bathymetry of Bridge Lake also controls the calving flux. While we note that the terminus of Bridge Glacier is partially buoyant, flotation remains dependent on the ice thickness at the terminus and the water depth~~ The bathymetry of Bridge Lake also plays a driving role, where inter-annual calving fluxes mirror average and maximum water depths at the terminus. ~~Any significant thickening of the glacier, without any concurrent increase in lake level, would theoretically increase the potential volume of ice lost to calving, but would also serve to reduce the buoyancy of the terminus and allow the terminus to become grounded. Grounding would stabilize the terminus, and significantly reduce potential calving losses. In other words, any increase in terminus thickness is more likely to reduce, rather than enhance, the~~

~~calving flux~~This relationship suggests that water depths are a large-scale control on calving in lacustrine environments. In particular the onset of terminus flotation remains the largest variable responsible for initiating rapid calving losses and retreat, a finding that mirrors results elsewhere (Boyce et al., 2007; Dykes and Brook, 2010; Trüssel et al., 2013; Sakakibara et al., 2013). However, this relationship does not necessarily suggest that water depth can drive annual (or sub-annual) calving rates. While floating temperate ice tongues have been shown to be unstable (Van der Veen, 1996; Benn et al., 2007a), often leading to disintegration and dramatic retreat, several examples exist of floating termini remaining intact for multiple years. For example, at Mendenhall Glacier an unstable floating terminus remained intact for approximately 2 years (Boyce et al., 2007), while Yakutat Glacier sustained a floating ~3 km terminus for over a decade (Trüssel et al., 2013). Similar results from Bridge Glacier, where the floating terminus had multiple seasons of negligible calving (2001, 2002, 2007) suggest that water depth offers insufficient predictive power for annual calving fluxes.

8.2 The ~~relative importance~~ Relative Importance of ~~calving~~Calving

From 1984 to 2013, the calving flux increased from an almost negligible annual yield to a flux responsible for between ~~20–45 %~~ 20-45% of the annual ice loss. The trend in calving flux closely follows water depth at the terminus, where the largest calving fluxes coincide with the terminus retreating into the deepest parts of Bridge Lake in ~~2003–2011. This~~ 2003-2011. While this relationship suggests that buoyancy is a primary driver of multi-annual calving at Bridge Glacier~~. It~~, it also implies that the high rate of calving currently observed is unsustainable over the coming decades, and is instead part of a transient phase as the glacier continues to retreat up-valley and into shallower waters.

Although calving contributed less than one quarter of the total ice loss from Bridge Glacier during the 2013 melt season, during three of the last ten years the volume of ice loss due to calving is on par with the volume lost due to surface melt. However, large annual calving fluxes do not persist over several consecutive seasons, and are instead followed by several years of ~~only~~ minor calving losses, even though the terminus remained in the deepest part of the lake. The pattern of a high magnitude calving year followed by several low-flux years is consistent with the notion that glacier dynamics respond to large calving events by alleviating terminus instability and inhibiting future calving (Venteris, 1999; Benn et al., 2007b). Following a large calving event, the glacier geometry changes, and buoyant forces can be redistributed or relieved, promoting terminus stability.

The historical reconstruction of calving and surface melt losses suggests that climate is the driving factor affecting the long-term health of Bridge Glacier. Although calving has produced substantial ice losses during the last 10 years, calving fluxes in most ~~calving~~ systems are driven by deep water and/or high flow speeds (Warren and Aniya, 1999; Van der Veen, 2002; Benn et al., 2007b). Given ~~the lake bathymetry, and observed flow speeds at Bridge Glacier~~Bridge Glacier is approximately 850 m from the proximal end of Bridge Lake (Figure 4), and that the average calving rate over the last 5 years is 299 ma^{-1}, it is ~~unlikely that the terminus will remain in deep water for many more years~~probable that calving will only remain a substantial component of ice loss for another decade, suggesting that current calving losses are transient, and unsustainable. ~~The primary contribution of surface melt to Bridge Glacier's mass loss suggests that~~ Given that surface melt is the primary contributor of ice loss at Bridge Glacier, the glacier's future health is more dependent on climatic conditions~~rather than calving losses, and surface melt is expected to become even more important as the glacier nears the end of this transient calving phase~~.

8.3 Bridge Glacier and ~~other lake-calving systems~~Other Lake-Calving Systems

Bridge Glacier falls in the middle of a continuum of magnitude and frequency of calving in other lake-terminating glaciers worldwide (see Table 1). The calving rate for Bridge Glacier (281 ma^{-1} in 2013) is larger than that for smaller glaciers in New Zealand, such as Maug, Grey and Hooker (Warren and Kirkbride, 2003), and for Mendenhall Glacier in Alaska ~~(Motyka et al., 2003; Boyce et al., 2007)~~(Motyka et al., 2002; Boyce et al., 2007). Conversely, calving rates at the larger Patagonian glaciers Leon, Ameghino, and Upsala are up to an order of magnitude greater than what we found at Bridge ~~(Warren and Aniya, 1999)~~(Warren and Aniya, 1999; Sakakibara et al., 2013).

Bridge Glacier's calving rate is controlled by moderate water depths and flow speeds. Higher calving rates are associated with greater water depths and significantly larger terminus velocities. Large Patagonian and Icelandic glaciers have terminus velocities of up to 1810 ma^{-1} (Haresign, 2004), an order of magnitude greater than what we measured at Bridge Glacier (140 ma^{-1}). Conversely, smaller calving glaciers in New Zealand terminate in shallow lakes (~~<50~~ $<$ 50 m) and many have low flow speeds (~~<70~~ $<$ 70 ma^{-1}). Bridge Glacier's calving rate in 2013 (281 ma^{-1}) also agrees ~~quite~~ well with first-order linear models relating calving to water depth (Funk and Röthlisberger, 1989). Using the revised relationship from Warren and Kirkbride (2003), the modelled calving rate for Bridge Glacier is calculated as 268 ~~, i.e.,~~ ma^{-1} (within 13 ma^{-1} of the rate we observed in ~~2013.~~ 2013). Our observed calving rate ~~at Bridge~~ falls along the linear spectrum of calving and water depth for lake-calving glaciers worldwide, which is an order of magnitude lower than calving rates from tidewater systems (~~Fig.~~ Figure 12).

Lake temperatures also appear to play a role in controlling the calving rate. Many Patagonian icefields terminate in large lakes where water temperatures are up to 7.6~~°~~°C (Warren and Aniya, 1999), significantly warmer than the well-mixed 1~~°~~°C water observed at Bridge Lake (Bird, 2014). This difference is most likely related to the surface area of the proglacial lakes. Bridge Lake~~is relatively large (~~, at 6.3 ~~), but~~ km^2, is small relative to the much larger lakes of Southern Patagonia, ~~that are greater~~ which are deeper than 300 ~~deep. This depth~~ m. Given the larger surface area to depth ratio of large Patagonian proglacial lakes, combined with large areas that are free of the strong cooling influence of glacier runoff and trapped icebergs, allows for ~~these proglacial lakes to warm significantly, and promote further calving~~ significant warming, thermal undercutting and further calving (Rohl, 2006; Rignot et al., 2010; Robertson et al., 2012).

Bridge Glacier shares similar calving characteristics with both Tasman and Mendenhall Glaciers, both of which have undergone significant retreat as they transitioned from grounded to floating termini (Boyce et al., 2007; Dykes et al., 2011). During this transition, terminus velocities increased at Tasman from 69 ma^{-1} to 218 ma^{-1} (Dykes and Brook, 2010; Dykes et al., 2011), while the calving rates for both glaciers increased from 50 ma^{-1} to between 227 and 431 ma^{-1} (Boyce et al., 2007; Dykes et al., 2011); these rates are consistent with what we found at Bridge Glacier. For both Tasman and Mendenhall Glaciers, water depth and buoyancy also control the magnitude of calving (Boyce et al., 2007; Dykes et al., 2011; Dykes, 2013), suggesting that the majority of the ice discharged from the terminus is triggered by buoyant forces. ~~As the multi-annual calving rate is driven primarily by water depth, unless glacier flow speeds remain high enough to continually transport ice to deeper lake waters,~~

The relative contributions of calving and surface melt to total ice loss at Bridge Glacier is comparable to other studies worldwide. While calving at Bridge Glacier is responsible for an average of 10 - 25% of total ice loss, Yakutat Glacier experienced calving losses between 7.9 - 16.8% of total mass loss from 2000-2007 and ~~maintain terminus flotation , the glacier will retreat into shallow water and regain stability~~2007-2010 (Trüssel et al., 2013). These percentages are much higher than what has been observed at Mendenhall Glacier, where calving is responsible for 2.6 - 4% of the long-term volume change (Boyce et al., 2007). The differences in the relative contributions of calving to total ice loss points to different stages in a relatively uniform ‘life-cycle’ of a lake-calving glacier. Studies from Patagonia (Sakakibara et al., 2013), Alaska (Boyce et al., 2007; Trüssel et al., 2013, 2015) and New Zealand (Dykes et al., 2011; Dykes, 2013) all report glacier thinning, followed by terminus flotation and a rapid step-like retreat, something that is echoed at Bridge Glacier. These findings hint at a common large-scale behaviour of retreating lake-termining glaciers, and suggests a broad applicability of the temporal trend of observed calving contributions to ice loss to other glaciers in the region and across the globe.

9 Conclusions

Bridge Glacier is a lake-terminating glacier in the Coast Mountains of British Columbia that has retreated over 3.55 km since 1972, with the majority of retreat occurring after 1991. This retreat was independent of regional warming trends, and was enhanced by significant calving losses as the glacier terminus retreated into deeper waters. While calving has accelerated Bridge Glacier’s retreat, estimates of surface melt and ~~the calving flux~~ calving for the 2013 melt season indicate that calving was only responsible for 23~~%~~ % of the total ice loss. The contribution of calving to ~~mass~~ ice loss was limited by modest terminus flow speeds, relatively narrow sidewalls in the lower glacial tongue, and lake depth at the terminus.

Estimates of calving and surface melt ~~rates~~ from 1984 to ~~present~~ 2013 suggest that calving did not ~~contribute to significant mass~~ significantly contribute to ice loss before 1991. From 1991 to 2003 calving rates increased~~significantly~~, and the calving flux was on par with ~~the volumetric~~ ice loss from surface melt in 2005, 2008 and 2010. Although individual years ~~can have~~ had large calving fluxes, multi-year averages show that calving only contributed between 10 and 25 ~~%~~ % of the total ice loss at Bridge Glacier. ~~Therefore, the dominant control on the mass balance of Bridge Glacier is surface melt, and future projections of glacier retreat should be closely tied to climate.~~ The rapid calving rates observed since 2009 at Bridge Glacier are part of a transient stage in retreat as the glacier terminus passes through an overdeepened, lake-filled basin, and are not expected to remain a consistently large source of ice loss in the coming decades. These findings are in line with observations from other lake-calving glacier studies across the globe, and suggest a common large-scale pattern in calving-induced retreat in lake-terminating alpine glaciers. Therefore, the dominant control on the ice loss of Bridge Glacier is surface melt, and future projections of glacier retreat should be closely tied to climate.

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Table 1. Characteristics of selected major lake-calving glaciers worldwide. ~~D_{w}~~ D_w is the mean water depth, ~~T_{w}~~ T_w is the mean water (depth averaged or range) temperature, ~~U_{T}~~ U_T is the terminus averaged flow speed, and ~~U_{c}~~ U_c is the calving rate. Citations: ~~a~~a: Boyce et al. (2007), ~~b~~Motyka et al. (2002), b: ~~Motyka et al. (2003)~~Trüssel et al. (2013), ~~c~~c: Warren and Kirkbride (2003), ~~d~~d: Dykes et al. (2011), ~~e~~e: Warren and Aniya (1999), ~~f~~f: Stuefer et al. (2007), ~~g~~g: Haresign (2004), ~~h~~h: ~~Chernos (2014)~~Warren et al. (2001), ~~i~~i: Sakakibara et al. (2013), j: this study.

Location	Year	~~D_w~~ D_w (m)	~~T_w (~~ T_w (°C)	~~U_T (~~ U_T (ma^{-1})
Alaska				
Mendenhall	~~1997–2004~~ 1997 - 2004	~~45–52~~ 45 - 52	~~1–3~~ 1 - 3	~~45–55~~ 45 - 55
	2000 - 2007		0.5 - 1.5	139 - 150
Yakutat				
	2007 - 2010	325	0.5 - 1.5	139 - 150
New Zealand				
Maud	~~1994–1995~~ 1994 - 1995	15	4.3	151
Grey	~~1994–1995~~ 1994 - 1995	12	4.2	52
Ruth	~~1994–1995~~ 1994 - 1995	4	3.1	6
Tasman	1995	10	0.5	11
	~~2000–2006~~ 2000 - 2006	50	~~1–10~~ 1 - 10	69
	~~2006–2008~~ 2006 - 2008	153	~~1–10~~ 1 - 10	218
Patagonia				
Upsala West	1995	300		1620
	2008 - 2011	516		1200 - 1500
Upsala				
Grey	1995	165		450
Ameghino	1994	130	2.8 ~~–3.3~~ - 3.3	375
Perito Mereno	~~1995–2006~~ 1995 - 2006	175	5.5 ~~–7.6~~ - 7.6	535
Leon	2001	65	4.5 ~~–7.0~~ - 7.0	~~520–1810~~ 520 - 1810
	1998	190		438 - 475
Nef				
Iceland				
Fjallsjokull	2003	75	1.5 ~~–3.0~~ - 3.0	258
Canada				
Bridge	2013	~~109~~ 91	1.1 ~~–1.5~~ - 1.5	140
	~~1984–1990~~ 1984 - 1990	61		~~70–210~~ 70-210
	~~1991–2003~~ 1991 - 2003	90		~~70–210~~ 70-210
	~~2004–2012~~ 2004 - 2012	102		~~70–210~~ 70-210

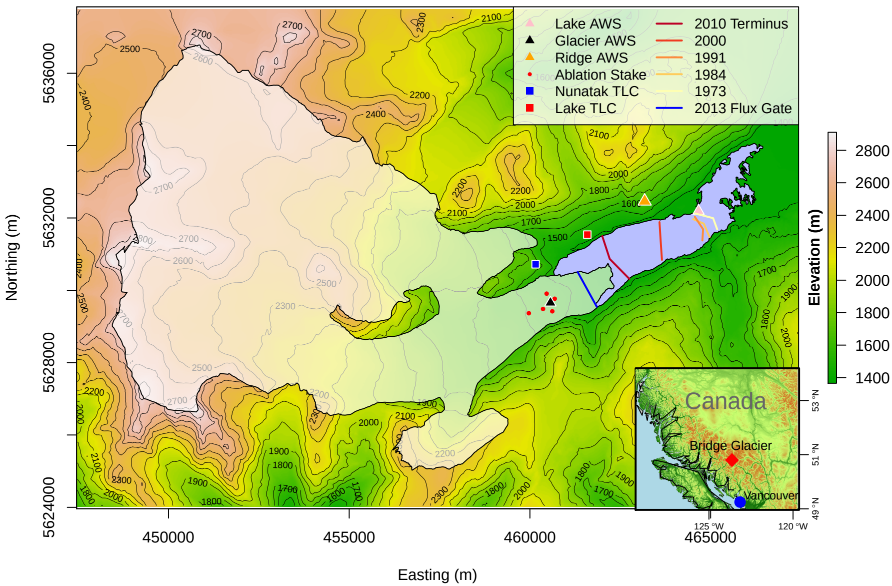
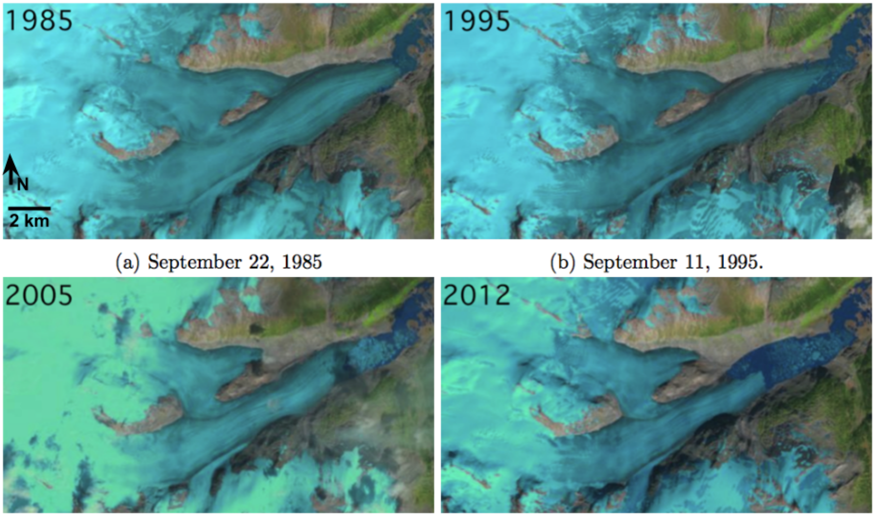


Figure 1. Bridge Glacier study area, instrumentation, and select terminus positions from 1973 to 2013. ~~Contour~~ The DEM is from winter 2006 and contour intervals are 100 m. Insert shows the location of Bridge Glacier within southwest British Columbia.



(a) September 22, 1985

(b) September 11, 1995.

(c) October 23, 2005

(d) October 10, 2012.

Figure 2. Landsat imagery from 1985 to 2012, showing retreat of Bridge Glacier and opening of Bridge Lake. All images have the same orientation and scale as the upper left panel.

~~Summary of climatic indicators and~~

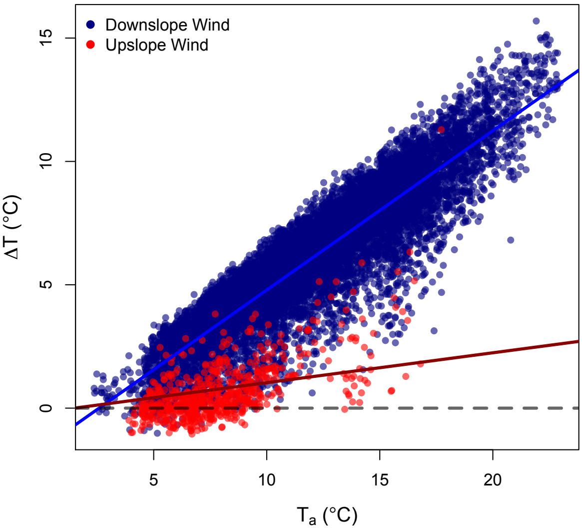


Figure 3. On glacier ~~response. **(a)** Vancouver winter precipitation anomaly ($\bar{x} = 819$), **(b)** Vancouver summer~~ temperature ~~anomaly~~ depression (~~$\bar{x} = 14.8$ °C~~$\Delta T = T_a - T_g$) ~~, **(c)** equilibrium line altitude~~ as a function of ambient air temperatures (~~$\bar{x} = 2089$~~ T_a) ~~, **(d)** Bridge River mean annual flow anomaly~~ from Ridge AWS (~~$\bar{x} = 10.7$~~ outside the katabatic boundary layer)~~, **(e)** Annual retreat rate~~. The blue line is the significant fit ($p < 0.01$) for downslope/katabatic winds and the red line is the non-significant fit for upslope winds, while the dashed grey line ~~is loess-smoothed retreat (span = 0.5)~~demarcates no temperature depression.

~~On glacier temperature depression ($\Delta T = T_\mathrm{a} - T_\mathrm{g}$) as a function of ambient air temperatures (T_a) from Ridge AWS (outside the katabatic boundary layer). The blue line is the significant fit ($p < 0.01$) for downslope/katabatic winds and the red line is the non-significant fit for upslope winds, while the dashed grey line demarcates no temperature depression.~~

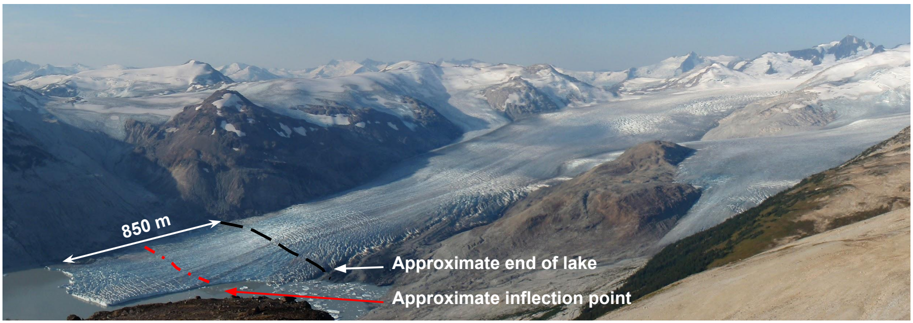


Figure 4. Photograph of Bridge Glacier terminus, ~~18 June 2013. Note~~ September 2013, showing the approximate location of the inflection point ~~(red arrow)~~and grounding line, ~~which indicates flotation. The yellow arrow indicates a large crevasse that led to calving~~ and of ~~a large tabular iceberg from~~ the ~~terminus to the left~~ proximal edge of ~~arrow~~Bridge Lake.

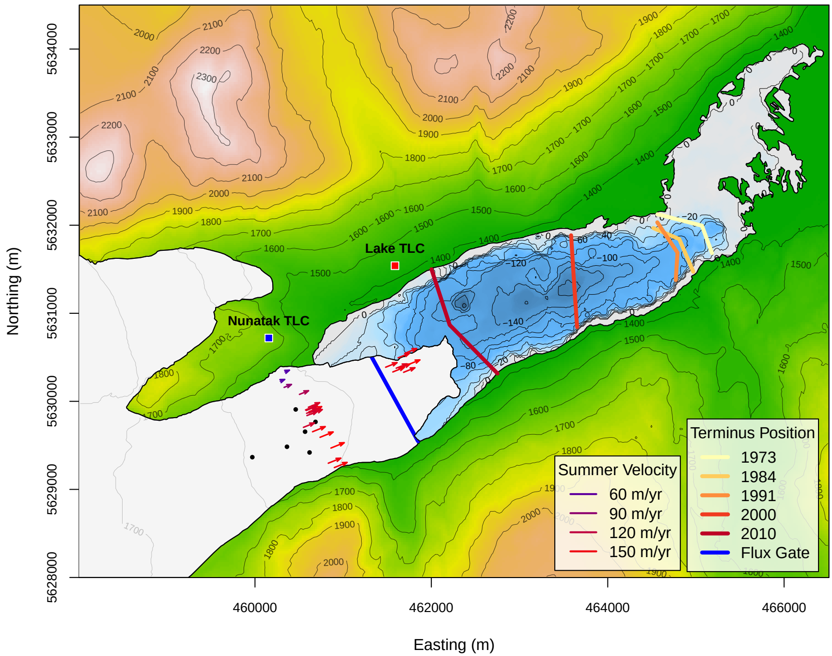


Figure 5. ~~Bathymetry for~~ Map showing 2013 Bridge Lake bathymetry, ~~taken over the~~ 2013 ~~field season~~study period flow vectors (arrows to scale), ablation/velocity stakes (black dots), flux gate, and historical terminus positions.

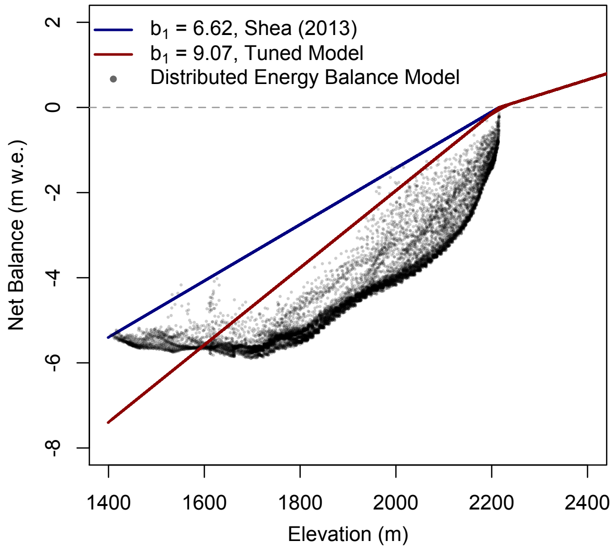


Figure 6. Modelled mass balance gradients from Shea et al. (2013) and a tuned coefficient using distributed energy balance modelling from the 2013 melt season.

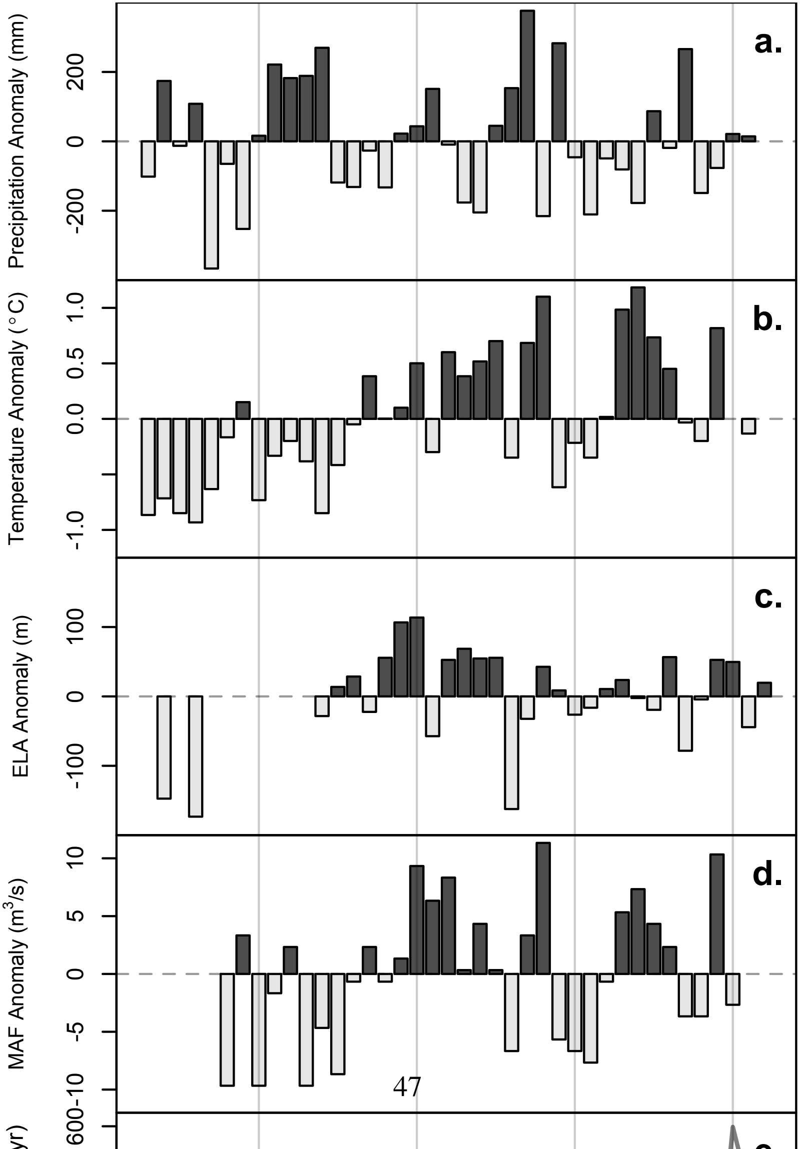

a.
Precipitation Anomaly (mm)
200
0
-200
b.
Temperature Anomaly (°C)
1.0
0.5
0.0
-1.0
c.
ELA Anomaly (m)
100
0
-100
d.
MAF Anomaly (m³/s)
10
5
0
-5
-10
600
yr)

Figure 7. ~~Modelled melt~~ Summary of climatic indicators and ~~ablation stakes~~ glacier response. **a.** Vancouver winter precipitation anomaly (~~black dots~~$\bar{x}$ = 819 mm) ~~for the study period 20 June to 12 September 2013.~~**b.** Vancouver summer temperature anomaly ($\bar{x}$ = 14.8°C), **c.** Equilibrium line altitude ($\bar{x}$ = 2089 m), **d.** Bridge River mean annual flow anomaly ($\bar{x}$ = 10.7 m^3s^{-1}), **e.** Annual retreat rate (m/yr), dashed line is loess-smoothed retreat (span = 0.5).

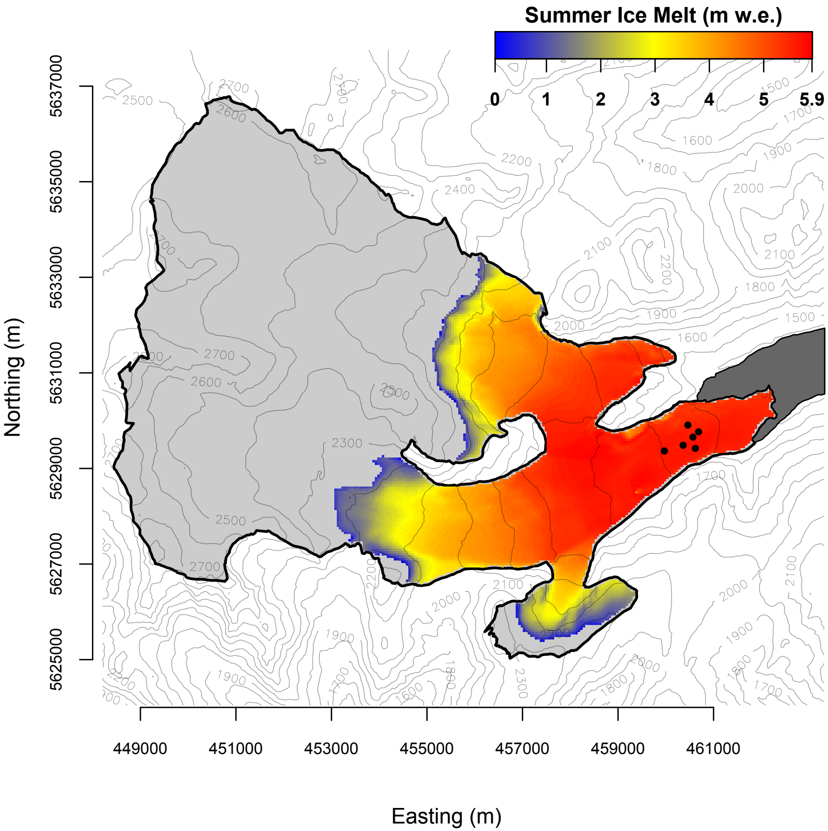


Figure 8. Modelled surface melt and ablation stakes (black dots) for the study period June 20 to September 12, 2013.

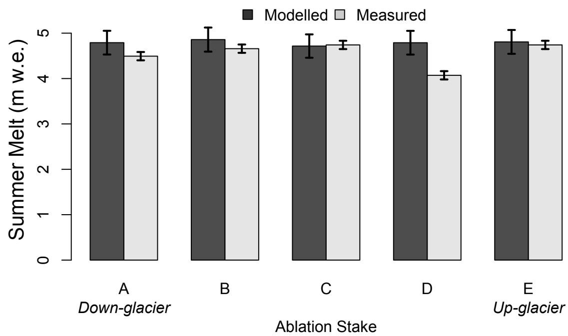


Figure 9. Observed (measured) melt from ablation stakes, and modelled melt from the DEBM~~.~~

~~Total volumetric ice loss~~

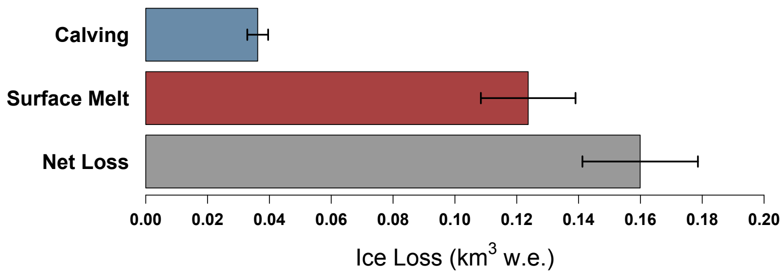


Figure 10. Ablation due to calving and surface melt (below the ELA) at Bridge Glacier during the 2013 melt season~~(ice equivalent)~~.

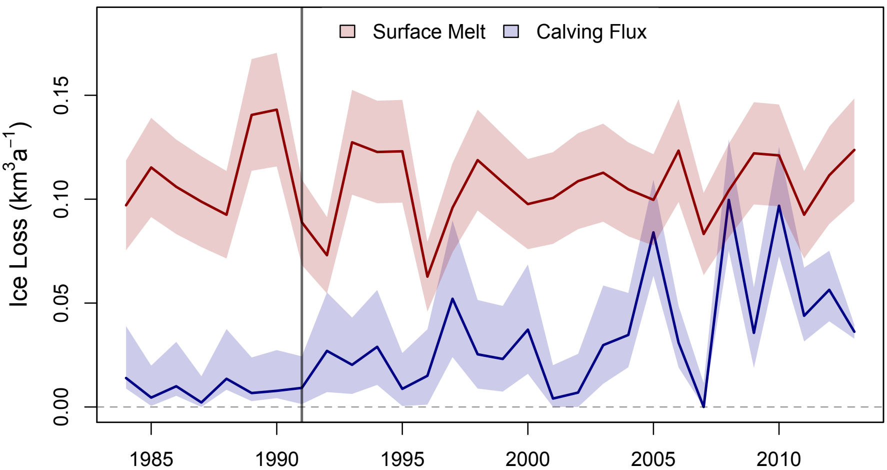


Figure 11. Historical ice loss from calving and surface melt (below the ELA), ~~1984–2013~~1984-2013. ~~Dark~~ The dark vertical line in 1991 indicates the period in which the terminus reached flotation and calving rates increased. Shaded areas correspond to calculated uncertainty.

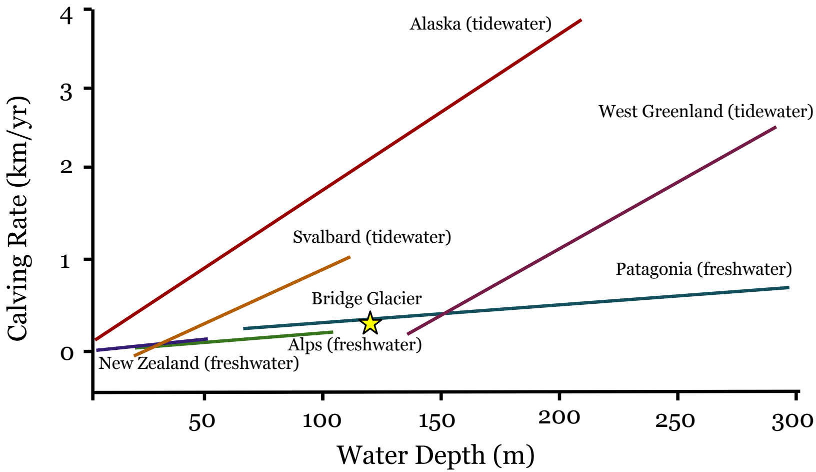


Figure 12. The relationship between calving rate and water depth for freshwater and tidewater glaciers worldwide. Bridge Glacier is denoted by the yellow star. Adapted from Haresign (2004).