RC1:

General comments:
This paper presents a dataset in the Upper Susitna Basin in Alaska and contains the data itself, the data collection and data processing of meteorological, glacier mass balance, snow cover and soil measurements. Data collection in this region is hard and this data can be great value for model validation or calibration in this region, however, I think not in the way it is framed now by focussing on implications for the dam (that is not there) and climate change (data is too limited).
We've made a set of changes to address the framing (see below), but the dam proposal was the main motivation for the project (and the reason the project was funded) so we chose to leave this mention in the intro. The wording makes it clear that the paper focuses on the data, this section of the intro is providing the context for why the data was collected. We added phrases about data scarcity and model validation and calibration to bolster the motivations.

I think the dataset presentation can be more thorough and better structured than is presented now. I miss at various places context of statements and the naming of the different stations can be structured better, such that it is clear to the reader which data you are referring to. I specified this in the specific comments below.
Addressed specifics below

I suggest major comments, predominantly since I think the focus of this paper should be on the data and not too strongly framed to dam-implication work and/or climate change work, since this work does not address that.

Specific comments:
The introduction does not focus on the relevant subjects. You present solely a measurement dataset and you focus in the introduction on climate change and (modelled) river runoff, which you did not do in the paper. Please restructure the introduction, remove this information or at least shift focus to the data. You could include more information about previous field works/data sets in this region?
We believe this larger context will be important to many readers. For people unfamiliar with the area, this gives them enough information that they don't have to search elsewhere for an understanding of why our data might be interesting or useful.

In general: update the captions of figures, such that those are complete. In Figure 1 I miss for example explanation of the subpanels. Also update the figure labels and text inside the figures such that those are readable (mainly Figure1) and resolution is high enough (also for the tables).
Added to caption of figure 1: "The main map focuses on the glacierized portion of the basin, the large inset shows the whole Upper Susitna basin which drains to the proposed dam site, and the small inset shows the basin in the context of the state of Alaska."

P1L16: You did not raise any questions yet. Please rephrase.
Done

P1L16: Your introduction is focused on climate change and river runoff, however I do not think 1 data set is sufficient to solve that. I would focus more on fundamental understanding rather than climate change. Please shift the focus of the importance of the data or even present it only as a dataset.
It is true that this data set won't "solve" climate change or changes to river runoff, but the introduction is meant to connect the paper to the larger topics that it relates to. That's what we're doing here. The wording makes it clear that the paper focuses on the data, this section of the intro is providing the context for why the data was collected. We added a sentence about data scarcity to bolster the motivations.

P2L1-4: in the paper itself you do not make the link to water runoff or the dam so I find this information misleading.
We include this information for context and motivation. On line 4 we clearly state "this paper focuses on the measurements."

P2L5: state 127 glaciers instead of ‘more than 120’. Be specific

While we are generally in favor of being specific, here we use ‘more than 120’ because the number of glaciers in the basin can change e.g. as climate change removes glaciers, or splits one into two. I changed it to a nice round ‘more than 100.’

P2L9-10 similar as stated above, you do not make this link to dam operations and environmental resources. Or looked at river discharge.

We include this information for context and motivation. On line 4 we clearly state “this paper focuses on the measurements.”

P2L11-14: So you do not include modelling (as stated in P2L3)?

We include the information on modeling for context and motivation. On line 4 we clearly state “this paper focuses on the measurements.”

Section 2. Study area: A lot of unnecessary information. Please exclude some information or make more clear why you discuss this information. Connect the information to your paper and rewrite to a smoother story.
Ice sheet
Surging
Permafrost

We believe all the information presented is useful background to introduce the reader to the area we’re focusing on. In fact we already connect the information to our paper: “The glacier monitoring work focused on the five largest glaciers...” We include a succinct summary of the characteristics of the glaciers (area, debris cover, area change, surging behavior, and velocities) to give the reader a sense of the glaciers’ behavior and previous work that has been completed on the glaciers. The one sentence on ice sheet extent provides context. The paragraph on surging is important because surging can dramatically influence the mass balance of a glacier (one of the main foci of this paper). The two sentences on permafrost and the map (figure 2) provide context for the soil temperature measurements.

P2L19: why Kienholz reference needed?

Because Kienholz and co-authors did the work we’re building on here. Their outlines were then incorporated into the RGI.

P2L24: “few”=how many glaciers?

Nine, as mentioned on line 32.

P2L28: change “ninety-three” → 93

Convention states that sentences should not start with Arabic numerals.

P2L28: “127 glaciers”: numbers are not congruent (“more than 120 glaciers” in L5, “Most glaciers (in total 127)” in L23). If the area contains 127 glaciers please change in L5 to “more than 120 glaciers” to “127 glaciers”, remove in L23 “(in total 127)”.

127 in Alaska Range + 9 in Talkeetna Mountains, but see also my reply to P2L5

P2L29: how did you estimate this volume? Explain in text.

The first part of this sentence explains how we estimate volume.

P2L30: why do you use these scaling coefficients? Please explain how you got those or insert reference.

Added:

Radic, V., Hock, R., and Oerlemans, J.: Analysis of scaling methods in deriving future volume evolutions of valley glaciers, Journal of Glaciology, 54, 601–612, https://doi.org/10.3189/002214308786570809, http://dx.doi.org/10.3189/002214308786570809, 2008.

P2L31. Place ‘.’ After m a.s.l..

Done

P2L33: change point into comma or insert ‘and’
That is a period at the end of the sentence.

Page 3: Figure1: Combine Figure 1 and 2 by shading/colouring the permafrost areas >50% in Figure 1. For reader it is not clear why permafrost is so important.
Figure 1 is too complicated to add the permafrost classes and keep it readable. I added text to explain significance. “Permafrost affects water runoff, soil temperature, vegetation, and soil carbon fluxes. These factors have complex interactions with climate change.”

P3L1: Why is debris cover relevant?
P3L4 explains why. I reordered these sentences.

P3L1-2 please rephrase and combine L1 and 2
No longer needed with reordering.

P3L5: include Östrom reference.
Upon searching, I can’t find any relevant reference by that author.

P3L6: Do you exactly study the same area?
Yes, which is why we felt we did not need to say that we study the same area.

P3L10: “History of surging”, are they still defined as surging glaciers or long time stable aleardy??
That’s an interesting debate, that we choose not to delve into here.

P4L1-8: why is surging relevant? Mass balance not tat different than non-surging glaciers.
Mass balance can in fact be affected by surging (and vice versa). The latest surge of West Fork occurred shortly after the 1981-83 mass balance measurements to which we are comparing our data. While the effect of a surge on the mass balance may not be quantifiable given the data that is available, the surge still needs to be mentioned.

P4L9: this line suggests that glacierized parts have vegetation and human development. Please rephrase.
Text reads “The non-glacierized part...”

P4L9-15: why is permafrost relevant?
Added text to explain significance. “Permafrost affects water runoff, soil temperature, vegetation, and soil carbon fluxes. These factors have complex interactions with climate change.”

Page 5 Figure 2: Do not understand the importance of this figure, maybe only the two upper permafrost colors needed? Than combine with Figure 1.
See above

Page 5 Figure 3: put all photos next to each other or make panel a and d bigger such that they are similar height as b+c.
Figure is designed to be one-column wide and be aesthetically pleasing with the mix of vertical and landscape orientations.

P6L4: do you refer to figure three, or do you mean you installed three AWS? Are those the ‘station type AWS” in Table A1? Not clear for reader that energy balance weather stations are ‘AWS’ and that simple AWS is ‘HOBO’ in table A1.
Added “Figure” to the 3. Edited appendix to remove “AWS” and “HOBO”.

P6L6: “floated” is not appropriate here.
Floated is the best descriptive word we have for this installation type. Added quotes around it to make clear that it is not floating in the literal sense.

P6L25: "The station records…surface elevation changes", put earlier in section (for example at the end of P6L4.
We mention this sensor on line 14, in what we think is a logical place to mention it.

Page 7: Figure 4: caption "(i) outgoing longwave radiation" use abbreviation LW as defined before.
Done

Page 8: Table 1: It is not clear to me whether the "energy balance weather stations" are the onces indicated by "AWS" of "HOBO" in Table A1? Please use consistent naming for all stations throughout paper.
Edited appendix to remove "AWS" and "HOBO".

P8L1-2 : what do you want to show with correlation coefficients in Table 2?
Section 3.1.2 describes what we want to show with the correlations.
P8L4: "variable", you indicate only the range of the data in Table 2. Please provide also the standard deviation of the values in Table 2 and refer to the standard deviations in the text.
The standard deviations are not particularly meaningful given the short records we're dealing with, so we chose not to include them. The reader can get a sense of the variability we refer to here by looking at figure 4.

P8L7: "more than 4 degrees Celcius lower": please rephrase to "temperatures by a minimal bias of 4 degrees" or similar.
Replaced "lower" with "cooler"

P8L8: connect the sentences by adding "when" P8L6-10: structure is missing, please rephrase
Reworded.

P8L11-13: please provide numbers instead of only calling it 'higher', 'greater availability', 'less variability' etc.
The table and figure have the numbers. Adding all the numbers here makes the text unreadable.

P9 Table 2: daily correlations? Add standard deviations to the means to indicate the variability. You can remove the range, since that does not add more information than the standard deviation
Standard deviation is not meaningful for wind speed, precipitation, or shortwave radiation since their distributions are so skewed. Range does give important information. The reader can see the variability in the figure.

P10L9: Incoming longwave radiation is also influenced by the surroundings, especially in complex terrain. Insert "mainly"→"which depends mainly on the effective.."
Done

P10L12: high correlations means meteorology is affected by larger scale forcings rather than micrometeorology. You could add discussion about that.
We can't generalize from "LW" to "meteorology." P10L2 already discusses the "relatively homogeneous cloud conditions at those sites"

P10L23: change "Figure 5" to "Figure 5C". and add ABC in Figure 5
Done

P10L25: not necessary melt when T>0 degress, the surface energy balance should be positive.
We are not directly measuring sensible or latent heat fluxes, so we can't calculate the surface energy balance precisely.

P10L30: What about the influence of precipitation.
There was no precipitation on these days, which is why we don't mention it.

P10L31: rephrase “in the ice rather than the snowpack” to “the layer consists of ice instead of snow” or similar
Done

P11 Figure 5: explain the reversed patter of ice temperature (red lines) with depth in the text. At 21 April lines are ordered from light to dark lines with depth, while in June this pattern is reversed. With other words explain why the temperature gradient reverses.
“As air temperatures rose, the subsurface temperatures of the upper layers increased but with a time lag that increased with 25 depth (Figures 5 and 6).”

P11 Figure 5: the lightest lines (Ice2.5m) are not clearly visible and Ice3m not present at all. Please make those lines more clear.
With 15 lines we did our best to have distinct colors that show the short term variability. Perhaps the confusion comes because we do not have data from 4 m depth so there is a visual gap between the data from 3 m and 5 m, particularly at the beginning of the record. The legend clearly indicates the depths.

P12 Figure6: the reversed temperature gradient is here not visible why (not)? Go more in depth in the data (general comment)
The reversed temperature gradient is visible. On 28 April the coldest temperatures are at the surface. On 26 May the coldest temperatures are at -1 m from the initial snow-ice interface, with warmer temperatures at the surface. The pattern continues through the end of the season.

P12L4: “simple weather stations”? Why is station type in Table A1 than indicated by “HOBO glacier”? please make naming consistent throughout the paper.
Edited appendix to remove “AWS” and “HOBO” in favor of “energy balance” “simple glacier” and “simple tundra.”

P13L7: which of the two sensors are more trustworthy? And why the comparison? Please explain in text.
The manufacturer’s stated accuracies are 0.1 C for Rotronic and 0.2 C for HOBO as shown in Tables 1 and 3. Whether that equates to “trustworthiness” is a matter of opinion. The comparison is done for calibration (as stated in the section header). Added a new first sentence: “To ensure the validity of data collected from many individual sensors scattered across our study area, we set them up side-by-side before deploying them to the field.”

P13L9-11: I think these argumentations do not match:
The HOBO sensor is slower than the Campbell, but coefficient of 1, and then conclusion is that there is a lack of consistent pattern. I do not follow this, please explain and rephrase
As stated in the text: 5 minute data show that the HOBO sensors are slower, but hourly averages have a correlation of 1. Figure 7 shows the lack of consistent pattern. Added references to figures in the conclusion sentence: “The lack of a consistent pattern in these comparisons (Figure 7) prevented us from adjusting the HOBO temperature data to match the Campbell data. The high correlation and low temperature offsets (Figure 8) among sensors gave us confidence that using HOBO stations to assess temperature patterns across the basin was valid.”

P13L20: add some explanation/conclusion. I miss in this whole section why you do the comparison between the sensors and eventually the physical interpretation or conclusion from your statements.
Added explanation to the top of the section and this physical interpretation to this paragraph: “Again, this gave us confidence that we could use our data to assess humidity variations across the basin.”

P14L1-2: did more people had this problem? Is it a random tip that can also occur during dry periods (since this can not be filtered out)? Or is the tip sometimes ‘stuck’?
We don’t know of others that have run into this problem. It is not a random tip because when the data show rain at one station, there is almost always also rain at other stations. We never observed the bucket getting stuck in our calibration.

P14L4: or conclusion is the HOBO has a sensor problem.

Yes that is the conclusion of the previous paragraph. This paragraph focuses on the Campbell sensor and the conclusion is that if the internal electronics create a double tip, the logger is filtering it out.

P14L16: is this katabatic flow measured or a assumption it develops?
We measured wind speeds and directions at the On-Ice station consistent with a katabatic flow in summer, as the text now notes.

P15 Figure 7: include the colours in the caption
Added "Each colored line represents a HOBO sensor, blue dots are for the reference Rotronic sensor, and red dots are for a Campbell 107 Temperature Probe."

P16-P17: Section 3.3 I do not think this section is a great addition to your purpose of the paper and not supported by any in depth discussion, please remove.
We included this section to help explain differences in glacier mass balance discussed later. For the revisions, I added text to the mass balance section to make the connection more direct. "These mass balance patterns are consistent with the warming temperatures and relatively stable precipitation measured at Talkeetna Airport."

P18 Figure 11: is this the same transect measured every week at same location? What do you mean with "plotted relative to a reference station"? Does this mean steepness in line is varying in time? Please explain in caption. Mention in caption what upper stations in winter are not operating/measurement problems.
The transect is not the same in every week. The stations are fixed in place, and whenever the station has enough data to calculate a weekly average, it gets plotted. Changed caption to: "Weekly air temperature profiles show the winter inversions and summer differences between glacier and tundra temperature. For each week, the reference station (Windy Creek Lower, 940 m a.s.l., triangles and black dots) was plotted on the horizontal axis according to the date. The other stations (triangles or circles) were plotted to the left or right of the reference station according to their temperature difference."

P19 figure 12: Add coloured lines for each of the dots to show whether the gradients change in time/how sensitive they are.
Given the inconsistent recovery of data from different sites in different years, we chose not to display best fit lines. It doesn't make statistical sense to try to compare these lines from year to year.

P19 figure 12: Add the resolution of the glacier inventory in the caption.
Vector outlines don't really have a resolution. The reader can see the detail of the outlines in Figure 1.

P19 figure 12: Insert in caption how the mass balance in computed (from the "HOBOglacier" station in Table A1?
Inserted "...measured with the glaciological method"

P19L1-2: or the measurements are not representative for the whole region.
Added "... or the best-fit line might be too sensitive to data from lower elevations."

P19L4-end: the linear interpolation is done with all data such that no division is made between years (1 average value for all glaciers and all times?)? If so this is a very simplified method and I am not convinced in the numbers you present. For example P is highly spatially variable, as you also state in P20L14-15.
Added "... for each year"

P20 Section 4.2 Very limited, please expand or consider removing or merging this section.
It might not take much space, but this section includes some key results. Reworded a few sentences to make it read better.

P20L17: I do not follow this, you did not do any model simulation of snow accumulation, or this is not mentioned.
Reworded to emphasize comparison to our stake network.

P21L2-3 please rephrase. Absolute difference at 2000 and 1000m or did you do some averaging?
This is an approximate estimate based on binned radar data and point measurements for multiple years and multiple glaciers. We're trying to convey the big picture here, and the reader can refer to the figure for the numerical details.

P21L4: how do you know surface roughness is responsible? Please add explanation or supporting material for this statement.
Added: "Over short spatial scales in the ablation zone, surface roughness is responsible for high spatial variability in SWE. The end-of-summer glacier surface is rough due to streams, crevasses, melt ponds, and moraine material. The end-of-winter snow surface tends to be relatively smooth compared to the summer surface, but can also have wind-derived roughness features that contribute to the variability in SWE over small distances."

P21L6-8 I am not convinced
What do you think it is then? We tried our best to adequately account for errors in our methods and this lists what we couldn't account for.

P22L9: again, why the roughness of the ice surface?
See above

P22L16: add explanation why data become noisier. Why does ice give more noise signal?
Added: This was likely caused when the acoustic signal bounced off different elements of the rough ice surface in successive measurements.

P22L20: you assumed constant density? What are the implications of this assumption?
Changed "assumed" to "used" since this is based on measurements. New sentence reads: "To calculate ablation from the observed distance change, we used a density of 350 kg m^{-3}, based on the average of 5 snow density measurements at the site."

P24 Table 6: increase fontsize
Table doesn't fit on the page with a larger font. The copy editors may be able to fudge this somehow.

Section 5.2: please remove, I do not think is Section is of additional value
Readers who are familiar with the prior work or the field site will be interested in this information.

P24L11: "though we did not do a detailed texture analysis", But still you know it matches with the STATSGO soil map? I am not convinced.
Soil texture is relatively easy to observe in the field and the soils we encountered were largely sandy loam. This matches with the STATSGO map. Sites with very little soil development (Windy Creek Upper, Valdez, Two Plate) show as bedrock on the STATSGO map. We also looked into some of the STATSGO attributes such as organic content and drainage characteristics, which aligned broadly with our field observations. As mentioned, we did not do a more detailed texture analysis (e.g. taking samples back to the lab), so what more do you want to convince you?
Changed: "Though we did not do a detailed texture analysis on the soils, the characteristics we observed generally matched up with the State Soil Geographic (STATSGO) soil map (https://datagateway.nrcs.usda.gov/)."
To: "Though we did not do a detailed texture analysis on the soils, our observations of soil texture, organic content, and drainage characteristics generally matched up with the State Soil Geographic (STATSGO) soil map (https://datagateway.nrcs.usda.gov/)."

P25 Section 6.2 Explain the uncertainties and effect by the disturbance of the disturbed soil on the measurements.
Added: "By pushing the sensors into the undisturbed soil on the side of the pit, we hope to minimize any temperature errors due to disturbance. We did not quantify the effects of disturbance on temperature, though we expect them to be small compared to the large temperature changes observed over the record. Deep sensors were deployed at the bottom of a 2.5

cm-wide hole drilled into the ground. Disturbance of the soil around the deep sensors may affect temperature too, but we tried to minimize that by using the smallest drill we could."

P27L11-13: why is this relevant, please remove.
Unclear what the reviewer thinks is not relevant - this whole paragraph is describing the data in figure 18.

P27L25: How do you relate this to the dam? No runoff analysis is done.
Deleted reference to dam here.

P27L27: this is only a minor section and for me not strong part of your paper and now you present the climate change numbers as one of your main conclusions.
I think it is totally fair to present our data as a baseline for future measurements. The point of concluding statements is to highlight how this paper and the data within it are relevant to the broadest audience possible.

P28 Figure 18: air temperature is gray colour?
Yes, as indicated by the legend.

P28L6: not new conclusion, snow amounts are generally higher at high elevations
True, but it has not been shown for this study area and time period, so it is still a valid conclusion.

P28L7: you did not measure the soil and your conclusion is that these match with the mapped soil descriptions. Please remove this statement out of your conclusions and preferably also out of the text
Detail added above to support these conclusions.

Conclusion in general: please do not focus on climate change and dam implications, but give conclusions about the data you found in the field. What did you find and why is it special?
We do give conclusions about our data and we highlight how the data are relevant to the broadest audience possible (people who are interested in climate change and runoff).

*****

RC2:

General Comments:

This study presents, validates and interprets a comprehensive and impressive data set, which covers a range of parameters in the variable environments of the Susitna Basin, Alaska. The data set includes meteorological, glaciological and soil parameters. The data set is unique, as many of the measurements were done in complex terrain where measurements generally are sparse. It is effortful and requires extensive planning to acquire meaningful data in this terrain. Problems in the data are addressed and generally, implications that arise with these problems are described in detail. Overall, the manuscript is well structured and provides a good overview of the data. The data set itself could be extremely valuable for model validation or comparison with future field studies.
Thanks!
However, the manuscript is not always coherent and suffers from redundant information (e.g. section 3.3, section 5.2, figure 9),
None of these sections or figure are redundant. Perhaps the reviewer meant to say relevant? That critique was addressed in response to reviewer 1 and can be summarized with: "Readers who are familiar with the prior work or the field site will be interested in this information."
which distracts the reader from following the key points and weakens the focus of the paper (see specific comments).
Addressed below

The introduction does not adequately motivate the manuscript, as it does not really make clear why the data set is important and what the purpose of the data set is (see specific comments).
Addressed below
In addition, some of the presented data appear isolated and need to be put into context better (e.g. section 4.4., how do continuous mass balance measurements compare to stake measurements nearby?) ***See P22L10: "The net depth of snow lost at the sonic distance sensor site was 1.97 m (17 April - 30 June), which is comparable to the 2.15 m snow depth measured in a snow pit about 6 m away on 14 April 2013." And see figure 5 which shows the ablation stake and continuous measurements together. Added reference to figure 5 in section 4.4.***

Therefore, I suggest a number of minor revisions to focus the main messages of the manuscript and to emphasize the uniqueness of the data set.

Specific Comments:

Introduction:
Mentioning climate change in the beginning of the introduction is not convincing, since you only acquire three years of data. Either remove the link to climate change, or emphasize that the data set is meant to be used for comparison with future studies (as you do in the conclusions).
We also compare our data to data from 30 years ago and see evidence of climate changes, so we assert that climate change is in fact relevant to the paper.

P2, l9-10: using changes in river flow on dam operations as a motivation here seems misplaced, since you mention in the beginning that the dam was not built. In addition, river flow is not covered in this study. Please rephrase or remove. You could motivate each of the data types (meteorological/climatological, glaciological, snow, soil) individually, as you do later in the manuscript. E.g., p4,l23-26 motivates meteorological/climatological measurements, p25,4-5 motivates soil measurements and should be placed in the introduction
This was the main motivation for the project (and the reason the project was funded) so we believe it to be relevant context. The wording makes it clear that the paper focuses on the data, this section of the intro is providing the context for why the data was collected. We added a sentence about data scarcity to bolster the motivations.

- p1, l6: since only the years 1981-83 were investigated, please do not write 1980s here but refer specifically to the years 1981-83
DONE

- p2, l5: state precise number instead of "more than 120 glaciers"
Changed to "more than 100", see notes to reviewer 1

- p3, l5: please add reference here
Added: Scherler, Dirk, Bodo Bookhagen, and Manfred R. Strecker. "Spatially variable response of Himalayan glaciers to climate change affected by debris cover." Nature geoscience 4.3 (2011): 156.

- p3, l10-p4,l3: detailed description of surge history seems unnecessary here, please shorten
We focus on mass balance, which can be affected by surging (and vice versa). The latest surge of West Fork occurred shortly after the 1981-83 mass balance measurements to which we are comparing our data. While the effect of a surge on the mass balance may not be quantifiable given the data that is available, the surge still needs to be mentioned.

- p6, l4: what does the number 3 in brackets mean?
Added "Figure" to the 3.

- p6, l26: first time abbreviation “DGGS” is mentioned, please provide full name

Spelled out: Alaska Division of Geological & Geophysical Surveys

- p7, figure 4: please provide figure in higher resolution

Done

- p8, l13: delete sentence “Data are not available from 18 January 2014 to 22 April 2014 when the station was buried in snow.” since this was mentioned before.

Done

- p9, table 2 caption: delete “18 January 2014 to 22 April 2014.” from caption, since it was mentioned before

Because readers may take values from the table without closely reading the text, we believe this mention should remain.

- p11, figure 5: please provide higher resolution figure

Done

- p12, figure 6: figure is not mentioned in text, please add reference to figure in text. Also, please provide figure in higher resolution

Added reference and higher resolution figure

- p13, l8: reference to figure 4: is this right or do you mean figure 7?

Good catch, thank you

- p13, l11: rather say “very close to 1.0”

Point taken that it is not exactly 1.0000000. But with two significant digits, I think it is appropriate to report it as 1.0 rather than “close to 1.0” implying it could have been 0.99.

- p13, l12/13: “The lack of a consistent pattern in these comparisons prevented us from adjusting the HOBO temperature data to match the Campbell data.” This is confusing since you mention an average offset the sentence before. Can you clarify this?

Added references to figures to clarify: “The lack of a consistent pattern in these comparisons (Figure 7) prevented us from adjusting the HOBO temperature data to match the Campbell data. The high correlation and low temperature offsets (Figure 8) among sensors gave us confidence that using HOBO stations to assess temperature patterns across the basin was valid.”

- p.14, l1/2: What is your confidence that no double tips are missed or that normal tips are identified as double tips?

For a complete discussion, please see Wolken et at 2015. Reference added here.

- p15, figure 7: how do you explain very high RH offset of some HOBO-sensor at higher RH, especially in 2013?

Simply different sensor performance, as mentioned in the text. It is notoriously difficult to accurately measure humidity at cold temperatures (e.g. -10 C).

- p14, l11: “Precipitation amounts did not correlate significantly with elevation, slope, aspect, or location.” How do you define “location”? What drives the variations in precipitation amounts?

Location can be defined with lat/long coordinates, or by logical grouping in mountain ranges. We chose not to speculate on what drives variation, but we can rule out the factors mentioned.

- p14, l15-17: katabatic wind flow: Can you back this with references or add a more thorough analysis based on your data, e.g. wind direction analyses? Or is this just an assumption you make?

Added a paragraph on wind direction to the “Meteorological data” section.

- p15, figure 7: colour codes are missing

Added to caption: Each colored line represents a HOBO sensor, blue dots are for the reference Rotronic sensor, and red dots are for a Campbell 107 Temperature Probe.

- p16, figure 9: what is the purpose of figure 9? There is no in-depth analysis provided in the text and patterns are trivial (yearly temperature cycle, lower temperatures with higher elevation). In addition, it figure again suffers from relatively low resolution. Please either remove figure or provide more detailed analysis

We believe the patterns are not trivial, but chose to spend more space in the paper describing mass balance data. Future papers may delve deeper into the spatial and temporal variations introduced here. We also feel it is best to present this "raw" data before looking at it in terms of lapse rates (figures 10 and 11). Fixed resolution issue.

- p16, section 3.3: this section does not provide a thorough analysis and is not useful for the manuscript since it is not based on your data. Either please remove or transform; rather than a trend analysis, the section could provide an assessment whether the years 2013-2014 were exceptional (in terms of temperature) or normal.

We later reference this section when discussing mass balance differences between the 1980s and recent periods.

- p18, figure 11: what purpose do the different colours serve? If none, please use black or dark grey

The colors help distinguish which data goes with each week. A grayscale version of this figure is illegible.

- p19, l12: Did you think about adding the line fit to the figure? This would allow the reader to clearly identify the equilibrium line altitude you derived

Given the inconsistent recovery of data from different sites in different years, we chose not to display best fit lines. It doesn't make statistical sense to try to compare these lines from year to year.

- p19, l1/2: Since you used only point measurements, it is also possible that the stake measurements do not fully represent the area that was covered by satellite. In addition, you mentioned earlier that most of the stakes were placed on the centreline of the glacier, which is typically higher than the margins (which are included in the satellite estimation?), potentially leading to higher estimation of the equilibrium line altitude

Reworded

- p19, l7/8: "Glacier-wide mass balance estimates were then calculated by summing the distributed mass balance over the whole glacier." Did you use hypsometry of each individual glacier? Or did you use hypsometry of the entire glacier area for the calculation of the individual glacier mass balances? If so, the numbers you get probably have very high uncertainties. Please clarify.

Changed "based on the glacier hypsometry " to "based on the individual glacier's hypsometry"

- p20, l2: "East Fork Glacier had a similar mass balance as Maclaren Glacier." Why do you stress this here? Seems misplaced, please delete

Done

- p20, l17: "To robustly validate model simulations of snow accumulation…"; please move to introduction, since this provides a motivation for your measurements and you are presenting results in this section

Removed reference to modeling as suggested by reviewer 1.

- p21, l2/3: "…at 2000 m measuring 2-3 times higher than at 1000 m." looks more like 2-4 times higher (see year 2014)

True, changed to 2-4.

- p21, l4: "A notable south-north decrease in total SWE and accumulation gradient indicates a strong orographic influence." Please remove: sentence is redundant since you mention elevation dependence the sentence before. In addition, this is not always necessarily a north-south gradient

Done

- p22, figure 14 caption: "In early August 2013, the sensor's mounting pole began to tip over and give bad readings. On 1-2 September 2014, 18 cm of snow accumulation was recorded, consistent with observations during a site visit. The sensor pinged off falling snow, so some points in that window are labeled as bad data." please remove or move to text
I think it is valid to leave this short description of the bad data in the figure caption, so the viewer doesn't have to search the text for the description of the bad data.

- p22, l16: "data became noisier as the surface transitioned from snow to ice." can this be seen in figure 14?
Yes, when zoomed in.
- p22, l21/22: "This leads to an average melt rate of 0.016 m w.e. d^{-1} for the summer of 2013 and 0.012 m w.e. d^{-1} for 2014." This information seems a bit isolated from the previous, interesting mass balance investigations. Can you provide a comparison here? How does this compare to nearby ablation stakes summer mass balances?
The previous paragraph mentions this comparison, and it is plotted in figure 5 (added reference here). "The net depth of snow lost at the sonic distance sensor site was 1.97 m (17 April - 30 June), which is comparable to the 2.15 m snow depth measured in a snow pit about 6 m away on 14 April 2013."

- p23, l7: "Snow water equivalent (SWE)": abbreviation has been initialized before
Deleted "SWE"

- p23, l14: "...generally showed a strong elevation dependence." dependence of what type? Maybe just write "increased with elevation"
Changed

- p23, l16/17: "At the Lower Windy Cr. site, about 40 mm of SWE (25%) was lost due to melt of the end-of-winter snowpack between 9 April and 22 April 2014 (Table 6)" Why is this stressed here? Please remove
Added context: "Lower Windy Creek was the only site where we collected SWE data more than once in a year. About 40 mm of SWE (25\%) was lost due to melt of the end-of-winter snowpack between 9 April and 22 April 2014 (Table \ref{tab:Snow})."

- p24, section 5.2: This section does not add any value to the paper but is very distracting; please remove
Readers who are familiar with the prior work or the field site will be interested in this information.

- p25, l1: "characteristics we observed"; please specify these characteristics so the agreement between soil pits and STATSGO becomes clearer
Done: "our observations of soil texture, organic content, and drainage characteristics"

- p25, l4/5: "Understanding the distribution of permafrost and seasonally-frozen ground across the basin is important for modeling of water moving across the landscape"; again, this provides a motivation for your measurements and you are presenting results in this section, so please move to introduction

- p27, l28/29: "Summer air temperatures in 2012-2014 were 1.1 ◦C warmer than 1981-1983. Annual temperatures were 0.5°C warmer in the recent period." Why do you add this here? This is not based on your own measurements and thus not a significant outcome. Please consider removing.
It is significant because it helps explain the glacial mass balance changes we observe. Since we do not do temperature index modeling in this paper, we do not directly attribute the mass balance change to the temperature change, though we assume (hope!) the reader will see the connection.

- p28, l2: since only the years 2012-14 vs. 1981-83 were investigated, please do not generally say 2010s vs. 1980s since you have no information on the other years
Done

Technical Corrections:

- p8, l12: move “On-Ice” to the end of this sentence

Done

- p6, l33: please remove “instead of every minute”

Done

- p16, l4: “most distinct“ instead of “least complicated”

Done

- p18, l2: “refers to the period October…” instead of “refers to October…”

Done

- p20, l11/12: “Therefore, lower annual balance in the latter period (-1.72±0.87 m w.e.) compared to the former period (0.04±0.25 m w.e.) were driven by the more negative summer balances.”

should be “balances… were driven…” or “balance… was driven”

Done

- p26, figure 17 caption: “soil” instead of “soils”; remove “,” after data

Done

Glaciers and Climate of the Upper Susitna Basin, Alaska

Andrew Bliss[1,2], Regine Hock[2], Gabriel Wolken[3], Erin Whorton[3,4], Caroline Aubry-Wake[2,5], Juliana Braun[2,6], Alessio Gusmeroli[7], Will Harrison[2], Andrew Hoffman[2], Anna Liljedahl[8], and Jing Zhang[9]

[1]Department of Anthropology, Colorado State University, 1787 Campus Delivery, Fort Collins, CO 80523, USA
[2]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA
[3]Alaska Division of Geological and Geophysical Surveys, Fairbanks, AK, USA
[4]USGS Washington Water Science Center, Tacoma, WA, USA
[5]Centre for Hydrology, University of Saskatchewan, Saskatoon, SK, Canada
[6]Willis Re, London, UK
[7]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA
[8]Water & Environmental Research Center and International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA
[9]Department of Physics and Department of Energy & Environmental Systems, North Carolina A&T State University, Greensboro, NC, USA

Correspondence: Andrew Bliss (andybliss@gmail.com)

Abstract. As part of a proposed hydropower facility, extensive field observations were conducted in the Upper Susitna basin, a 13,289 km^2 glacierized catchment in central Alaska in 2012-2014. This paper describes a comprehensive data set of meteorological, glacier mass balance, snow cover and soil measurements, as well as the data collection and processing. Results are compared to similar observations from the 1980s. Environmental lapse rates measured with weather stations between about 1000 and 2000 m a.s.l. were significantly lower over the glaciers than the non-glaciated areas. Glacier-wide mass balances shifted from close to balanced in ~~the 1980s~~ 1981-1983 to less than -1.5 m w.e. yr^{-1} in 2012-2014. Winter snow accumulation measured with ablation stakes on the glaciers closely matched observations from helicopter-borne radar. Soil temperature measurements across the basin showed that there was no permafrost in the upper 1 m of the soil column. The data produced by this study is available at http://doi.org/10.14509/30138 and will be useful for hydrological and glaciological studies including modeling efforts.

1 Introduction

Climate change is projected to have significant impacts on future water resources. In snow- and ~~glacier dominated~~ glacier-dominated catchments the response is strongly affected by changes in snow and glacier storage (Bliss et al., 2014; Huss and Hock, 2018). Changes in precipitation amounts and seasonality, air temperature, glacier mass balance, and vegetation type all contribute to changes in river runoff and water availability. Understanding present-day relationships among these contributing factors can help improve projections of future river runoff. ~~To address these questions intensive glaciologic and hydrologic fieldwork was conducted in the~~ However, long-term spatially-representative hydro-meteorological observations in mountain regions are scarce, making it difficult to study these relationships or calibrate and validate modeling studies.

The headwaters of the Susitna River's watershed ~~, central Alaska , during~~ in central Alaska provide an interesting case study of these factors. During the 1980's ~~in~~ intensive glaciologic and hydrologic fieldwork was conducted in the Upper Susitna basin in connection with a proposed hydro-electric dam ~~construction~~ on the Susitna River (Clarke, 1991; R&M Consultants and Harrison, 1981; Clarke et al., 1985). The dam was not built, but when the proposal resurfaced approximately 30 years later (Susitna-Watana Hydroelectric Project, http://www.susitna-watanahydro.org/), we performed extensive field measurements in the same area. Our work combined field measurements with glacier runoff modeling to make projections of the effect of climate change induced future glacier mass changes on the inflow to the proposed dam; this paper focuses on the measurements.

More than ~~120~~ 100 glaciers flow down the southern flanks of the central Alaska Range into the three forks of the Upper Susitna River (Figure 1). The glaciers provide a significant portion of the total runoff within the Upper Susitna drainage. It is well documented that glaciers across Alaska are currently retreating (Gardner et al., 2013; Luthcke et al., 2013). Changes to the timing and amount of runoff due to continued melting of glaciers have been projected to occur worldwide (Bliss et al., 2014; Huss and Hock, 2018). Therefore, it is important to understand how changes to the Upper Susitna basin glaciers and river flow could affect dam operations and environmental resources.

This paper describes the data collected during the 2012-2014 field campaign detailing the instrumentation, method of deployment, and results for each set of data. Observations included meteorological variables, glacier mass balance, snow depth and density, and soil type and temperature. Where possible we also compare the data with the results from the 1980s field campaign.

2 Study area

The watershed above the proposed Susitna-Watana dam (62.822523°N, 148.538986°W; henceforth referred to as the Upper Susitna basin) covers an area of 13,289 km^2 with elevation spanning from 450 to 4,200 m above sea level (a.s.l., Figure 1). About 4% of the basin is glacierized. The total glacier area is 678.4 km^2 according to the Randolph Glacier Inventory version 6.0 (Pfeffer et al., 2014; Kienholz et al., 2015), which is based on satellite imagery from 3 July 2009. Modern glaciers are well within the limit of the Late Wisconsinan glacial advance (20-25 ka BP), when this part of the Alaska Range hosted the northern extent of the Cordilleran Ice Sheet (Kauman and Manley, 2004).

Almost all of the basin's glacier area is found in the Alaska Range whose highest ridges and peaks form the basin's northern boundary. This area is characterized by high relief (Figure 1). Most glaciers (in total 127) in the study area are located in the Alaska Range, but a few small glaciers exist in the Talkeetna Mountains which form the southwest boundary of the basin.

The glacier monitoring work focused on the five largest glaciers in the Alaska Range: West Fork Glacier (193.4 km^2), Susitna Glacier (209.6 km^2), East Fork Glacier (39.8 km^2), Maclaren Glacier (56.5 km^2), and Eureka Glacier (34.0 km^2). Apart from a former tributary of the West Fork Glacier (33.0 km^2), which is now disconnected, the remaining glaciers are smaller than 7 km^2. Ninety-three of the 127 glaciers in the Alaska Range are smaller than 1 km^2 and their total area is 32.3 km^2. Using a volume-area scaling relationship (Bahr et al., 1997), we estimate a total glacier volume of 137 km^3 for the Upper Susitna basin. We use scaling coefficients for mountain glaciers ($c = 0.2055$ m$^{3-2\gamma}$, $\gamma = 1.375$, Radić et al. (2008)). If we assume an

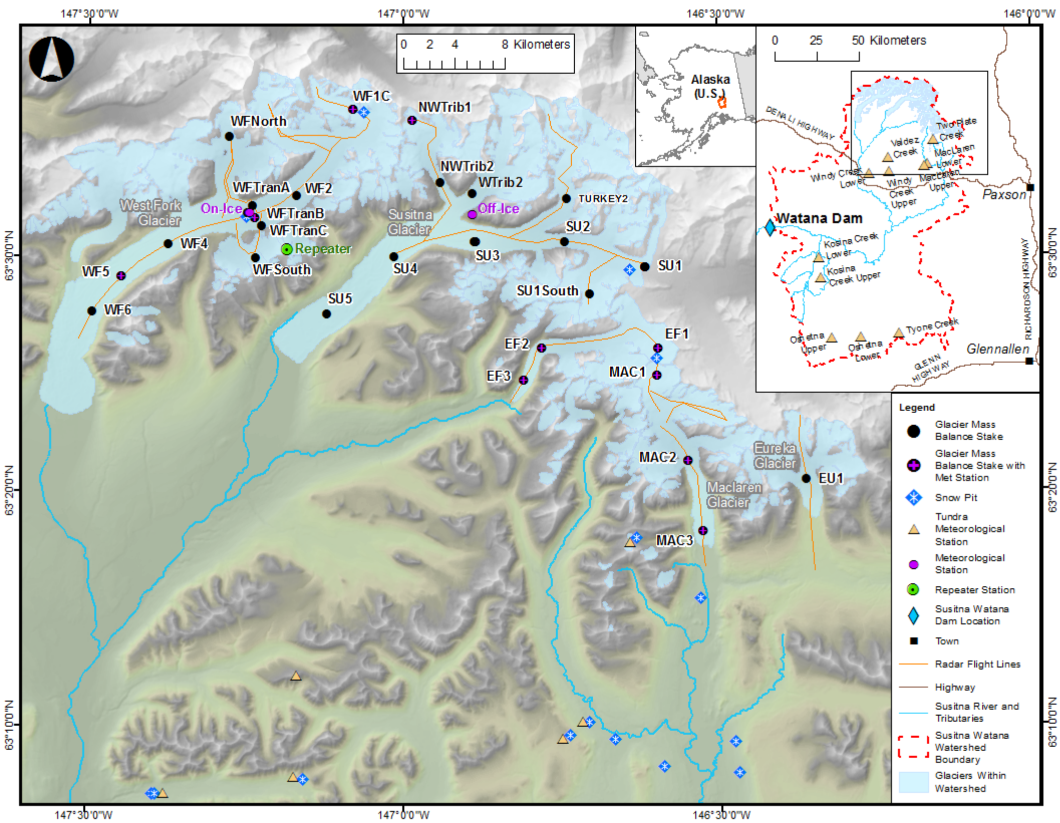

Figure 1. Map of study area including measurement locations. From west to east, the major glaciers are West Fork Glacier (stations with the prefix WF), Susitna Glacier (SU), East Fork Glacier (EF), Maclaren Glacier (MAC), and Eureka Glacier (EU). The main map focuses on the glacierized portion of the basin, the large inset shows the whole Upper Susitna basin which drains to the proposed dam site, and the small inset shows the basin in the context of the state of Alaska.

ice density of 900 kg m^{-3}, this represents 123 Gt of ice. Some of the larger glacier termini reach elevations between 800 and 900 m a.s.l.

The nine glaciers in the Talkeetna Mountains draining to the Susitna river have a combined area of 8.9 km^2. The largest glacier, located at the head of the Black River, is 7.3 km^2. The total glacier volume is less than 0.6 km^3 (0.5 Gt).

Significant portions of the large glaciers in the Alaska Range are covered by rock debris. Debris of sufficient thickness, like that found on West Fork and Susitna Glaciers in particular, has an insulating effect on the ice underneath, reducing the amount of ice melt compared to bare ice areas (Scherler et al., 2011). A Landsat image from 15 September 2010 revealed that the disconnected tributary of West Fork Glacier was 7% covered by debris. Debris covered 18% of West Fork Glacier, 26% of Susitna Glacier, 3% of East Fork Glacier, 6% of Maclaren Glacier and 7% of Eureka Glacier. ~~Debris of sufficient thickness, like that found on West Fork and Susitna Glaciers in particular, has an insulating effect on the ice underneath, reducing the amount of ice melt compared to bare ice areas.~~

Wastlhuber et al. (2017) determined glacier area and mass changes of the basinâ€™s glaciers between 1951 and 2010 and found substantial glacier retreat and mass losses. During this period the glaciers lost an area of 128±15 km^2 (16%) and thinned on average by 0.41±0.07 m yr^{-1}. The average thinning rate almost tripled (1.20±0.25 m yr^{-1} during the later period 2005-2010. Using satellite imagery, the average equilibrium (1999â€“2015) line altitude was found to be at 1745±88 m a.s.l..

Both Susitna and West Fork glacier have a history of surging. Surge-type glaciers experience episodic acceleration of flow at many times their normal velocities, transferring large amounts of ice to lower elevation, and usually result in rapid terminus advance and outburst floods. The last known Susitna Glacier surge occurred in 1951 or 1952, with a pronounced terminus advance and a maximum ice movement of about 4 km (Post, 1960; Clarke, 1991). West Fork glacier surged in 1935 or 1937, and again from 1987 to 1988. The latter produced a maximum ice displacement of 4 km and a surface elevation increase of up to 120 m observed near the terminus (Clarke, 1991; Harrison et al., 1994). Harrison et al. (1994) report that during the termination of the 1987-88 surge that runoff and sediment fluxes sharply increased from the glacier to the Susitna river.

During quiescent periods, mean annual glacier surface velocities in the Upper Susitna basin are estimated to range from 0 to 0.73 m d^{-1} (Burgess et al., 2013); the highest velocities occur on Susitna and West Fork glaciers. Some glaciers experience brief periods of acceleration in spring, which have been linked to enhanced basal lubrication caused by meltwater (MacGregor et al., 2005; Bartholomaus et al., 2008). Periods of deceleration in late summer have been connected to warm summers and greater meltwater production (Sundal et al., 2011).

The non-glacierized part of the basin is characterized by sparse vegetation and little human development. The southeastern part of the watershed is characterized by low relief, numerous lakes, and open spruce forest. The largest lakes are Susitna Lake and Lake Louise. A low divide to the south and east separates the Susitna basin from the Copper River and its tributaries.

The majority of the area draining into the proposed dam is estimated to be underlain by discontinuous and continuous permafrost (Figure 2). Maximum depth to the base of permafrost near the Maclaren River junction with the Susitna River is about 200 m (United States Army Corps of Engineers, 1975), while it is 40 m at Gulkana, approximately 50 km southeast of the basin (Romanovsky et al., 2010). Permafrost affects water runoff, soil temperature, vegetation, and soil carbon fluxes. These factors have complex interactions with climate change.

Nearby weather stations with long-term records include Talkeetna Airport (west of the basin, 1067 m a.s.l.) and Gulkana Airport (east of the basin, 467 m a.s.l.). Annual mean temperature for the period 1985-2014 at Talkeetna was 1.4 ° C and at Gulkana -1.5 ° C (http://ncdc.noaa.gov). Precipitation averaged 710 mm yr^{-1} at Talkeetna and 288 mm yr^{-1} at Gulkana.

Flow of the Susitna River at Gold Creek (62°46'04" N, 149°41'28" W, downstream of the basin considered in this paper) was 8.8±1.2 km^3 yr^{-1} (mean ± standard deviation), or 277.8±36.8 m^3 s^{-1}, over the period 1950-2015 with a measurement hiatus from 1997-2000. Peak flow was usually in mid-June.

3 Climatological and meteorological data

Climate exerts the primary influence on river runoff and glacier mass balance. The meteorological and climatological knowledge of mountainous areas of south-central Alaska, including the Upper Susitna basin, is generally poor, largely due to the

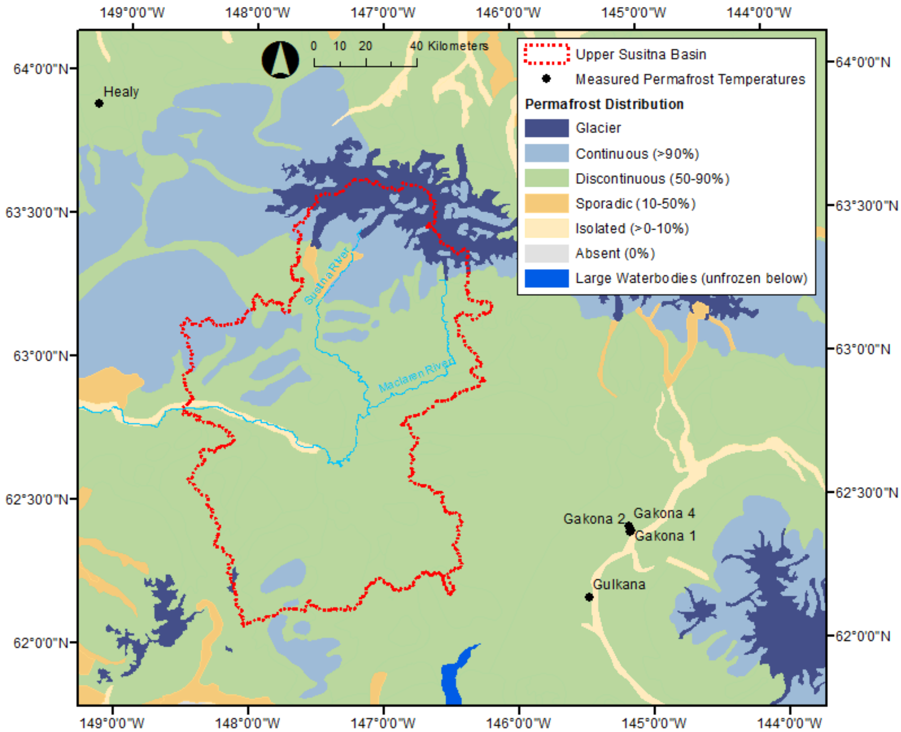

Figure 2. Distribution of permafrost in study area (modified after Jorgenson et al. (2008)).

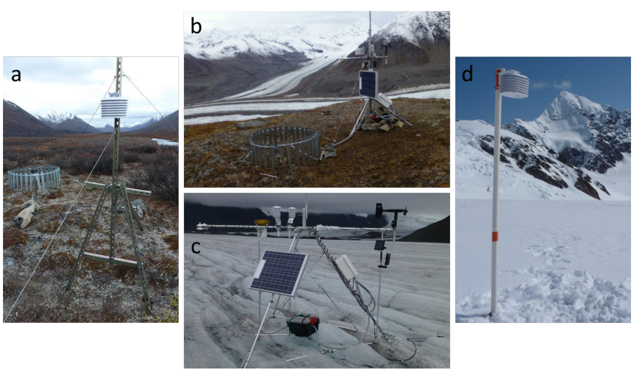

Figure 3. Photos of employed weather stations: (a) Example of a tundra station, (b) Off-Ice station perched on a Susitna Glacier nunatak, (c) On-Ice station located on West Fork Glacier, (d) Example of simple glacier station.

sparse and poorly distributed data (no in-situ data available from high elevations) and the lack of consistent, long-term measurements. To improve the coverage, we strategically placed two energy balance weather stations in the Alaska Range, and 25 simple weather stations throughout the entire watershed (Figures 1 & 3). Table A1 lists the location and elevation of all meteorological stations used in this study.

3.1 Energy balance weather stations

3.1.1 Instrumentation

Two energy balance weather stations were installed in the upper part of the basin, one on the West Fork Glacier and one on a ridge between the two branches of the Susitna Glacier (Figure 3).

The glacier station (On-Ice) was installed on 16 April 2013 in the glacier's ablation area at 1398 m a.s.l., and operated until 6 September 2014 (Figure 1). The station ~~floated~~ "floated" on the ice surface keeping the air temperature sensor at a consistent height as the surface melted (approximately 2 m above the ice surface). All the variables listed in Table 1 were recorded during the summers of 2013 and 2014. Snow temperatures were measured at three levels (0.65 m, 1.15 m, and 1.65 m below the initial snow surface; the snow depth was 2.15 m at installation on 17 April 2013). Sensors were attached to the tip of 20 cm long aluminum poles which were pushed into the snow (from a snow pit) at a slight upward angle from horizontal to minimize measurement errors caused by the effect of water percolation along cables. Ice temperatures were measured at 14 levels with a thermistor string lowered into a borehole close to the weather station drilled with a hot water drill. The upper seven thermistors were spaced 0.5 m apart, while the remaining ones were 1 m apart. At installation, the uppermost thermistor was at 0.1 m and the lowest one at 10 m below the ice-snow interface. Surface elevation change was measured with a sonic ranger on a separate pole drilled into the ice 5.6 m north of the weather station. A camera on the weather station mast took pictures of the sonic ranger pole every hour, providing visual information on surface type (snow, ice) and the surface elevation change. The sonic ranger pole was marked with tape at 10 cm intervals for visual clarity.

For winter 2013/2014, some instruments were removed (radiometers, precipitation gauge, sonic ranger, and camera) and data are not available for the period 4 September 2013 - 25 April 2014 (Figure 4). Based on the relative humidity values at the On-Ice station and precipitation data from nearby manned weather stations (Alpine Creek Lodge, Talkeetna Airport, Gulkana Airport), we estimate that the station's air temperature and relative humidity sensors were buried by snow from 19 January 2014 until the field visit on 22 April 2014. During the field visit, we excavated the station, placed it on top of the winter snowpack and reinstalled the instruments removed for winter.

A second multi-variable weather station (Off-Ice) was installed at 1516 m a.s.l., 18 km east of the On-Ice station (Figure 1). The station records all the variables listed in Table 1 except for snow and ice temperatures and snow surface elevation changes. The station was installed on 16 July 2012 and continues to operate under ~~DGGS stewardship~~ the stewardship of Alaska Division of Geological and Geophysical Surveys (here we present data through 6 September 2014). A low battery caused the station to stop working on 24 March 2013 but it was restarted on 16 April 2013. Liquid precipitation data are not continuous during the 2012-2014 record since the rain gauge was removed each fall and reinstalled in spring.

Both multi-variable stations sampled their sensors every minute and recorded averages (or sums in the case of precipitation) for hourly and daily values. Wind speed and direction were sampled on a 3-second interval to capture maximum wind speeds during gusts, yet average wind speeds were recorded for hourly and daily intervals. Barometric pressure was sampled every 30 minutes~~instead of every minute~~.

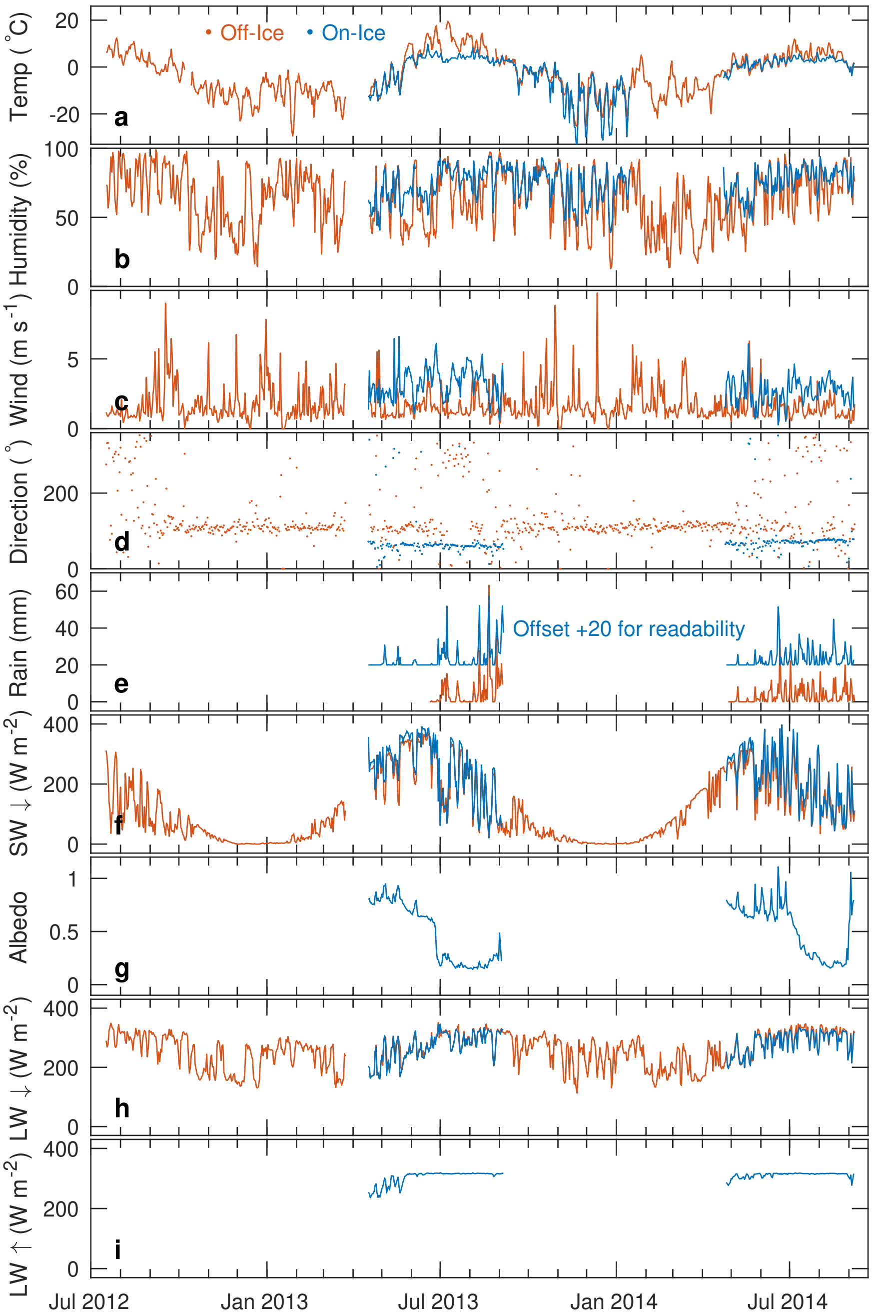

Figure 4. Meteorological data from the On-Ice and Off-Ice stations from July 2012 to September 2014. (a) Daily temperature, (b) relative humidity, (c) wind speed, (d) wind direction, (e) precipitation, (f) incoming shortwave (SW) radiation, (g) albedo, (h) incoming longwave (LW) radiation, and (i) outgoing ~~longwave~~ LW radiation. All values are daily means except for precipitation which is the daily sum. Data gaps occur in winter when some sensors were removed. The On-Ice temperature/humidity sensor was buried in the snowpack in mid-January 2014 and re-exposed during a station visit on 22 April 2014 so data are not included for that interval.

Table 1. Sensors used for the energy balance weather stations (On-Ice and Off-Ice).

Variable	Sensor	Unit	Accuracy
Temperature	Rotronic HygroClip2 Temperature/RH Probe*	°C	0.1°C
Relative humidity	Rotronic HygroClip2 Temperature/RH Probe*	%	0.8%
Barometric pressure	Vaisala PTB110 Barometer	hPa	1 hPa
Incoming longwave radiation	Hukseflux 4-Component Net Radiation	W m^{-2}	10%
Outgoing longwave radiation	Hukseflux 4-Component Net Radiation	W m^{-2}	10%
Incoming shortwave radiation	Hukseflux 4-Component Net Radiation	W m^{-2}	10%
Outgoing shortwave radiation	Hukseflux 4-Component Net Radiation	W m^{-2}	10%
Rainfall	Texas Electronics Rain Gage**	mm	1%
Tilt of the radiation sensors	Turck Inclinometer B2N45H-Q20L60-2LU3-H1151	degrees	0.5 degrees
Wind direction	RM Young Wind Monitor, Alpine version	degrees	5 degrees
Wind speed	RM Young Wind Monitor, Alpine version	m s^{-1}	0.3 m s^{-1} or 1%
Distance to ice surface (ablation)***	SR50A	m	1 cm or 0.4%
Snow temperature***	Thermistor 3K Ohm from Digikey	°C	0.1 °C
Ice temperature***	Thermistor 3K Ohm from Digikey	°C	0.1 °C
Datalogger	Campbell Scientific CR1000	-	-

* Shielded with a RM Young 10-plate Gill shield.

** Installed at the Off-Ice station at 0.6 m (top of gauge to ground surface) and shielded with a Novalynx Alter-type Rain Gage Wind Screen. Installed at the On-Ice station on top of the instrument arm at 2 m above the surface and unshielded (Figure 3). Gauges were not heated and hence gave most accurate results when precipitation was liquid rather than solid.

*** Only at the On-Ice station

3.1.2 Meteorological data

The daily meteorological data for both the On-Ice and Off-Ice station are shown in Figure 4, and seasonally averaged correlation coefficients between the two station's daily data are given in Table 2. Air temperatures at each station were significantly more variable in winter than in summer due to frequent winter weather systems. Both station's daily temperatures correlated well in all seasons except summer (June-August), when temperatures at the On-Ice station exhibited considerably less day-to-day variability than the Off-Ice station. In addition, albeit 118 m lower in elevation, the On-Ice station's temperatures were ~~also~~ more than 4°C ~~lower than at~~ cooler than the Off-Ice station. These differences are attributed to the fixed glacier surface temperature of 0°C during ~~the~~ extended periods of glacier melting during summer. The cold glacier surface cooled the air above it. Though differences were not as pronounced, lower air temperatures at the On-Ice station were also observed during other seasons. This is due, in part, to the high albedo at the On-Ice station.

Relative humidity at the On-Ice station was typically higher than at the Off-Ice station, consistent with lower air temperatures ~~On-Ice~~ and greater availability of moisture for evaporation over the glacier. The On-Ice station also displayed less day-to-day

Table 2. Seasonal means of meteorological variables for the On-Ice and Off-Ice stations based on data between 18 April 2013 and 6 September 2014. All data are for times when both stations were operating, so these data do not represent full season averages. Data were excluded from the period when the On-Ice station was buried by snow: 18 January 2014 to 22 April 2014. Correlations for precipitation excluded days when both stations had no precipitation.

Variable		Range	DJF	MAM	JJA	SON
Temperature $(^{\circ}C)$	On-Ice	-33.6 to 9.7	-15.2	-3.1	3.5	-5.9
	Off-Ice	-25.6 to 19.5	-9.7	-4.6	7.2	-5.0
	r		0.91	0.93	0.64	0.96
Relative humidity $(\%)$	On-Ice	39.0 to 94.4	70.0	65.6	79.2	75.2
	Off-Ice	12.9 to 97.7	54.6	53.7	69.3	71.6
	r		0.91	0.68	0.84	0.93
Wind speed (ms^{-1})	On-Ice	0.3 to 6.5	$\cdots$	2.8	3.1	2.5
	Off-Ice	0.0 to 9.8	1.9	1.6	1.5	1.8
	r		$\cdots$	0.23	0.26	0.83
Wind speed max (ms^{-1})	On-Ice	2.1 to 16.8	$\cdots$	7.5	6.9	8.3
	Off-Ice	0.0 to 30.6	8.1	7.3	7.2	8.4
	r		$\cdots$	0.67	0.64	0.78
Precipitation (mm)	On-Ice	0.0 to 37.4	$\cdots$	0.8	3.9	8.9
	Off-Ice	0.0 to 63.2	$\cdots$	0.8	4.7	7.6
	r		$\cdots$	0.86	0.72	0.63
Incoming shortwave (Wm^{-2})	On-Ice	21 to 397	$\cdots$	286	217	129
	Off-Ice	0 to 369	16	215	200	49
	r		$\cdots$	0.93	0.97	0.99
Incoming longwave (Wm^{-2})	On-Ice	161 to 345	$\cdots$	237	295	293
	Off-Ice	113 to 351	225	227	301	265
	r		$\cdots$	0.94	0.94	0.94

variability than at the Off-Ice station. Data are not available from from 18 January 2014 to 22 April 2014 when the station was buried in snow.

Daily mean wind speeds were typically higher at the On-Ice station than at the Off-Ice station which can be attributed to the relatively smooth glacier surface, longer fetch, and summer-time katabatic wind. Highest wind speeds occurred during winter with maximum wind gusts (3-second averages) up to 30.5 m s^{-1} (11 December 2013).

Vector-averaged daily wind directions were commonly in the down-glacier direction (65° On-Ice, 100° Off-Ice), consistent with a katabatic wind. In summer, the wind direction would often reverse during part of the day, causing the daily directions to be more variable.

Total precipitation at the Off-Ice station was slightly higher (9%) than at the On-Ice station during the periods both stations were functional, however, direct comparison is difficult since the instrumental set-up was different with no wind shield and installation higher above the surface at the On-Ice station.

Incoming solar radiation displayed pronounced seasonal variability consistent with the site's latitude close to the polar circle. Daily mean values varied between just 16 W m^{-2} in winter and approximately 400 W m^{-2} in summer. Cloudy days in summer are clearly discernible due to their lower shortwave radiation compared to neighboring sunny days. High correlation (r=0.97) between both daily time series indicates relatively homogeneous cloud conditions at those sites. A portion of the difference between the two stations may be due to topographic shading.

In both 2013 and 2014, daily albedo in May and June had peaks between 0.7 and 1 and by late July and August albedo fell to 0.2. The summer of 2013 featured a drop in albedo from 0.6 to 0.2 over 5 days starting 25 June 2013 indicating the transition of a snow-covered to a snow-free surface. In 2014, the same transition took one month starting 4 July 2014. We did not measure reflected shortwave radiation at the Off-Ice station, but expect it to be significantly lower than the On-Ice station due to the low albedo of the rocky surface compared to the On-Ice glacier surface.

Incoming longwave radiation, which mainly depends on the effective radiative temperature of the atmosphere, showed a slight seasonal cycle (Off-Ice station) with an amplitude of roughly 80 W m^{-2}. Large daily variations superimposed on the seasonal cycle and negatively correlated with incoming solar radiation indicate variations in cloud cover. Incoming longwave was well-correlated between the On-Ice and Off-Ice stations (r=0.94 for summer).

In both summers (2013 and 2014), outgoing longwave radiation increased through the spring to just below 320 W m^{-2} in mid-June and then plateaued through the end of August. Blackbody radiation from an object at 0 °C would be expected to be 316 W m^{-2}, indicating that the effective radiative temperature of the ice surface and air between the surface and the sensor was just above 0 °C, and the surface was melting uninterruptedly for extended periods in summer.

3.1.3 Snow and ice temperatures

The thermistor string we deployed in a hot-water-drilled borehole needed time to equilibrate to its surroundings after installation. We consider the thermistor ice temperature measurements to be reliable starting on 25 April 2013, about 8 days after installation. By that time, the 5 m deep thermistor temperatures were within 0.02 °C of the trend they held for the subsequent 4 weeks.

Temperatures within the upper 10 meters of the glacier surface ranged from approximately -10°C in the upper layers of snow pack in early May 2013 to close to the melting point of 0°C at 10 m below the ice surface (Figure 5~~).~~

c). As air temperatures rose, the subsurface temperatures of the upper layers increased but with a time lag that increased with depth (Figures 5 and 6). When the air temperature rose above 0°C, surface melt began to occur. As meltwater or rain percolated into the snowpack it refroze, causing abrupt temperature increases of the uppermost thermistors (e.g. 10 and 25 May 2013, Figure 5). The glacier surface lowered with respect to the subsurface sensors by roughly 5 m between late April and early September 2013 as the melt season progressed (Figure 5b). The three snow sensors and uppermost 6 ice sensors were exposed to the air sequentially during the summer melt season. On 24-25 June, the ice temperature sensors at 0.1, 0.5,

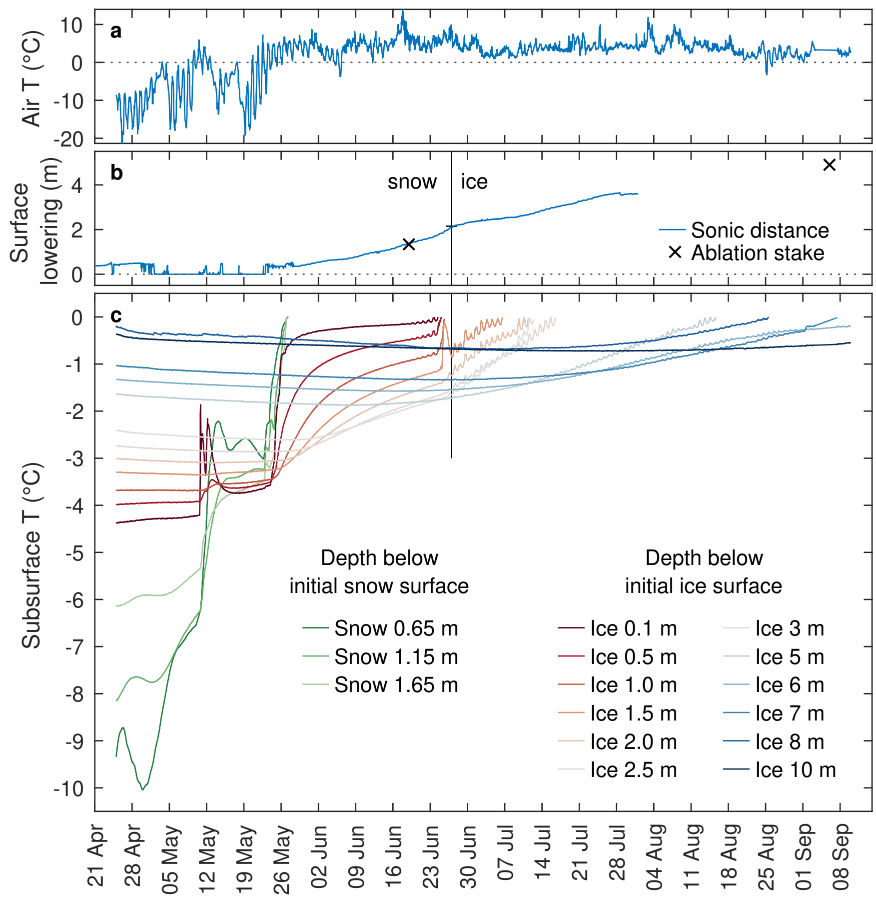

Figure 5. Hourly ice and snow temperature (T) measurements from thermistors installed at depth in the snow and ice adjacent to the On-Ice weather station in 2013 (c). Panel (a) shows air temperature, (b) shows cumulative surface lowering measured by the sonic ranger and ablation stakes. Initial thermistor depths are listed in the legend given in depth below the initial snow surface for the three snow thermistors and depth below the snow-ice surface interface for the 12 ice thermistors. The snow depth at installation on 19 April 2013 was 2.10 m. Note that the instrumentation depth becomes shallower as the glacier surface ablates during the melt season. The onset of large diurnal temperature fluctuations above 0°C indicates that the thermistors have melted out and are affected by solar radiation. After a sensor exceeds 0°C, we do not plot the remaining data.

1, and 1.5 m below the snow-ice interface all experienced rapid warming to about 0°C. The 1.5 m sensor then cooled back down to -0.85°C. We interpret this to be another meltwater event but this time in the upper layers of glacier ice rather than the snowpack. It is difficult to know whether the event was representative of conditions in the glacier (i.e. water moving through cracks and along grain boundaries in the ice) or simply conditions along the thermistor cable. By 27 June, all 2.1 m of snow at the site had melted and the ice surface was exposed, as measured by the SR50 and confirmed with the time lapse imagery.

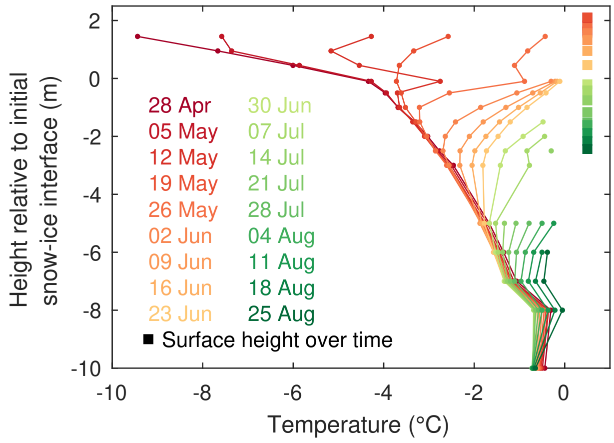

Figure 6. Vertical profiles of temperature in the upper 10 m of the glacier at the On-Ice station in summer of 2013. After a sensor exceeds 0°C, we do not plot the remaining data.

After 27 June, sensors at 2, 2.5, and 3 m depth exhibited diurnal temperature wiggles with an amplitude of up to 0.2°C. By mid-July the diurnal wiggles appeared in the sensors at 5, 6, and 7 m depth too. Some of the ice temperature sensors at depths $\geqslant$5 m recorded temperatures greater than 0°C starting in late August 2013. These measurements are likely errors, perhaps due to faulty voltage sensor outputs. The data-logger continued to record reasonable results for other variables.

3.2 Simple weather stations

3.2.1 Instrumentation

To supplement the multi-variable weather stations described above and constrain the spatial patterns of temperature and precipitation within the basin, we installed 26 simple weather stations across the basin both on and off the glaciers (Figure 1; Table A1). The 14 stations on or very near the glaciers (EF1, EF2, EF3, Mac1, Mac2, Mac3, Repeater HOBO, NWTrib1, Off-Ice HOBO, SU1, SU3, WF1, WFTranB, WF5; letters refer to glacier names) measured air temperature and relative humidity at a nominal height of 1.75 m above the glacier surface. We refer to these stations collectively as the "glacier" weather stations. The sensor mounts for the glacier stations were designed to maintain approximately the same sensor height relative to the glacier surface throughout the ablation season. This was accomplished by allowing the mount to slide down the ablation stake as the glacier surface melted (Figure 3). The other 12 simple weather stations are referred to as the "tundra" stations. The typical tundra station measured temperature, relative humidity, rainfall, and soil temperature at 10 cm and 1 m depths. Simple weather station instruments are listed in Table 3.

Temperature and relative humidity were recorded every 10, 15, 30 minutes (most stations), or 60 minutes, depending on the station. Each station's data was then averaged in post-processing to hourly and daily values. Hourly and daily precipitation sums were calculated for each tip of the rain gauge tipping bucket.

Table 3. Sensors used for the simple glacier and tundra weather stations. Glacier stations included only temperature and relative humidity while tundra stations also included precipitation and soil temperature measurements.

Variable	Sensor	Unit	Accuracy
Temperature	HOBO Pro v2 U23-001 *	°C	0.21 °C
Relative humidity	HOBO Pro v2 U23-001 *	%	3.5%
Rainfall	HOBO RG3-M **	mm	1%
Soil temperature	HOBO Pro v2 U23-003 2x External Temp.	°C	0.21 °C

* shielded with a HOBO M-RSA Gill-type shield.
** shielded with a Novalynx Alter-type Rain Gage Wind Screen.

3.2.2 Sensor calibration

To ensure the validity of data collected from many individual sensors scattered across our study area, we set them up side-by-side before deploying them to the field. Eight factory-calibrated HOBO temperature and relative humidity sensors were co-located with a factory-calibrated Rotronic sensor connected to a Campbell datalogger in April 2013 in Fairbanks, Alaska~~, for calibration~~. To avoid errors due to direct solar radiation the sensors were installed in an outside area shaded during most hours, in particular during mid-day. Another set of 14 HOBO sensors were calibrated at the same location in April 2014. Measurements were ~~done~~ taken and logged every 5 minutes~~and hourly averages were logged.~~ . Hourly averages were also logged.

Temperatures during the 2013 calibration period ranged from -22 °C to -5 °C and from -15 to +10 °C in 2014 (Figure 7). The temperature offset of hourly-mean HOBO sensors relative to an arbitrarily-chosen reference HOBO station was typically within ±0.1 °C and rarely beyond ±0.3 °C. Over both periods, the temperature offset had a mean of 0.02 °C and a standard deviation of 0.07 °C (Table 4).

Compared to the Campbell/Rotronic sensor, HOBO temperatures were lower by 0.2-0.3 °C on average ~~°C~~ (Table 4) but differences exhibited a diurnal cycle with temperatures more than 1 °C lower during mid-day in many cases (Figure ~~4~~7). Five-minute data showed that the response time of the HOBO sensors was slower than the Campbell sensors, but this can not explain the differences in hourly or daily means (Figure 8). The correlation coefficient between hourly values of temperature from the Rotronic sensor and HOBO sensors was 1.0.

The lack of a consistent pattern in these comparisons (Figure 7) prevented us from adjusting the HOBO temperature data to match the Campbell data. The high correlation and low temperature offsets (Figure 8) among sensors gave us confidence that using HOBO stations to assess temperature patterns across the basin was valid.

Measured relative humidity ranged from approximately 25% to 90% during the April 2013 calibration period and about 20% to 90% in April 2014 (Figure 7). HOBO sensors generally recorded higher relative humidity compared to the Rotronic sensor (Table 4). The offset in temperature (HOBO was colder than Campbell) explains part of that difference, though absolute humidity calculations show that the HOBO sensors are registering higher total moisture content for both the cold (2013) calibration period and the warmer one (2014). Relative humidity values from the HOBO sensors were well-correlated (r=0.99)

Table 4. Statistics of air temperature and humidity sensor calibration. Eight HOBO sensors were calibrated in 2013 (5-8 April) and 14 sensors in 2014 (15-18 April). For each year the differences in hourly means between each HOBO station and a reference station were calculated; then the differences from all stations were concatenated before calculating the mean, standard deviation, range, and skewness of the distribution. Two reference stations were used: a Rotronic HygroClip2 Temperature/RH Probe measured by a Campbell datalogger and an arbitrarily chosen HOBO station (data in parenthesis).

Variable	Year	Mean	σ	Range	Skewness
Temperature (°C)	2013	-0.3 (0.0)	0.2 (0.1)	1.1 (0.6)	-0.6 (-1.1)
Temperature (°C)	2014	-0.2 (0.0)	0.3 (0.2)	2.2 (1.8)	-1.1 (3.0)
Relative humidity (%)	2013	5.6 (1.4)	3.4 (1.2)	19.4 (10.5)	1.2 (2.2)
Relative humidity (%)	2014	2.2 (-1.0)	2.0 (1.0)	13.2 (6.2)	0.9 (-0.7)
Vapor pressure (hPa)	2013	9.3 (3.3)	6.0 (2.9)	50.0 (27.3)	2.4 (2.1)
Vapor pressure (hPa)	2014	14.5 (-8.5)	11.1 (8.2)	65.3 (54.1)	0.1 (-0.7)

with those from the Rotronic (Figure 8). Again, this gave us confidence that we could use our data to assess humidity variations across the basin.

In mid-April 2014, a laboratory calibration of the tundra station precipitation tipping bucket gauges revealed an intermittent instrument signal problem (Wolken et al., 2015). Single tips in the rain gauge were being recorded as two tips on the datalogger; thus the recorded precipitation amount appeared twice as much as the actual rainfall amount. In the field data, all HOBO stations recorded some of these double tips. A few tundra stations recorded up to 10% double tips (Kosina Creek Upper, Kosina Creek Lower, and Windy Lower). Precipitation rates that could cause two tips within 2 seconds (360 mm/hr) far exceed the actual precipitation rates observed in the basin. To correct this data problem, for every pair of tips that occurred within 2 seconds, we zeroed out the second tip. The analysis done in this paper uses the corrected rainfall data.

We looked for similar double tips in the On-Ice and Off-Ice station data, but did not find any. The HOBO and Campbell sensors use the same internal electronics to detect tips, so we surmise that the Campbell logger is filtering out any double tips before recording the data.

3.2.3 Spatio-temporal variability of air temperature, humidity, and precipitation

Time series of daily air temperature, humidity and precipitation of all stations (On-Ice, Off-Ice, and tundra stations) are shown in Figure 9.

Cumulative measured precipitation amounts for the summers 2012, 2013, and 2014 varied significantly across the domain, while the timing of events was generally consistent among the stations (Figure 9). Precipitation amounts did not correlate significantly with elevation, slope, aspect, or location.

Air temperatures at all sites showed similar seasonal variations but as expected temperatures varied with elevation. Figure 10 shows largely linear trends of monthly mean temperature with cold temperatures at high elevations in summer of 2013

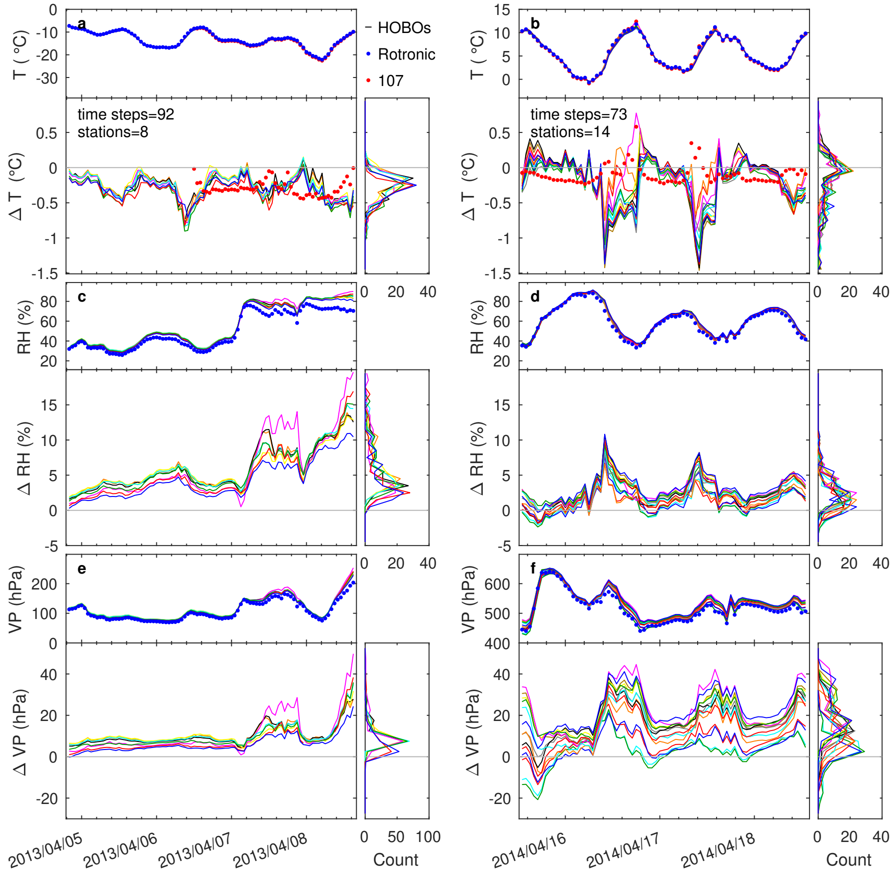

Figure 7. Time series of hourly air temperature T (a, b), relative humidity RH (c, d), and derived vapor pressure VP (e, f) of eight HOBO sensors during the calibration period in 2013 (a, c, e) and 14 sensors in 2014 (b, d, f), and their differences to the Rotronic reference sensor. Each colored line represents a HOBO sensor, blue dots are for the reference Rotronic sensor, and red dots are for a Campbell 107 Temperature Probe. Also shown is the count of differences between HOBO and reference values in bins of 0.1 °C, 1 % and 5 hPa.

and 2014. Environmental temperature lapse rates showed a larger temperature gradient for the tundra stations compared to the glacier stations. In summer, when air temperatures were above freezing, the ice surface cooled the air over the glacier. This cold air descended due to its greater density than the air around it, setting up a katabatic flow. Continued cooling from the glacier partially offset adiabatic warming as the air descended and led to the lower temperature gradient at the glacier stations.

Given the difficulty of calculating monthly lapse rates due to missing data (Figure 10), we also calculated weekly average temperature and plotted it to illustrate the changing lapse rate with the seasons across the basin (Figure 11). The summer glacier/tundra pattern transitioned back to a single lapse rate when the air temperature fell below 0°C. Winter inversions (with warmer air at higher elevation stations) are common, such as in January 2013 and January 2014. The glacier station at 1400

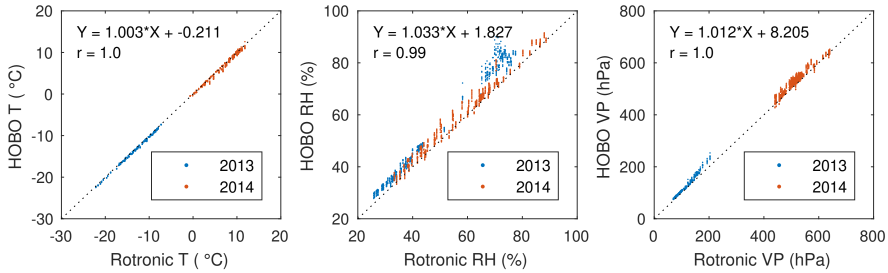

Figure 8. Hourly-averaged data from all HOBO sensors compared to the Rotronic sensor for the calibration periods in 2013 (5-8 April) and 2014 (15-18 April). Equations of the best fit lines and correlation coefficients are listed in each panel.

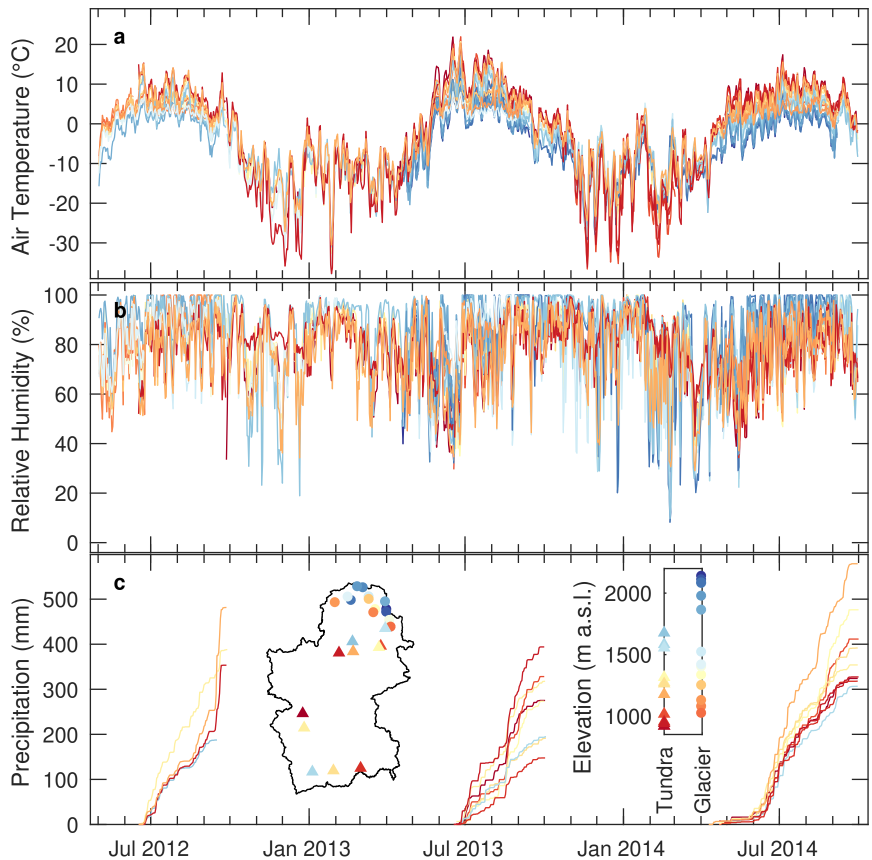

Figure 9. Daily mean temperature (a), relative humidity (b), and cumulative precipitation (c) for the tundra and glacier stations. Data is colored by station elevation (inset graph). The inset map shows station locations.

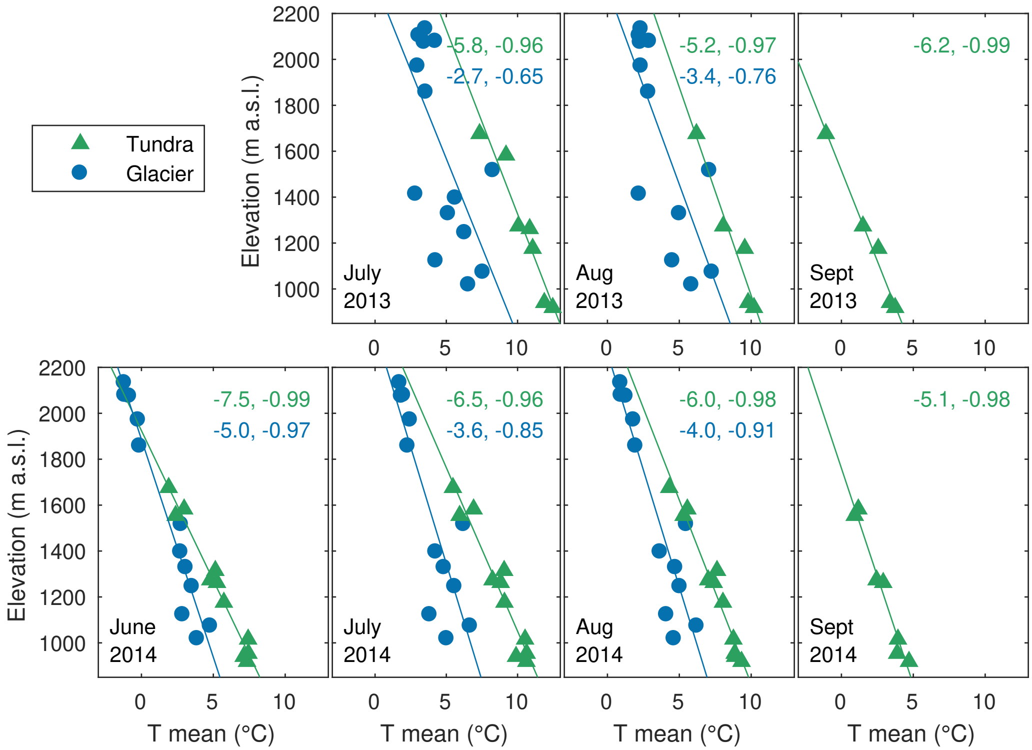

Figure 10. Monthly air temperature profiles from simple weather stations on the glaciers and on the tundra. Environmental lapse rates (°C km^{-1}) were calculated by linear regression between monthly average data and station elevations and are reported in the upper right of each subplot, along with the r-value of the fit.

m a.s.l. was buried by snow for part of each winter and therefore stands out as a warm outlier during those times. Springtime lapse rates are the ~~least complicated~~ most distinct - most stations fall along the best fit gradient.

3.3 Trends

Our field measurements did not cover enough time to establish long term trends of temperature or precipitation. For context, we evaluated nearby stations with long term records from the National Climatic Data Center. The best correlations with our On-Ice station, for temperature and precipitation, came from Talkeetna Airport. The Talkeetna station was 197 km southwest of the On-Ice station and almost 1300 m lower, at 107 m a.s.l. Summer temperatures at Talkeetna Airport in 2012-2014 were 1.1°C warmer than 1981-1983. Annual temperatures were 0.5°C warmer in the recent period. Precipitation was variable year to year, but showed little trend. Annual precipitation for the three-year interval in the 1980s averaged 746 mm and in the 2010s it averaged 747 mm.

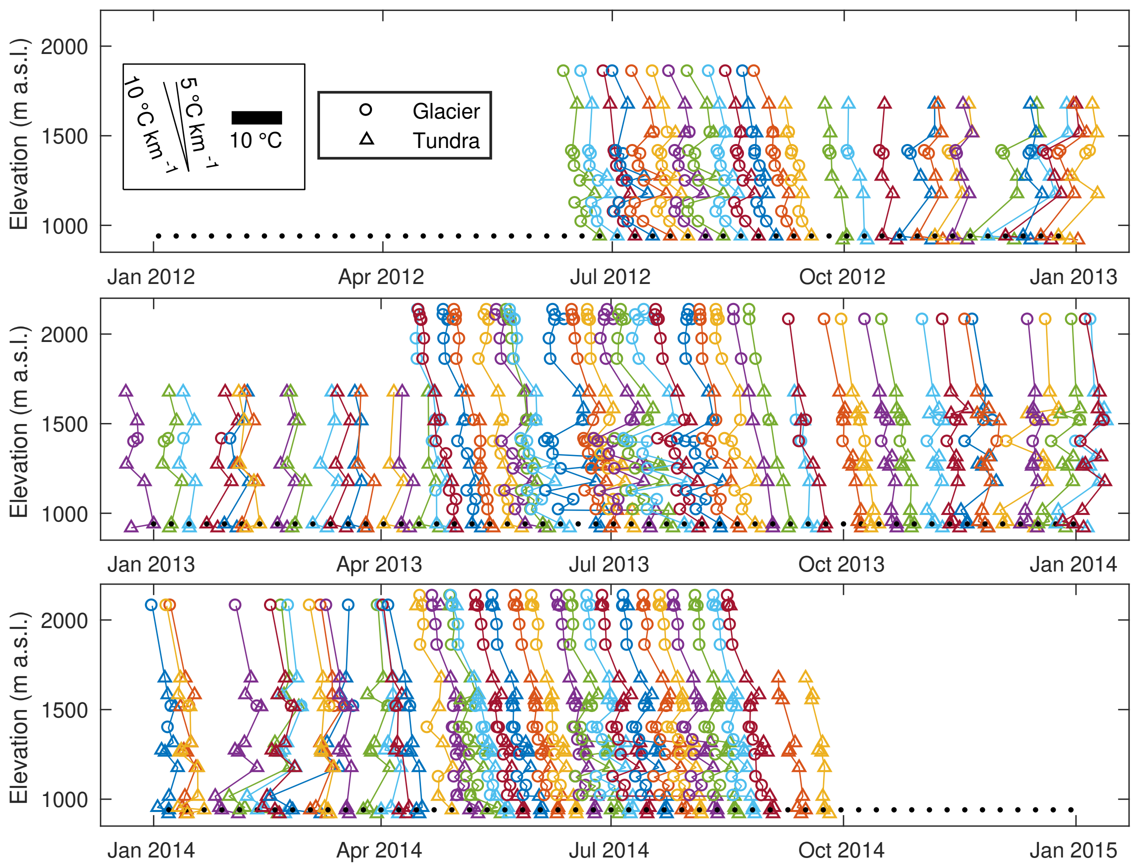

Figure 11. Weekly air temperature profiles show the winter inversions and summer differences between glacier and tundra temperature. Each For each week's profile is plotted relative to a , the reference station (Windy Creek Lower, 940 m a.s.l., triangles and black dots) was plotted on the horizontal axis according to the date. The other stations (triangles or circles) were plotted to the left or right of the reference station according to their temperature difference. Stations with significant data gaps in a week were not plotted. Many glacier stations were removed in winter due to snow.

4 Glaciological data

Glacier mass changes were determined from in-situ point observations in spring and fall of each year, snow radar measurements in spring and continuous measurements of relative surface elevation change at the On-Ice Weather station.

4.1 In-situ point mass balance measurements and derived glacier-wide balances

Winter, summer and annual mass balances were measured at 27 to 29 locations spread across the five largest glaciers, West Fork, Susitna, East Fork, Maclaren, and Eureka (Figure 1) using the glaciological method (Cuffey and Paterson, 2010). The stake distribution was designed to reoccupy the approximate stake positions used in the Clarke et al. (1985) study covering 1981-1983, and to sample the elevation range of each glacier. Most measurement sites followed the centerline of glaciers. We performed measurements for three mass balance years: 2012, 2013, and 2014, where a mass balance year refers to ~~the period from~~ October to the following September. For example, year 2012 refers to October 2011 to September 2012. Winter snow accumulation on glaciers was estimated at each stake by snow probing and/or snow pit measurements in late April of each year. The amount of snow and ice that melted each summer was measured at each stake in early September.

The most negative annual point balance among the measured glaciers was almost -6 m w.e. (2013 at 1100 m a.s.l. on East Fork Glacier), while the most positive was nearly 2 m w.e. (2014 at 2000 m a.s.l. on Susitna Glacier). Figure 12 indicates a strong elevation-dependence of all point balances. The equilibrium line altitude for the region ~~varied~~ was about 1730 m a.s.l. in 2012 and 1960 m a.s.l. in 2013, as estimated from the zero-crossing of the best-fit line to the mass balance profile data (Figure 12). With a large fraction of the glacier at higher elevations (Figure 12) this corresponds to an accumulation area ratio of 0.58 for 2012 and 0.34 for 2013. Wastlhuber et al. (2017) used Landsat imagery to derive equilibrium line altitudes for the set of 5 large glaciers of about 1675 m a.s.l. for 2012 and 1800 m a.s.l. for 2013. Their 2012 value matches ours within uncertainties, but our 2013 value is significantly higher, indicating the surface mass balance might not have been accurately estimated from satellite data or the best-fit line might be too sensitive to data from lower elevations.

The point mass balance measurements were used to compute the glacier-wide winter, summer and annual mass balance for each of the five glaciers for the mass balance years 2012, 2013, and 2014. First, we linearly interpolated the mass balance measurements across elevations to get a continuous mass balance profile for each glacier for each year. Glacier elevations above and below the measurement range were assigned the mass balance value of their nearest neighbor. The mass balance profiles were distributed to the entire glacier area based on the glacier hypsometry (50 m elevation bins). Glacier-wide mass balance estimates were then calculated by summing the distributed mass balance over the whole glacier. Annual balance was calculated from the sum of winter and summer balance (Table 5). Winter glacier-wide balances ranged from 0.74 m w.e. to 1.3 m w.e.. Glacier-wide summer balances ranged from -4.42 to -1.81 m w.e. The summer balance in 2014 was less negative than in 2012 and 2013. Annual balances ranged from -0.71 to -3.67 m w.e. The glacier-wide annual balance was negative for all years and all glaciers, indicating that the summer mass loss was greater than the winter accumulation. The annual balance in 2014 was less negative than in 2012 and 2013. ~~East Fork Glacier had a similar mass balance as Maclaren Glacier.~~

4.2 Glacier mass balance: comparison to 1980's data

~~The glacier mass balances~~ Mass balance on the glaciers changed substantially from 1981-1983 to 2012-2014 (Figure 12). ~~Our measurements for 2012-2014 show that the glaciers~~ Glaciers in the early 1980's generally had more positive or less negative mass balance than the early 2010's across all elevations (Figure 12). Year 2013 had the most negative mass balance of the six years measured and the highest equilibrium line.

~~Consequently glacier-wide~~ Glacier-wide summer mass balances became more negative between the 1980s (-0.81±0.21 m water equivalent, mean±std of 4 glaciers) and 2010s (-2.69±0.77 m w.e. mean±std of the same 4 glaciers with stakes in approximately the same locations). In contrast, winter balance was similar between the 1980s (0.88±0.22 m w.e.) and

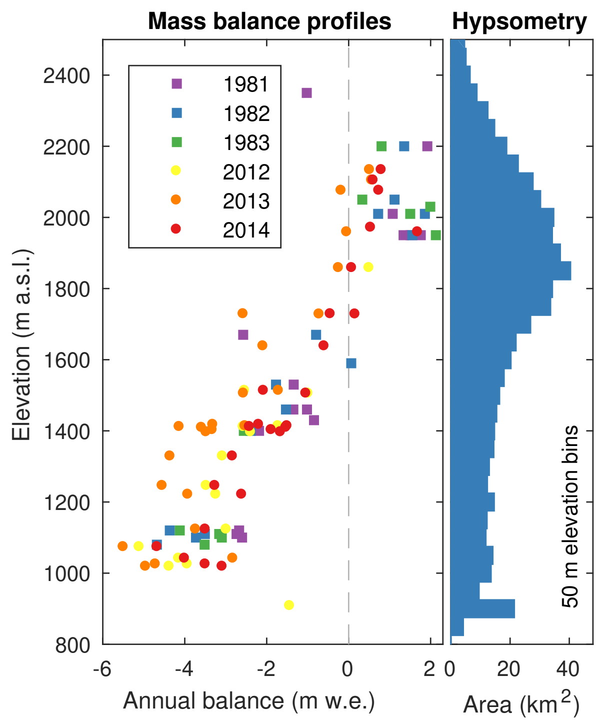

Figure 12. Annual point mass balances measured with the glaciological method on West Fork, Susitna, East Fork, Maclaren, and Eureka Glacierversus elevation. The apparent outlier in 2012 (-1.4 m w.e. at 908 m a.s.l.) was due to debris cover at the site. The hypsometry of all 127 glaciers in the Alaska Range portion of the Susitna basin is also shown in 50 m elevation bands. The hypsometry comes from the Randolph Glacier Inventory (Pfeffer et al., 2014), which used glacier outlines from 2009 and elevation from airborne interferometry (http://ifsar.gina.alaska.edu) collected in summer 2010.

2010s (0.97±0.20 m w.e.). Therefore, lower annual balance in the latter period (-1.72±0.87 m w.e.) compared to the former period (0.04±0.25 m w.e.) were was driven by the more negative summer balances. balance. These mass balance patterns are consistent with the warming temperatures and relatively stable precipitation measured at Talkeetna Airport.

4.3 Radar-derived accumulation in glacierized terrain

Unlike ablation, which tends to be spatially coherent and well correlated with elevation, snow accumulation typically shows pronounced small-scale variability, making it difficult to accurately measure and model (Sold et al., 2013). This is especially true in complex terrain, where topography and meteorological processes vary over short distances (McGrath et al., 2015).

To robustly validate model simulations evaluate how representative our stake measurements of snow accumulation were of the broader glacier area, we conducted helicopter-borne ground penetrating radar (GPR) common-offset surveys of snow accumulation over the five main glaciers and glacier foreland areas in the Upper Susitna basin following Gusmeroli et al.

Table 5. Glacier-wide winter, summer, and annual mass balance (m w.e.) on the five largest glaciers in the Upper Susitna basin, 2012-2014. Mass balances were measured during site visits in the following date ranges: 26 April to 2 May 2012, 26-28 September, 15 -21 April 2013, 6-15 September 2013, 22-27 April 2014, and 7-9 September 2014. Exact dates for individual stake measurements are listed in the dataset.

Glacier Name	Winter			Summer			Annual		
	2012	2013	2014	2012	2013	2014	2012	2013	2014
West Fork Glacier	0.86	0.85	0.97	-2.96	-3.35	-2.28	-2.10	-2.50	-1.31
Susitna Glacier	0.88	0.60	1.17	-1.95	-2.37	-2.10	-1.07	-1.77	-0.93
East Fork Glacier	0.74	1.04	1.30	-4.17	-2.55	-2.04	-3.43	-1.51	-0.74
Maclaren Glacier	0.94	1.17	1.09	-3.86	-2.88	-1.81	-2.92	-1.70	-0.71
Eureka Glacier	···	0.74	0.89	···	-4.42	-3.32	···	-3.67	-2.43

(2014) (Figure 13)~~, and using~~ . We then used in-situ measurements of snow density to calculate end of winter snow water equivalent (SWE) for each year during the period 2012-2014. Radar-derived estimates of winter snow accumulation illustrate the high spatial variability across the elevation range of each glacier and from one glacier to another across the basin (Figure 13). Elevation is the dominant influence on SWE at the Upper Susitna basin scale, with snow accumulation on the glaciers at 2000 m measuring ~~2-3~~ 2-4 times higher than at 1000 m. ~~A notable south-north decrease in total SWE and accumulation gradient indicates a strong orographic influence.~~ Over short spatial scales in the ablation zone, surface roughness is responsible for high spatial variability in SWE. The end-of-summer glacier surface is rough due to streams, crevasses, melt ponds, and moraine material. The end-of-winter snow surface tends to be relatively smooth compared to the summer surface, but can also have wind-derived roughness features that contribute to the variability in SWE over small distances.

There is good correspondence between the radar measurements and the traditional method (Figure 13). A few points at high elevation where the discrepancies are largest might be explained by a misinterpretation of the location of the previous summer surface, either by manual measurement (probe) of a shallow ice layer, or by selection of a deeper firn layer in the radar data.

4.4 Continuous point mass balance measurements

Adjacent to the West Fork Glacier weather station (1398 m a.s.l.) we installed an acoustic distance sensor and a Wingscapes time lapse camera to measure snow accumulation and melt with high temporal resolution. The distance sensor was fixed vertically by mounting it on a pole drilled a few meters into the glacier, allowing the distance measured from the sensor to the surface to be directly related to melt or accumulation. The time lapse camera was mounted to the On-Ice weather station and maintained a fixed height above the glacier surface. It took a picture facing the distance sensor every hour for the summer of 2013 and 2014.

Early in the 2013 record (16 April-28 May), the distance sensor was repeatedly covered by fresh snow accumulation, giving inconsistent readings (Figure ~~??~~14). From 28 May through 1 August 2013 the sensor gave reliable data and the measured net surface lowering due to surface mass balance was 3.3 m. After 1 August 2013, the sensor's mounting pole began to tip over

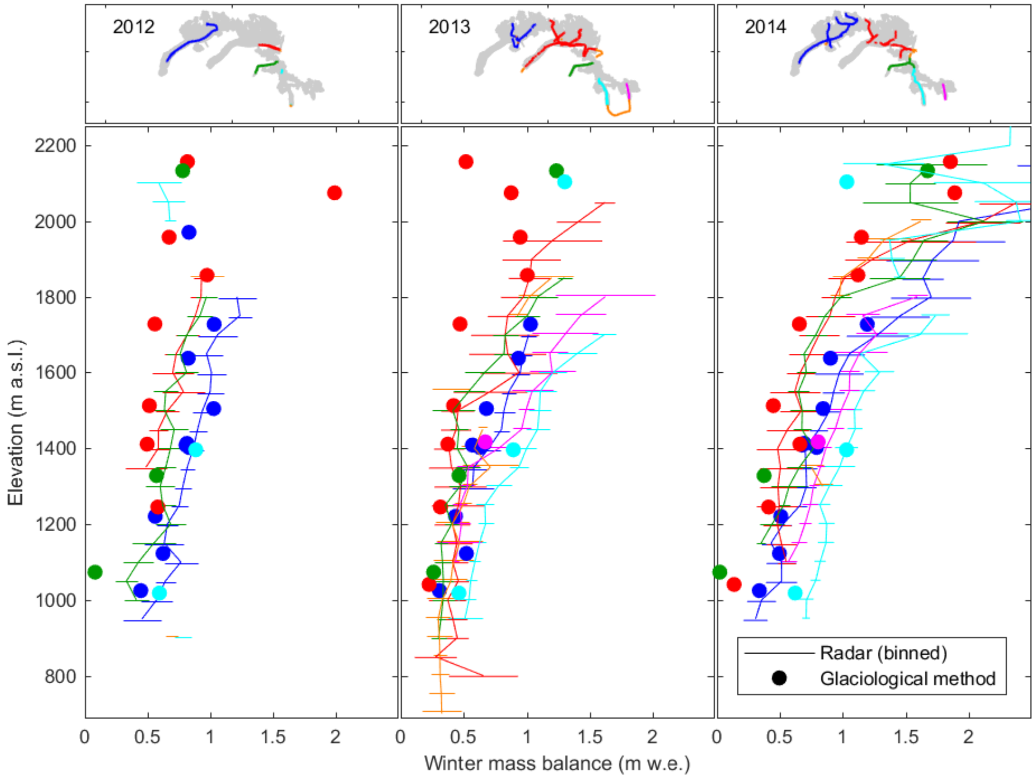

Figure 13. Winter mass balance profiles in 2012-2014 derived from point mass balance measurements (filled symbols) and from helicopter-based radar data. Horizontal lines represent mean ± std over 50 m elevation bands).

and give meaningless readings. The tilt was observed in the time lapse imagery (sensor absent from 26 August 2013 image in Figure 15). There was very little summer snowfall in 2013. There ~~is~~ was a distinct increase in measurement noise after the transition from snow to ice. This ~~is likely due to the roughness of the ice surface~~was likely caused when the acoustic signal bounced off different elements of the rough ice surface in successive measurements. The height change rate while the surface was snow-covered (28 May - 25 June) was 0.053 m/day. The net depth of snow lost at the sonic distance sensor site was 1.97 m (17 April - 30 June), which is comparable to the 2.15 m snow depth measured in a snow pit about 6 m away on 14 April ~~2013.~~ 2013 (Figure 5). The ice surface lowered at a rate of 0.043 m/day (30 June - 1 August).

In 2014, the distance sensor gave good readings from 26 April to 1 September when the sensor was removed after a two-day snowstorm. The 2014 measured net surface lowering from the last significant spring snowfall (28 April) to the first fall snowfall (1 September) was 3.8 m; summer snowstorms added 0.86 m of snow to the glacier which also melted away, for a total summer melt of 4.7 m. As in 2013, the 2014 data became noisier as the surface transitioned from snow to ice. The snow-covered surface lowered at a rate of 0.037 m d^{-1} (28 April - 3 July) and the ice surface lowered at a rate of 0.030 m d^{-1} (3 August - 1

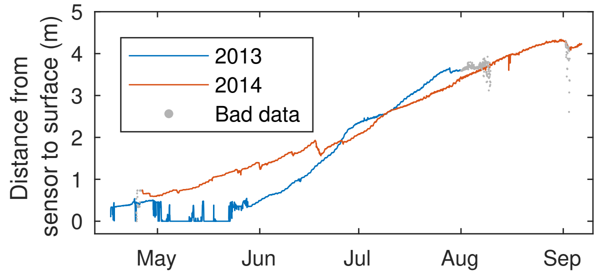

Figure 14. Distance from the acoustic sensor to the snow or ice surface. Increasing distance is a result of snow or ice melt and snow settling. Decreasing distance is due to snow accumulation. In early August 2013, the sensor's mounting pole began to tip over and give bad readings. On 1-2 September 2014, 18 cm of snow accumulation was recorded, consistent with observations during a site visit. The sensor pinged off falling snow, so some points in that window are labeled as bad data.

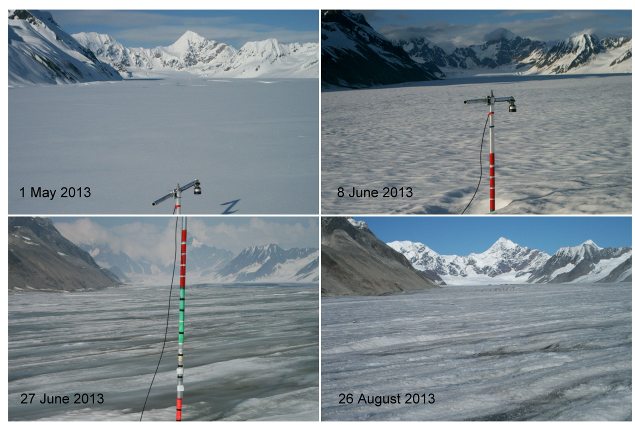

Figure 15. Photos from the time lapse camera on West Fork Glacier show surface conditions: Smooth fresh snow (1 May 2013), aged snow with rougher surface (8 June 2013), recently exposed bare ice with some water-saturated snow (27 June 2013), aged ice surface (26 August 2013).

September). Although the rate of surface lowering is larger for the snow surface than the ice surface, the rate of mass change is lower due to lower density.

To calculate ablation from the observed distance change, we ~~assumed~~ used a density of 350 kg m^{-3}, based on the average of 5 snow density measurements at the site. This leads to an average melt rate of 0.016 m w.e. d^{-1} for the summer of 2013 and 0.012 m w.e. d^{-1} for 2014.

Table 6. Spring snow depth and density measurements in non-glacierized terrain, April 2012, early April 2014, and late April 2014. Snow depths were averaged from about 50 measurements in the vicinity of each site. Density were averaged from three to five sites.

Site	Northing (m)	Easting (m)	Elevation (m a.s.l.)	Veg. type	Date	Snow depth (mm)	Depth σ (mm)	Density (kg m^{-3})	SWE (mm w.e.)
Early April 2012									
Maclaren R.	7003216	516825	941	Shrub	April 04	1300	90	290	371
Windy Cr. Upper	6999971	492008	1185	Shrub	April 04	880	370	280	248
Windy Cr. Lower	6998884	480035	939	Shrub	April 04	760	160	270	202
Open spruce forest	6992239	478016	817	Spruce	April 04	1050	100	130	141
Early April 2014									
Maclaren Glacier Lower	7014353	523593	943	Shrub	April 11	1430	150	310	440
Maclaren Glacier Trail	7001006	520732	996	Shrub	April 11	1320	80	330	435
7mile Lake Trail Upper	7003041	526340	1023	Shrub	April 11	940	80	250	234
7mile Lake Trail Lower	7000569	526655	965	Shrub	April 11	790	100	250	197
Top of Denali Hwy	6995546	528779	1207	Shrub	April 12	950	170	300	287
Clearwater/Denali Hwy	6990546	507510	942	Shrub	April 11	860	70	240	202
Clearwater Cr.	6974167	493626	711	Spruce	April 10	630	50	210	134
Windy Cr. Upper	6999971	491995	1198	Shrub	April 09	1000	590	330	328
Windy Cr. Lower	6998893	480306	946	Shrub	April 09	690	120	220	153
Shrub/Tundra	7009898	466122	911	Shrub	April 08	510	140	280	141
Spruce forest	6992367	470690	781	Spruce	April 09	680	100	220	150
Open spruce forest	6992232	478023	809	Spruce	April 08	720	70	240	173
Low sparse shrubs	6986486	468969	931	Shrub	April 09	1090	130	280	306
Late April 2014									
Two Plate Cr.	7019108	518464	1555	Rock	April 22	2590	230	270	687
Maclaren Upper	7003457	513239	1266	Shrub	April 22	1760	230	350	610
Maclaren Lower	7004506	514754	1016	Shrub	April 22	1310	80	270	348
Windy Cr. Lower	6998893	480306	946	Shrub	April 22	540	170	210	114
Tyone Cr.	6903793	498152	954	Spruce	April 28	110	100	270	30
Oshetna Cr. Lower	6901721	475712	1263	Shrub	April 28	570	60	270	152
Oshetna Cr. Upper	6900723	458329	1583	Shrub	April 28	430	140	270	113
Kosina Cr. Upper	6937020	451554	1274	Shrub	April 28	320	280	230	72
Kosina Cr. Lower	6948876	450371	919	Shrub	April 28	230	130	270	60

5 Snow depth in non-glacierized terrain

5.1 Field measurements of snow in spring 2012 and 2014

In-situ snow measurements were made with a double sampling method (Rovansek et al., 1993) in non-glacierized settings (forest and tundra, see Figure 1 for locations). At each site, three to five snow cores capturing the entire snowpack were extracted and weighed to calculate snow density. In 2012 we used an Adirondak snow tube and in 2014 a SnowHydro snow tube. A larger number (∼50) of snow depth measurements were also taken to improve the statistical properties of the sample. Snow water equivalent ~~(SWE)~~ was calculated by multiplying the average snow depth with the average snow density. The sites were reached by helicopter (4 April 2012 and 22-28 April 2014) and via snow machine (8-12 April 2014). No measurements were obtained in 2013. The compiled measurements are presented in Table 6.

The field measurements showed variations in SWE according to elevation, region, and vegetation type but with the small number of sites, definitive statistics were not feasible. The SWE measurements illustrated a general increase with elevation in 2014, which became more significant in late April. Basin-wide SWE data distinguished three major regions (Maclaren, Clearwater and Talkeetna), where the Maclaren sites represented the highest SWE and the Talkeetna region the lowest. Within each region, the SWE data generally showed a strong ~~elevation dependence~~increase with elevation. Among the two main vegetation types, shrubs presented larger SWE than the spruce locations (Table 6).

~~At the Lower Windy Cr. site , about~~ Lower Windy Creek was the only site where we collected SWE data more than once in a year. About 40 mm of SWE (25%) was lost due to melt of the end-of-winter snowpack between 9 April and 22 April 2014 (Table 6).

5.2 Snow depth in non-glacierized terrain: comparison to 1980s data

A total of 165 snow depth measurements, at 16 locations in both glacierized and non-glacierized terrain, were collected in 1981 and 1982 by R&M Consultants (1982). Direct comparisons to our data are hampered by differing measurement locations and dates, though the 1980s generally had larger snow depths.

6 Soils

6.1 Soil pit characterization

At each of 9 tundra sites, we dug a soil pit from the surface down to the top of the mineral soil between 1-3 October 2013 (see Figures 1, 16). We recorded the type of vegetation growing in the soil, visual characteristics of each soil horizon, as well as our estimation of the soil texture (Table A2). Two sites were too rocky to dig a pit (Two Plate Creek and Valdez Creek). The thinnest soils were generally observed at high elevation sites. The thickest organic-rich soils were observed in low-slope low-elevation environments at Tyone Creek and Maclaren Lower. Though we did not do a detailed texture analysis on the soils, ~~the characteristics we observed~~ our observations of soil texture, organic content, and drainage characteristics generally matched up with the State Soil Geographic (STATSGO) soil map (https://datagateway.nrcs.usda.gov/).

6.2 Soil temperatures

Understanding the distribution of permafrost and seasonally-frozen ground across the basin is important for modeling of water moving across the landscape. At each of the simple tundra weather stations installed over soil, we deployed soil temperature sensors at two depths below the surface (Figure 17). Shallow sensors (10 cm depth) were deployed into the side of the soil pits described above and then the pits were back-filled. By pushing the sensors into the undisturbed soil on the side of the pit, we hope to minimize any temperature errors due to disturbance. We did not quantify the effects of disturbance on temperature, though we expect them to be small compared to the large temperature changes observed over the record. Deep sensors were deployed at the bottom of a 2.5 cm-wide hole drilled into the ground. Disturbance of the soil around the deep sensors may affect temperature too, but we tried to minimize that by using the smallest drill we could. At some locations, the drill ran into rocks and was not able to reach the desired 1 m depth.

Broad patterns that we observed in the data include: no permafrost in the upper layers of soil at the sites we sampled although it may persist in deeper layers. The annual range of temperature at the shallow soil sensors is less than the air temperature

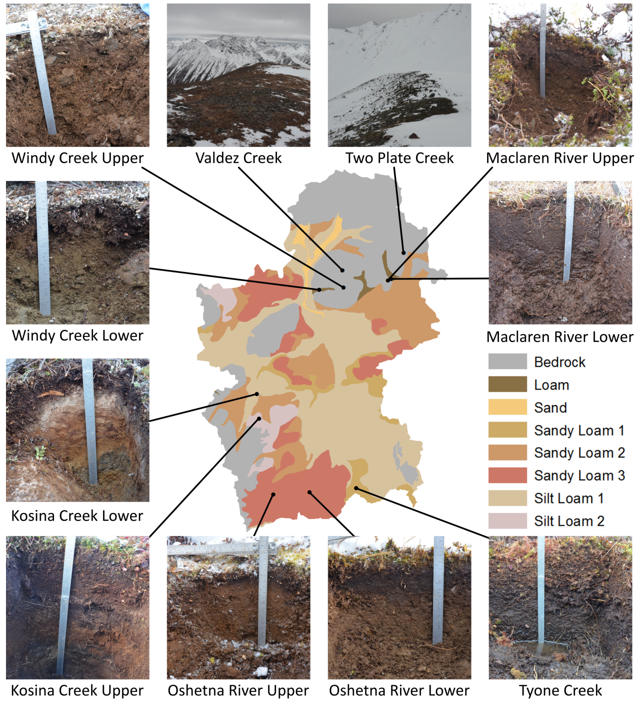

Figure 16. Photos of shallow soil pits. The map shows STATSGO soil type boundaries and pit locations. The ruler in each photo is 1.5 cm wide. Pit depths range from about 10 to 35 cm.

range, and the day-to-day variability is damped too. The temperature cycles at the deep sensors (between 25 cm and 1 m depth, depending on the station) are even more damped than the shallow sensors.

Soil temperature at three sites (Tyone Creek, Maclaren Lower, and Maclaren Upper) was nearly constant through the winter at or just above 0°C. At Tyone Creek and Maclaren Lower the ground surface was boggy and we observed liquid water seeping into our soil pits less than an hour after digging them (Figure 16), indicating that water flow through the upper unfrozen layer may have contributed to the nearly constant soil temperatures. Soils at Windy Creek Upper and Kosina Creek Upper get colder than the other stations in the winter due to the rocky soil and relatively high elevation of those two sites.

Figure 18 shows an example of summertime soil temperature fluctuations from the Windy Creek Upper station. Daily mean air and soil temperatures were all above 10°C. The shallow soil (0.1 m depth) at this rocky site heated up even more than the air each day, particularly when it was sunny. The diurnal cycle was smaller in the shallow soil than in the air and the deep soil (60 cm depth) showed only a very subtle diurnal cycle.

The middle panel of Figure 18 shows a soil freezing event from fall 2013 at Kosina Creek Upper. Both the shallow (0.1 m depth) and deep (1 m depth) sensors start the period at about 4 °C and show a cooling trend over the interval due to heat loss to the atmosphere (sub-zero air temperatures). For the first day of the period, the shallow sensor exhibited a diurnal cycle of temperature with a magnitude of 2 °C compared to diurnal amplitude in air temperature of 10 °C. In combination with the

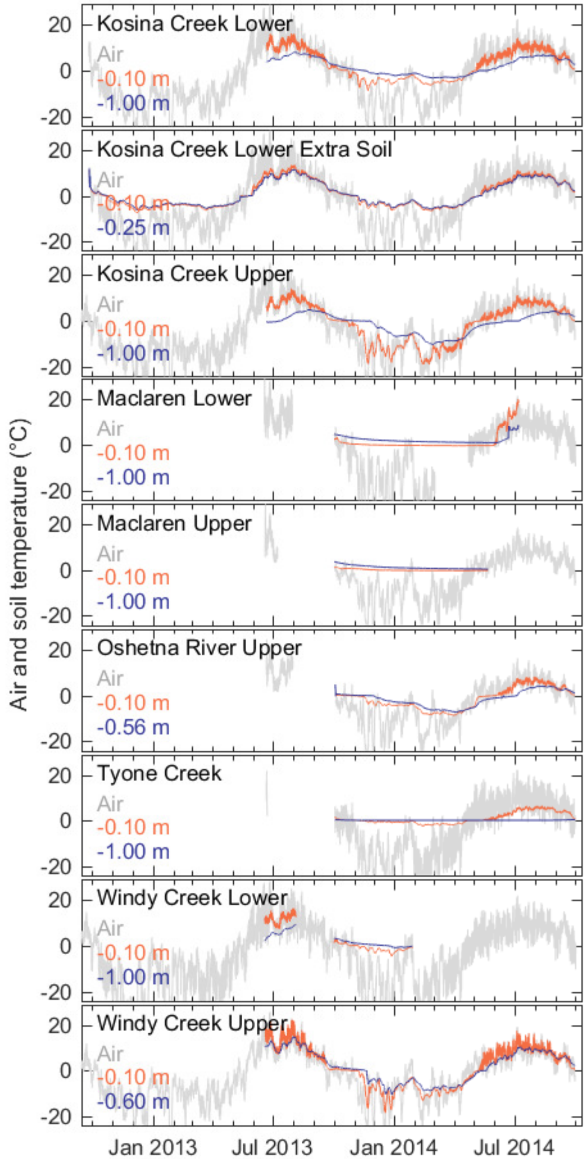

Figure 17. Hourly soil temperatures at depth below the soil surface for all sites with ~~soils~~ soil data ~~,~~ and air temperatures from each site's simple AWS. Each panel lists the depth of the soil temperature probes.

cold air temperatures, it is likely that this site received snow on 17 September 2013. The Gulkana Airport National Climatic Data Center (NCDC) station to the east received 8 and 12 mm w.e. of snow on 17 - 18 September. The Matanuska station to the south received 4 and 8 mm w.e. of snow on 18 - 19 September. Interestingly, Talkeetna Airport to the west did not receive

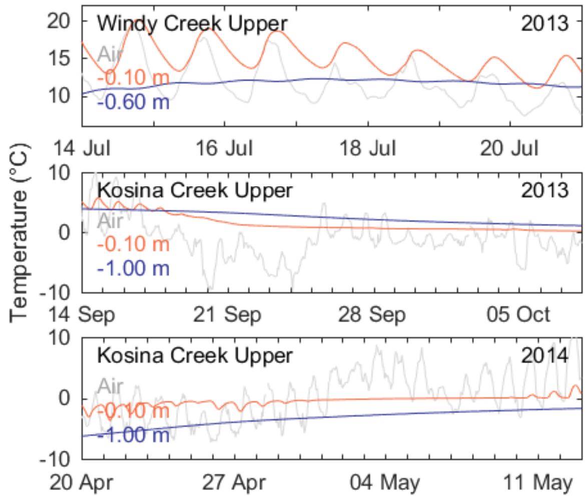

Figure 18. Hourly soil temperatures at depth below the soil surface illustrating three time periods: diurnal fluctuations in summer, soil freezing in fall, soil thaw in spring. Air temperature data is repeated from Figure 9 for context. Each panel lists the depth of the soil temperature probes.

snow during this period. The diurnal cycle of temperature disappeared by 18 September. The soil continued to cool throughout the interval, reaching 0.2 °C at 0.1 m depth and 1.1 °C at 1 m depth by 7 October 2013.

Spring thaw of the upper 0.1 m of soil at Kosina Creek Upper occurred over a period of about two weeks in 2014. On 20 April the shallow soil temperature sensor recorded a mean temperature of -1.9 °C and a diurnal cycle variation of 2°C while the air temperature diurnal amplitude was about 8 °C. As the air temperature warmed over the week of 27 April, the soil warmed to the freezing point and held steady until most of the soil had thawed. On 10 May, the shallow soil temperature exceeded 0°C for the first time that year and thereafter resumed a diurnal cycle. The 1 m deep soils warmed from -6.3 °C to -1.7 °C over this interval.

7 Data availability

Data is available at http://doi.org/10.14509/30138 (Bliss et al., 2019).

8 Conclusions

Comprehensive observations of meteorology, snow cover, glacier mass change, and soil properties are important for assessing basin-wide changes and providing input to hydrological modeling. In this study we focused on the Upper Susitna watershed~~-the source area that would feed a proposed hydroelectric dam~~. Our measurements reoccupied many of the same sites used by an initial study of the region 30 years ago. The 1980's measurements in combination with those presented here provide a baseline for future studies in the area.

Summer air temperatures in 2012-2014 were 1.1°C warmer than 1981-1983. Annual temperatures were 0.5°C warmer in the recent period. We found lapse rates to be significantly lower over glacierized surfaces in summer than over non-glaciated areas. Our meteorological stations filled a large gap in observations (spatially and elevation). Through correlations with long-running NOAA sites, we can better estimate past conditions within the basin.

Glacier surface mass balance measurements showed that during the melt season the glaciers were losing mass more than 3 times more rapidly in ~~the 2010s than in the 1980s~~2012-2014 than in 1981-1983. Winter snow accumulation measured by traditional methods closely matched measurements gathered from a helicopter-borne snow radar. Annual glacier-wide mass balance went from being close to 0 m w.e. (balanced) in the 1980s to losing more than 1.5 m w.e. yr^{-1} in recent years.

Snow depth in non-glacierized areas showed wide variability from site to site, reflecting complex deposition and redistribution patterns. Within local areas, higher elevations received more snow than lower elevations.

Our observations of soils in the basin generally match up with mapped soil descriptions. Soil temperature measurements revealed that none of the sites had permafrost in the upper 1 meter of soil. Most sites froze in the winter, though three sites remained at the freezing point despite air temperatures of -20°C.

The data sets described here provide new data in an extremely data scarce region. The data are valuable as baseline to assess future changes and will aid calibration and validation of hydrological, glaciological and other environmental models.

9 Author contributions

AB processed the data, performed all calculations and created all figures except Figure 1 (GW) and wrote most of the manuscript. RH, GW, and EW contributed significantly to the development of the analyses and figures, and the writing. AG processed the raw radar data. All authors but WH and JZ contributed to the field work in the 2010s. WH provided information on the 1980s data. CA and AH contributed to some initial data analyses. RH, GW, AL, and JZ secured funding from the Alaska Energy Authority.

10 Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements. The authors appreciate support and funding from: University of Alaska Fairbanks, Alaska Division of Geological and Geophysical Surveys, Alaska Energy Authority, and Colorado State University. Katreen Wikstrom Jones helped create Figure 1. Joanna Young and A. Cody Beedlow were instrumental in launching the study.

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Appendix A

Table A1. Properties of meteorological stations referenced in this study. See figure 3 for example photos of our station types.

Station name	Station type	Latitude	Longitude	Northing	Easting	Elevation
West Fork On-Ice ESG1	~~AWS~~ energy balance	~~63.532~~ 63.5322	-147.246	~~7044911~~ 7.04491e+06	487787	1398
Susitna Off-Ice ESG2	~~AWS~~ energy balance	~~63.531~~ 63.5307	-146.888	~~7044726~~ 7.04473e+06	505559	1516
Repeater ESR9	~~AWS~~ repeater	~~63.504~~ 63.5038	-147.184	~~7041738~~ 7.04174e+06	490839	2079
EF1	~~HOBO~~ simple glacier	~~63.436~~ 63.4358	-146.596	~~7034211~~ 7.03421e+06	520153	~~2133~~ 213
EF2	~~HOBO~~ simple glacier	~~63.436~~ 63.4359	-146.782	~~7034175~~ 7.03417e+06	510895	~~1328~~ 132
EF3	~~HOBO~~ simple glacier	~~63.413~~ 63.4127	-146.811	~~7031586~~ 7.03159e+06	509419	~~1073~~ 107
Mac1	~~HOBO~~ simple glacier	63.416	-146.599	~~7032005~~ 7.03201e+06	520038	~~2104~~ 210
Mac2	~~HOBO~~ simple glacier	63.355	~~-146.550~~ -146.55	~~7025220~~ 7.02522e+06	522529	~~1396~~ 139
Mac3	~~HOBO~~ simple glacier	~~63.305~~ 63.3054	-146.527	~~7019700~~ 7.0197e+06	523689	~~1018~~ 101
NWTrib1	~~HOBO~~ simple glacier	~~63.598~~ 63.5976	-146.986	~~7052170~~ 7.05217e+06	500703	2075
Off-Ice HOBO	~~HOBO~~ simple glacier	~~63.531~~ 63.5307	-146.888	~~7044725~~ 7.04473e+06	505561	1516
Repeater HOBO	~~HOBO~~ simple glacier	~~63.504~~ 63.5038	-147.184	~~7041736~~ 7.04174e+06	490842	2079
SU1	~~HOBO~~ simple glacier	~~63.493~~ 63.4929	-146.617	~~7040563~~ 7.04056e+06	519096	~~1858~~ 185
SU3	~~HOBO~~ simple glacier	~~63.512~~ 63.5116	-146.887	~~7042599~~ 7.0426e+06	505625	~~1245~~ 124
WF1	~~HOBO~~ simple glacier	~~63.605~~ 63.6052	-147.079	~~7053029~~ 7.05303e+06	496062	~~1971~~ 197
WF5	~~HOBO~~ simple glacier	~~63.487~~ 63.4865	-147.449	~~7039879~~ 7.03988e+06	477642	~~1123~~ 112
WFTranB	~~HOBO~~ simple glacier	~~63.529~~ 63.5287	-147.237	~~7044519~~ 7.04452e+06	488236	~~1413~~ 141
Kosina Creek Lower	~~HOBO~~ simple tundra	~~62.667~~ 62.6671	-147.969	~~6948875~~ 6.94887e+06	450373	~~919~~ 918.8
Kosina Creek Lower Extra Soil	~~HOBO~~ simple tundra	~~62.667~~ 62.6671	-147.969	~~6948875~~ 6.94887e+06	450373	~~919~~ 918.8
Kosina Creek Upper	~~HOBO~~ simple tundra	~~62.561~~ 62.5609	-147.942	~~6937020~~ 6.93702e+06	451553	~~1274~~ 127
Maclaren Lower	~~HOBO~~ simple tundra	~~63.170~~ 63.1695	-146.707	~~7004512~~ 7.00451e+06	514754	1016
Maclaren Upper	~~HOBO~~ simple tundra	~~63.160~~ 63.1602	-146.737	~~7003466~~ 7.00347e+06	513262	1315
Oshetna River Lower	~~HOBO~~ simple tundra	~~62.246~~ 62.2464	-147.468	~~6901717~~ 6.90172e+06	475705	~~1263~~ 126
Oshetna River Upper	~~HOBO~~ simple tundra	~~62.236~~ 62.2359	-147.802	~~6900720~~ 6.90072e+06	458336	~~1583~~ 158
Two Plate Creek	~~HOBO~~ simple tundra	~~63.300~~ 63.3004	-146.632	~~7019112~~ 7.01911e+06	518467	~~1555~~ 155
Tyone Creek	~~HOBO~~ simple tundra	~~62.266~~ 62.2659	-147.036	~~6903805~~ 6.90381e+06	498150	954
Valdez Creek	~~HOBO~~ simple tundra	~~63.203~~ 63.2029	~~-147.170~~ -147.17	~~7008206~~ 7.00821e+06	491438	~~1676~~ 167
Windy Creek Lower	~~HOBO~~ simple tundra	~~63.119~~ 63.1188	~~-147.390~~ -147.39	~~6998890~~ 6.99889e+06	480303	~~941~~ 940.6
Windy Creek Upper	~~HOBO~~ simple tundra	63.129	-147.159	~~6999977~~ 6.99998e+06	491975	~~1177~~ 117
ALPINE CREEK LODGE AK US	NCDC	~~63.043~~ 63.0429	-147.248	~~6990393~~ 6.99039e+06	487462	~~945~~ 944.9
GULKANA AIRPORT AK US	NCDC	~~62.159~~ 62.1591	-145.459	~~6892859~~ 6.89286e+06	580297	~~476~~ 476.1
TALKEETNA AIRPORT AK US	NCDC	~~62.320~~ 62.32	-150.095	~~6913666~~ 6.91367e+06	339639	~~107~~ 106.7

Table A2. Soil pit observations.

Site Depth (cm)	Soil horizon	Description	Comments in the field
Kosina Creek Lower (East face of pit)			
-36 to 0	Vegetation		Willows, shrubs
-15 to 0	Vegetation		Crowberries, lowbush cranberries
-2 to 0	Vegetation		Green part of moss, lichens
0 to 2	Oi	Hemic	Moderately decomposed roots (MPM), dark brown color
2 to 6	1 B	Mineral	Light buff color, 100% silt
6 to 15	2 B	Mineral	Mottled coloration. Buff to reddish brown, 100% silt (slightly coarser than 1 B layer)
15 to 18	3 B	Mineral	Yellowish brown color, 60% silt, 40% sand
18 to 22	4 B	Mineral	Reddish brown color, 70% coarse grained sand, 30% silt
22	Bedrock	Bedrock	Granitic bedrock or boulder encountered
Kosina Creek Lower (North face of pit)			
-2 to 0	Vegetation		Green part of moss, lichens
0 to 2	1 Oi	Moss	Brown part of moss
2 to 10	2 Oi	Fibric	Slightly decomposed plant material (SPM)
10	Bedrock	Bedrock	Granitic bedrock or boulder encountered
Kosina Creek Upper			
-3 to 0	Vegetation		Lowbush cranberry, moss, lichen, occasional sedge tufts
0 to 1	1 Oi	Moss	Brown part of moss
1 to 6	2 Oi	Fibric	Slightly decomposed plant material (SPM)
6 to 10	Oe to Oa	Hemic to Sapric	Moderately to very decomposed roots (MPM transitioning to HPM)
10 to 11	1 B	Mineral	Light brown, 80% silt, 20% sand, up to coarse-grained sand (quartz xl)
11 to 16	2 B	Mineral ?	Dark brown color, predominately clay or HPM, 20% silt
16 to 21	3 B	Mineral	Reddish light brown color. >90% fine-grained sand
21 to 24	2 B	Mineral	Dark brown color, predominately clay or HPM, 20% silt
24 to 32	4 B	Mineral	Light brown, 60% medium-grained sand, 30% silt
Maclaren River Lower			
-20 to 0	Vegetation		Sedges, grasses, arctic cotton plants
-1 to 0	Vegetation		Green part of moss, lichens
0 to 1	1 Oi	Moss	Brown part of moss
1 to 4	2 Oi	Fibric	Slightly decomposed plant material (SPM)
4 to 35	Oe	Hemic	Moderately decomposed roots (MPM), could not find mineral horizon
35	Base of pit		
Maclaren River Upper			
-6 to 0	Vegetation		Willows, crow berry, lowbush cranberry, some moss
0 to 2	Oi	Fibric	Slightly decomposed plant material (SPM)
2 to 11	Oe	Hemic	Moderately decomposed roots (MPM)
11 to 20	B	Mineral	40% silt, 20% sand, 40% clay (estimated percentages)
20	Base of pit		
Oshetna River Lower			
-10 to 0	Vegetation		Grass, sedges
-2 to 0	Vegetation		Green part of moss, lichens
0 to 1	1 Oi	Moss	Brown part of moss
1 to 5	Oa	Sapric	Highly decomposed plant material (HPM), dark brown soil color
5 to 13	B	Mineral	Medium brown soil, 5% reddish medium brown spots, 90% silt, <10% clay, occasional gravel (1 -3 cm diameter)
13	Base of pit		
Oshetna River Upper			
-8 to 0	Vegetation		Shrubs
-2 to 0	Vegetation		Green part of moss, lichens
0 to 1	1 Oi	Moss, Fibric	Brown part of moss + SPM
1 to 2	Oe	Hemic	Moderately decomposed plant material (MPM)
2 to 17	B	Mineral	Moderate brown color, clay % > silt % > gravel % (2-3 cm diameter)
17	Base of pit		
Tyone Creek			
-10 to 0	Vegetation		Sedges, shrubby pine up to 20 cm tall in site vicinity
-4 to 0	Vegetation		Blueberries, crow berries
-3 to 0	Vegetation		Green part of moss
0 to 2	1 Oi	Moss	Brown part of moss
2 to 7	2 Oi	Fibric	Slightly decomposed plant material (SPM), light brown soil color
7 to 27	Oe	Hemic	Moderately decomposed plant material (MPM), small % of live shrubby pine roots
27	Base of pit		
Windy Creek Lower			
-2 to 0	Vegetation		Lichen, lowbush cranberry, willows
0 to 3	Oi	Fibric	Slightly decomposed plant material (SPM)
3 to 5	Oe to Oa	Hemic to Sapric	Moderately to very decomposed roots (MPM transitioning to HPM)
5 to 15	B	Mineral layer	Sandy % > silt %
15	Base of pit		
Windy Creek Upper			
-1 to 0	Vegetation		Lichen, lowbush cranberry
0 to 6	?	Thin, sparse roots	Medium brown soil, not much organic material, 70% silt, 30% clay, gravel (1 - 5 cm)
6 to 17	B	Rocky	Medium light brown soil, 70% silt, 30% clay
17	Base of pit		