Quantifying near-surface temperature lapse rates: a path to improved melt estimates for the Juneau Icefield, Alaska

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Background and Motivation

Alaska's glaciers are among the top contributors to sea level rise [1, 2, 3]. These large glaciers are only beginning to retreat due to recent warming [4], and are expected to continue losing mass over the coming decades [5, 6]. In addition to contributing to sea level rise, this mass loss will change the timing and quantity of runoff, disrupting downstream ecosystems. This is of particular concern in coastal watersheds, where cold glacier meltwater plays a key role in sustaining temperate rainforests and nearshore marine ecosystems [7]. Projections of mass loss for Alaska's glaciers, however, remain highly uncertain, with estimates suggesting anywhere from about 30 to 50% by the end of the 21st century [8, 9, 10]. It is therefore critical to improve our understanding of how these glaciers will evolve under continued climate change.

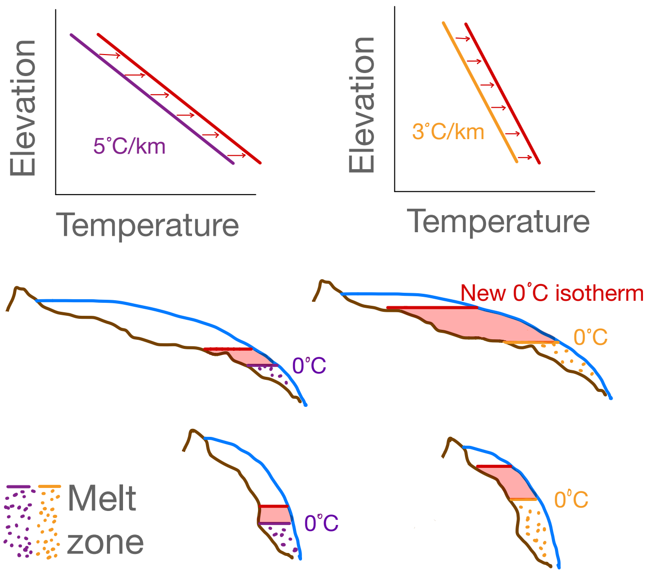

Figure 1: Schematic showing the effect of different lapse rates on melt area (defined as the area below the 0 °C isotherm). Given the same reference temperature at sea level, a smaller lapse rate (3 °C/km, here) translates to a greater melt area, especially for shallow surface slopes. Red markings indicate the impact of an increase in temperature at sea level: regions with shallower surface slopes combined with smaller lapse rates see a greater increase in melt area.

To project glacier change and melt evolution, most studies exploit the simple dependence of melt on near-surface temperature (e.g. [11, 12]), which is typically taken from global climate model projections. Because most climate models are too coarse to resolve mountain landscapes, a common and simple approach to down-scale to the local topography is to use **near-surface temperature lapse rates – the rate of temperature change with elevation** (Fig. 1, inset) [13]. To do this, a reference temperature at a specific elevation is found (either the average over the model grid cell or the nearest weather station), which is then extrapolated to other elevations using the lapse rate. Studies using this approach almost always assume a fixed lapse rate of about 5 °C/km (e.g., [14, 15, 4]). This assumption is problematic because lapse rates have been shown to vary in space and time. For example, one study in the Cascade mountains observed a range of lapse rates between 2.5 – 8 °C/km, fluctuating diurnally, seasonally, and spatially [16]. Studies have also been done for mountainous regions in England, Italy, Idaho, Arctic Canada and Greenland [17, 18, 19, 20], which altogether show that lapse rate variability is highly tied to the local climate, environment and topography, depending on factors such as solar insolation and humidity. Therefore, we expect the lapse rates over glaciated regions in Alaska to be unique as well. Unfortunately, the lack of long-term weather stations in mountain environments means that we cannot fully characterize lapse rate variability with existing measurements. This uncertainty in lapse rates translates to uncertainty in near-surface temperature, impacting projections in glacier change and meltwater production in Alaska.

Here, we propose to directly measure the spatial and temporal variability of temperature lapse rates for the Juneau Icefield (JIF), a glacier complex in Alaska, to better estimate current and future melt in this critical region. The JIF is one of the largest icefields in Southeast Alaska, ranging in elevation from sea level to 2300 m [21] (Fig. 3). The upper area of the icefield is broad and relatively flat, with outlet glaciers spilling out onto steeper slopes. Due to the low surface slopes of the plateau, the icefield is especially sensitive to the lapse rate because a small shift in the elevation of the 0 °C isotherm could expose large areas to melt (Fig. 1). Weaker lapse rates (less cooling with elevation) result in a higher 0 °C isotherm and more area exposed to melt, while the reverse is true for stronger lapse rates. Climate change is expected to warm higher elevations faster [22], thereby reducing the lapse rate and making the icefield more sensitive to future warming.

The JIF is currently losing mass [23], and epitomizes glaciers in Southeast Alaska where future meltwater projections could be significantly influenced by assumptions about the near-surface lapse rate. The work proposed here would build on preliminary measurements collected on the JIF during the Summers of 2022 and 2023, which demonstrated considerable spatial and temporal lapse rate variability (further details provided below). Through the efforts outlined in this proposal, we aim to collect enough data to establish the grounds for a larger future proposal to either the National Science Foundation (NSF) or the National Oceanic and Atmospheric Administration (NOAA).

Preliminary Results

We have started testing the viability of the work we propose here by leveraging the logistical support of the Juneau Icefield Research Program (JIRP). JIRP is a field school where undergraduates learn the fundamentals of glaciology, mountaineering skills, and gain research experience using field-based methods. Over the course of the Summer, JIRP students and faculty traverse the JIF from Juneau, Alaska to Atlin, British Columbia, doing fieldwork based out of rudimentary research stations interspersed across the icefield (Fig. 3).

In Summer 2022, Jessica Badgeley (UW ESS alum) initiated a lapse-rate project as a JIRP faculty member. She helped students deploy low-cost temperature loggers along elevation transects (Fig. 2c-e). In 2023, Mira Berdahl (UW ESS research scientist) and Daniel Otto (UW ESS graduate student), collaborated with Jessica to continue the project. **We found that lapse rates on the JIF have strong spatial and temporal variability that can deviate significantly from the standard 5 °C/km used in most glacier studies (Fig. 2a).** We measured a strong diurnal cycle spanning 4 to 12 °C/km, with peak values occurring in the mid afternoon [24]. Different transects also indicated that the range and shape of these diurnal cycles vary regionally. We also tested lapse rate sensitivity to other variables such as surface type (snow versus rock), local slope, and aspect (Fig. 2b-e). Although we found regional variability in all of these parameters [25], our results are not definitive because our tests have been limited to small transects with a maximum of a week's worth of coverage. We did find, however, that this approach is tractable and promising. Indeed, the 2022 and 2023 JIRP field seasons resulted in student-led poster presentations at the American Geophysical Union Fall Meeting, showcasing how this data is useful for both scientific discovery and pedagogical engagement [24, 25].

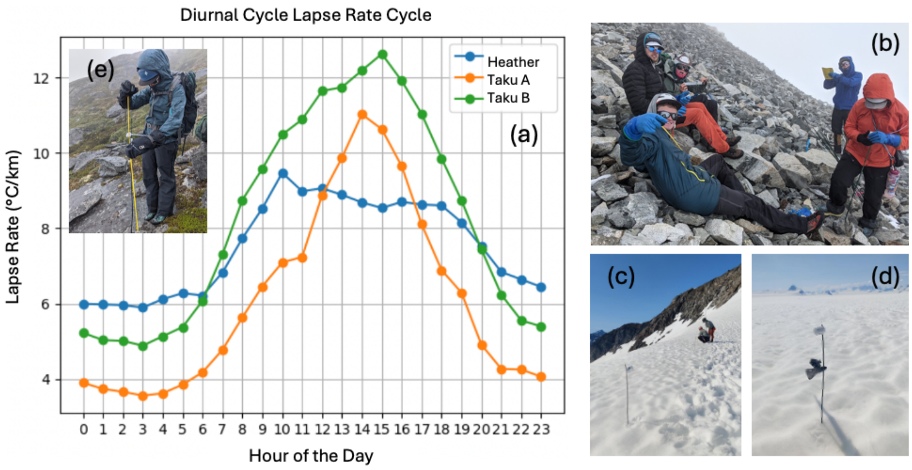

Figure 2: Preliminary lapse rate measurements from 2022 and 2023. Panel (a) shows data from three transects deployed for almost a week each in July 2023 near Camps 10 and 18 (see Fig. 3 matching colors). Pictures (b)-(e) show students deploying loggers in 2022 and 2023.

Proposed Work

The PCC Climate Acceleration Fund would help propel this work from short-term, isolated measurements to a more formal and targeted pilot study. With a larger NSF or NOAA proposal, we aim to answer the following overarching questions:

1) What are the drivers of spatial and temporal variability of lapse rates across the icefield?
2) How do our measured lapse rates compare to values used in previous literature?
3) Does the observed variability impact glacier mass loss projections?

To do this, we must characterize and quantify the near-surface temperature lapse rate on the JIF. As a first step toward this goal, **in Summer 2025 we propose to deploy two long-term observational transects – one over the icefield and one in a comparable ice-free zone – to capture a range of possible drivers of lapse rate variability** (Fig. 3). Specifically, these elevation transects are designed such that they should characterize the known difference in maritime and continental lapse rates [16] and between glacierized and ice-free landscapes [26] over a Summer melt season. Both transects will span the maritime-continental transition and have similar elevation ranges. We have identified low-cost temperature loggers that are well-suited to measure dense time series of relative temperature differences along these transects (similar loggers used in [20, 27, 28]).

For the icefield transect, we will deploy 60 loggers, spread over 40 sites (doubling up on half of the sites for redundancy) for three months, taking measurements every fifteen minutes (Fig. 3). To do this, we will leverage JIRP's logistical support by deploying our loggers along the established traverse path across the icefield. Loggers will be attached to the top of 4-meter bamboo stakes and deployed early in the spring. Then, as JIRP students traverse the icefield later in the Summer, they will simply need to collect the loggers and deployment materials. This will allow us to collect coincident data for a minimum of one month and up to three months for many of the locations. Coordinating with JIRP, we will be able to haul materials (e.g. ice augers/drills, bamboo stakes) to and from the icefield with the regularly-scheduled helicopter flights to camps along the traverse. These synergistic projects with

JIRP are strongly encouraged by JIRP administrators, and we have already been in communication on the services they can provide our team.

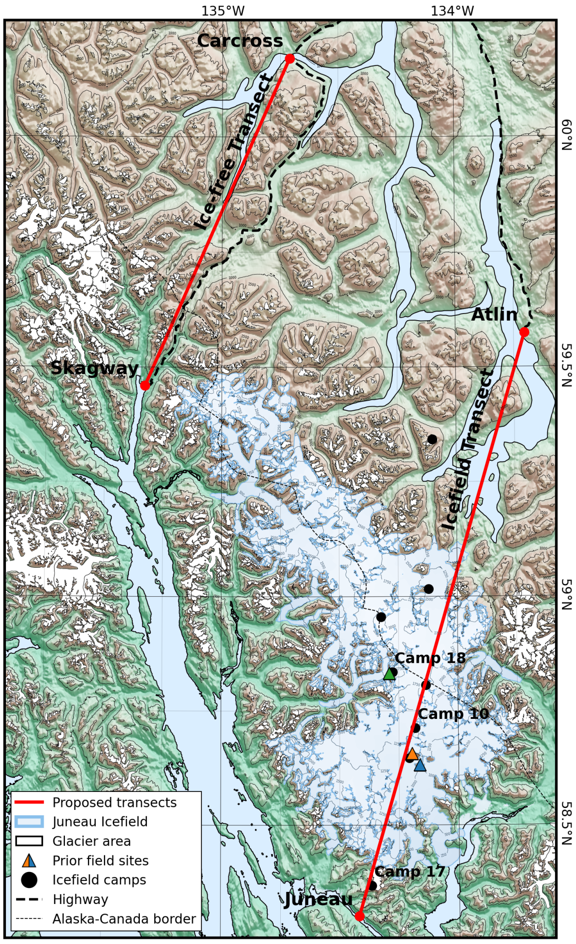

Figure 3: Map of the Juneau Icefield and the proposed transects (red) across the maritime-continental climate transition. The location of JIRP camps are marked (black) as well as the locations of the preliminary work shown in Fig. 2 (colored dots).

The second elevation transect will serve as an ice-free 'control'. It will allow us to verify that our measured lapse rates are consistent with literature values and physics-based expectations for continental and maritime climates over ice-free terrain [16], thereby giving us confidence in our methods. This ice-free transect will be deployed along a major road from Skagway, Alaska to Carcross, Yukon with similar heading and elevation to the the icefield transect. Similar to the icefield, we will deploy 60 loggers at 40 stations (Fig. 3) by drilling stakes into the deep, early Spring snow adjacent to the road. JIRP staff have agreed to re-visit the sites midway through the Summer to transfer loggers to shorter poles supported by rock cairns as the snow melts, and to collect the loggers at the end of the Summer.

In order to prototype and test our logger deployment methods, we will establish a transect over the icefield for a few weeks in Summer 2024. Daniel Otto has received a small amount of funding from UW ESS for a few new loggers and ancillary materials. He will test several methods and materials for deploying the loggers (e.g. testing bamboo poles and trying different logger housings). He will adopt practices used by other field campaigns in high snowfall and wet maritime environments (personal communication with Jeremy Littell - USGS, Jessica Lundquist - UW CEE, and David Sheen - UW CEE). The expected outcome of these tests is a robust methodology for the 2025 field season.

Expected Results & Broader Impacts

Together, our two pilot transects – one ice-covered, and the other ice-free – that span the continental-maritime transition will allow us to test and characterize lapse rate variability in four different climate zones over most of a Summer melt season. Our results will not only help determine the best field methods, but will also show whether lapse rate variability is truly unique over glacierized catchments, as well as in different climatological zones (maritime/continental). Due to orographic effects, we expect an increasingly continental climate towards the eastern (lee) side of the mountain range. We expect to see a stronger lapse rate resulting from air drying as it passes over the divide, particularly in the ice-free transect. However, it is not clear whether this signal will be strong over the icefield. **By initially characterizing these four climate zones, we can begin to test the extent to which observed lapse rate variability matters for glacier modeling studies.**

Ultimately, the results will inform the design of a more extensive logger network for a future NSF or NOAA proposal. We have already identified a few calls that would be relevant for this work: the NSF Arctic Natural Science, Arctic System Science, and Physical and Dynamic Meteorology programs and the NOAA Climate Program Office: Climate Variability and Predictability Program (competition #3167176).

UW College of the Environment has an extensive record of student and faculty involvement at JIRP that began in the program's earliest years (ca. 1950s). This project likewise originated with, and has been carried forward for multiple seasons, by UW personnel. Now we are seeking funding from the PCC Climate Acceleration Fund to support the expansion of this research. We hope to create an ongoing research program in partnership with JIRP for logistical support to advance research into fundamental climate questions conducted by UW scientists.

This project will support a UW graduate student (Daniel Otto) to carry out this pilot project, with the aim to turn it into a an NSF or NOAA-funded project which would provide him with necessary PhD funding to continue his studies at UW. As a research scientist, Mira has secured salary support for at least 2.5 more years at UW, and expects to stay long term. The work will contribute to the broader UW Glaciology community, and continue to build our knowledge of glacier micro-climates in order to improve projections of glacier melt in the future.

A guiding principle for this project is to be a model of collaborative science. While UW personnel will lead this project, faculty and students on JIRP will have the opportunity to participate and learn along the way. Use of these datasets have already proved to be an accessible entry point for undergraduate research [24, 25]. The data from temperature loggers is easy to process and interpret, yet can be applied to a remarkable breadth of scientific questions. We plan to partner with the existing UW ESS OGIVE program to bring in UW undergraduate students interested in climate and glaciology to work on this project. For both students and faculty, our goal is to create the infrastructure to support easy and ongoing engagement in this project.

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Budget Narrative

Here, we propose to purchase and deploy an array of temperature loggers on the Juneau Icefield (JIF) in early Summer 2025. To do this, we will rely on field logistics coordination provided by Seth Campbell and the JIF Research Program (JIRP). The capability to do this project comes from both this existing logistical support and the choice of logger: inexpensive, small temperature loggers. Relative to a weather station, these loggers are less accurate and more sensitive to environmental biases (e.g. solar forcing); however, they require very little supporting infrastructure, and can be deployed at many field sites in rugged terrain for a fraction of the price. We circumvent issues with inaccuracy by measuring lapse rate rather than absolute temperature, and by being able to bias-correct to existing weather stations. By taking averages over many locations and longer time intervals, we expect to be able to capture the signal amongst any noise and logger bias differences.

The following budget includes travel, food, lodging, and equipment for one field season for a team of three individuals: two UW science leads, Mira Berdahl and Daniel Otto, and one mountaineering guide (Table 1). The mountain guide will be certified in Wilderness First Responder and will have extensive mountaineering experience on the icefield and elsewhere. We have talked with several graduate students who fit this description (including some at UW), who are able to both join us and be supported through their own Research Assistant fellowship. Costs for each of the items for the field expedition are calculated based on standard (reduced) rates JIRP charges scientists for logistical support. Additional costs were obtained from websites appropriate for each item (e.g., ferry costs were obtained from the Alaska Department of Transportation and car rental costs were obtained from estimates from Avis and Budget) and adjusted as necessary based on experience working in Juneau and on the icefield.

Timeline:

- **Juneau, AK - 6 days**: Arrive on flight from Seattle. Hike up to Camp 17 to deploy the southern part of the JIF transect. Return to Juneau and regroup. Helicopter flight to Camp 10.
- **Icefield (Camp 10) - 17 days**: Arrive in camp. Deploy center and northern part of the JIF transect starting in the South and working North (same direction the loggers will be picked up by the JIRP participants). Use snow machines to access the farthest locations to the South and North that are too far to ski in a day (40-50 miles round trip is the longest anticipated travel day on a snow machine). Helicopter flight back to Juneau.
- **Juneau, AK - 2 days**: Prep for Atlin trip and pickup rental car.
- **Skagway, AK - 5 days**: Travel from Juneau to Skagway (minimum 10 hour travel each way), which requires a ferry crossing. Starting in Skagway, deploy the ice-free transect (these are the last loggers that will be picked up at the end of the Summer by JIRP students and staff).
- **Juneau, AK - 2 days**: Return rental car and fly back to Seattle.

Travel: Funds in the amount of $5,100 for the field team will be used to get to Juneau, access both ends of the JIF transect, access the center of the JIF transect, and access the ice-free transect for a total of a 32-day field campaign. Additional time is built in for weather delays, which occur commonly in this region and season. All travel will be in accordance with University of Washington travel regulations.

Room and Board: Funds in the amount of $4,800 are requested for lodging and food for the field team for when they are in Juneau, Skagway, and JIF field camps.

Field Supplies: Funds in the amount of $19,780 are requested for field supplies for this project expansion into a formal pilot study. These supplies will augment our existing collection of loggers, bamboo poles, and miscellaneous logger deployment equipment. It will also provide us with a field computer dedicated to this project and time on snow machines to access the parts of the JIF transect that are too far from a field camp to ski in one day.

Item	Description	Cost Per	Quantity	Cost
Travel				
Airline flights	round-trip flights Seattle, AK to Juneau, AK	$500	3	$1,500
Helicopter flights	round-trip flight to Camp 10 on the icefield	$2,000	1	$2,000
Ferry	round-trip ferry Juneau, AK to Skagway, AK	$600/3 people+1 car	1	$600
Car rental	drive to Skagway, along the ice-free transect, and back (including gas)	$200/day	5 days	$1,000
Travel Subtotal				**$5,100**
Room and Board				
Juneau	lodging and food for 10 days in Juneau, AK, including travel days	$50/day/person	30	$1,500
Camp 10	lodging and food for 17 days on the icefield	$50/day/person	51	$2,550
Skagway	lodging and food for 5 days in Skagway, AK, including travel days	$50/day/person	15	$750
Room and Board Subtotal				**$4,800**
Field Supplies				
Snow machine transport	use of JIRP snow machines to travel around on the icefield. Round trip from Camp 10 to the icefield divide is about 40 miles. We expect to need to travel about that distance in both directions from Camp 10 at least four times to deploy the center and northern parts of the JIF transect.	$8/mile	160 miles	$1,280
Loggers	Hobo pendant temperature loggers from Onset to augment current supply of loggers	$100	100	$10,000
Field computer	rugged tablet or computer for deploying and downloading logger data in the wet, cold field environment	$5,000	1	$5,000
Miscellaneous field equipment	logger shielding material, poles (bamboo or PVC), logger attachment materials (zip ties, tape, screws, wire), logger accessories	$3,000	N/A	$3,000
Carnet	customs document for transporting scientific equipment in Canada	$500	1	$500
Field Supplies Subtotal				**$19,780**
Total				$29,680

Table 1: Proposed Budget.