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## Blowing Hot and Cold: Glacier Microclimate can Help Understand Impacts of Climate Change on Forests Communities

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# Geophysical Research Letters®

## COMMENTARY

10.1029/2022GL100883

This article is a comment on Gaglioti (2022), <https://doi.org/10.1029/2022GL098574>.

### Key Points:

- Current rates of global warming are expected to double within decades, at a much faster pace than what most ecosystems experienced over several millennia
- Fast warming threatens ecosystems as elevational ranges at which species occur will need to shift to be able to respond to changes in their thermal niches
- Using the rainforest of La Perouse Glacier as a “natural laboratory,” Gaglioti et al. (2022, <https://doi.org/10.1029/2022GL098574>) analyze effects of past and anticipated future climate change

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## Blowing Hot and Cold: Glacier Microclimate can Help Understand Impacts of Climate Change on Forests Communities

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**Abstract** Mountain regions cover roughly one-fourth of the Earth's surface, store most snow and ice outside polar regions and are hotspots of species richness. Regrettably, they are also viewed as climate hotspots where change can anticipate/amplify what is occurring elsewhere on Earth. Current rates of warming are expected to double within decades, thereby becoming an order of magnitude faster than what most ecosystems have experienced over millennia. By monitoring contemporary microclimatic conditions around La Perouse Glacier (Alaska) and reconstructing locations of past ice margins, Gaglioti et al. (2022, <https://doi.org/10.1029/2022GL098574>) quantify local climate change over the last two centuries. Rates of cooling and warming at their site are beyond expectations, and outside human experience. Their “natural laboratory” experiment provides key insights into likely impacts of future climate change on tree vitality and growth and therefore is a stepping stone for the assessment of how trees have responded (and will likely respond) to fast-paced warming.

**Plain Language Summary** Mountains are known for their glaciers, perennial snow and high biodiversity. Yet, together with the Arctic and Antarctic, they are also among those regions experiencing highest rates of global warming and are thus considered as climate hotspots where ongoing and future climate change can anticipate what is occurring elsewhere on Earth. In these fragile environments, warming is expected to occur at a much faster pace than what most ecosystems have experienced over the course of the Holocene. Documenting and monitoring changes in these fragile environments should thus be a priority, but only very few “natural laboratory experiments have looked into longer-term changes of climate and their effects on ecosystems so far. By investigating old-growth conifers growing next to retreating La Perouse Glacier (Alaska), Gaglioti et al. (2022, <https://doi.org/10.1029/2022GL098574>) provide a unique timeseries of past climate cooling and warming covering the past two centuries. The trees they analyzed have therefore witnessed climate change that can be considered outside human experience - at least for larger spatial scales - and can serve as a real-life example of what likely impacts of future climate change could be on tree vitality and growth.

## 1. Introduction

Mountain regions cover roughly one-fourth of the Earth's surface, store most snow and ice outside polar regions (Hock & Huss, 2021) and provide water for billions of people (Barnett et al., 2005; Viviroli et al., 2020). Mountains also harbor various distinct ecosystems and are therefore hotspots of considerable species richness (Antonelli et al., 2018). As such, they contribute disproportionately to terrestrial biodiversity and endemism: Albeit occupying only 25% of all land areas, mountain regions host roughly 87% of terrestrial global diversity (Rahbek et al., 2019). Yet, the significance and influence of mountain regions as hosts for biodiversity is at stake as these environments have been warming at a rate that is *c.* 25%–50% larger than in adjacent lowlands since around 1950 (Pepin et al., 2022). This enhanced warming is somewhat similar to a phenomenon known at high northern latitudes as the Arctic amplification (England et al., 2021), even if rates observed in mountains tend to be slightly lower than those in the Arctic (IPCC, 2021). The accelerating warming also affects the transport and rise of air masses on mountain slopes and resulting precipitation: although a speed-up of the hydrological cycle with enhanced evaporation and more heavy precipitation episodes should be expected in a warming world according to theory (Berg et al., 2013; Pall et al., 2007), such a tendency is not yet very marked in observational records of mountain regions (Pepin et al., 2022). These ongoing changes are first of all detrimental for snow, ice, and

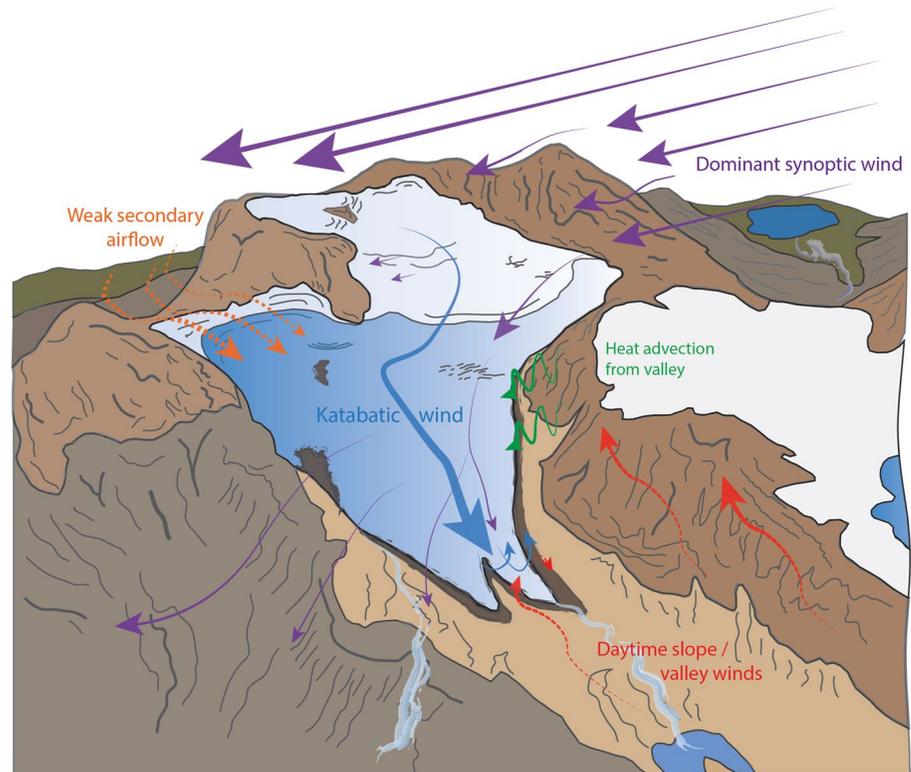
glaciers (Beniston et al., 2018; Pörtner et al., 2019): a shift of snowmelt from summer into spring (Musselman et al., 2017) and the emergence of greener landscapes (Rumpf et al., 2022), a transition from snowfall to more frequent rainy episodes, even in winter (Stoffel & Corona, 2018), accelerated wasting of glaciers (Hugonnet et al., 2021; Immerzeel et al., 2020) or an accelerated thawing of permafrost (Biskaborn et al., 2019; Smith et al., 2022) are now reported almost routinely. The rapid loss of ice has been reported to lead to the formation and expansion of glacial lakes (Zheng, Allen, et al., 2021). If their waters are released suddenly, glacial lake outburst floods can devastate lives and livelihoods up to hundreds of kilometres downstream of their source, thereby posing a severe threat to downstream communities and infrastructure (Schwanghart et al., 2016; Zheng, Bao, et al., 2021). Regrettably, mountain regions are now viewed as climate hotspots where change can anticipate or amplify what is occurring elsewhere on Planet Earth (Kohler et al., 2010; Pörtner et al., 2019; Pepin et al., 2022).

Current rates of global warming are expected to double within the next few decades (Dix et al., 2019; Lee et al., 2021), thus becoming an order of magnitude faster than what most ecosystems have experienced over the past several millennia. Such a fast and massive warming is considered to represent a major threat for ecosystems as elevational ranges at which individual species occur will need to shift for the fauna and flora to be able to respond to changes in their thermal niches (Chen et al., 2011; Elsen & Tingley, 2015; Steinbauer et al., 2018). The anticipated further warming is not only thought to act as an escalator for species to move to higher elevations (Freeman et al., 2018; Lu et al., 2020), but also considered to lead to the extinction of species already living on mountaintops under current conditions as they may run out of room (Urban, 2018). Yet, ecological studies investigating likely effects of climate warming on species response have hitherto, by a vast majority, been realized with plot-level warming experiments (Stuble et al., 2021). In the context of the anticipated, unprecedented changes, such experiments are of course extremely valuable, but they remain logistically intensive and inherently restricted in spatial and temporal scope. At the same time, environmental scientists have lacked examples of real-world situations for which retrospective studies could be realized to understand how ecological communities have responded to past climate changes at rates and with magnitudes similar to those predicted for the 21st century.

## 2. Glaciers Amplify Cooling and Warming in Ice-Margin Forests

In their recent paper published in *Geophysical Research Letters*, Gaglioti et al. (2022) analyzed growth patterns of trees from an old-growth rainforest of Southeast Alaska bordering La Perouse Glacier. The convincing initial assumption of their “natural laboratory” approach is that both global warming and cooling trends are accentuated with respect to adjacent environments by the changing influence of La Perouse Glacier's cold microclimate as it advances and retreats in response to regional climate change. Their assumption is as simple as ingenious and based on the idea that glaciers and their immediate downslope surroundings tend to experience microclimatic conditions that are harsher than in the wider environment of La Perouse Glacier. The presence of a significantly colder microclimate next to the glacier is linked to the presence of massive ice, but also the result of katabatic – or drainage – winds (Figure 1) carrying high-density air from higher elevations of the glaciated catchment down the slopes under the force of gravity (Poulos & Zhong, 2008; Shaw et al., 2017). Conversely, when a glacier melts, it will expose darker surfaces, thereby changing surface albedo and favoring the occurrence of daytime up-valley winds and a distinctive warming (Beniston et al., 2018), thereby amplifying regional climate trends in glacier-adjacent environments.

By monitoring contemporary microclimatic conditions around La Perouse Glacier over several years, and by reconstructing the location of past ice margins with in situ glacier-killed trees as well as remote sensing, Gaglioti et al. (2022) quantify the magnitude, seasonality, and timing of local climate change during the last two centuries to estimate that summer (June–September; JJAS) temperatures next to La Perouse Glacier were  $-3.9^{\circ}\text{C}$  colder during the last Little Ice Age advance (c. 1850–1895) than today. They also demonstrate that microclimate at their study site episodically cooled and warmed by up to  $0.5\text{--}0.7^{\circ}\text{C}$  per decade. The authors document a first episode of marked warming (1900–1930;  $0.68^{\circ}\text{C}$  per decade) during a period that is known to climatologists as the Early Twentieth Century Warming (Hegerl et al., 2018) and for which observations in remote, high-elevation environments remain scarce. Over the last 50 years, the authors reconstruct decadal JJAS warming between  $0.55$  and  $0.7^{\circ}\text{C}$ .



**Figure 1.** Idealized illustration of potential wind flow and complex interplay of different flows on a glacier: Down-glacier katabatic winds (blue arrows) are considered to be at the origin of the cooler conditions reconstructed in yellow-cedars from the rainforest growing next to the ice margin at La Perouse Glacier (Alaska; Gaglioti et al., 2022). Up-valley winds and/or local heat sources (red arrows) may favor milder conditions, especially after glacier retreat. At larger spatial scales, winds can form as a result of potential heat emitted from the warmer valley surroundings (green arrows) or down-valley airflow from well constrained surface depressions (or “cold spots”) during calm, high pressure conditions. Last but not least, winds on a glacier will also – and very strongly – be controlled by the dominant synoptic wind (purple arrows) as well as by secondary airflows (orange arrows) [Credit: Thomas Shaw, adapted, used with permission].

These massive rates of cooling and warming are not only beyond expectations, but also – and by far – outside human experience. At larger spatial and temporal scales, the only comparable climate changes for which reasonably reliable estimates exist would date back to millennial scale ice-age episodes such as the Dansgaard-Oeschger or Younger Dryas events for which rates of change were estimated to 0.7–1.0°C per decade (Alley, 2000; Wolff et al., 2010).

By contrast, science has so far been lacking any recent analogue for the accentuated rates of warming that are projected later this century in regional climates (Dix et al., 2019). By using La Perouse Glacier as a natural laboratory, Gaglioti et al. (2022) mimic the consequences of likely future regional climate change on Alaska yellow-cedar (*Calitropsis nootkatensis*) trees growing in the temperate rainforest adjacent to La Perouse Glacier. Their paper therefore is a stepping stone for its assessment of how trees have responded to fast-paced warming, and lessons learned from this case study will help predict the response of this species to rapid climate changes in decades to come. Yet, and while microclimatic effects of La Perouse Glacier can probably be considered typical of other temperate-zone glaciers of comparable size, a clear need exists for more studies in comparable natural laboratories and on other, more threatened tree species. Their paper should thus also be seen as a call for the establishment of a wider network in which the international tree-ring community should aim at multiplying the number of natural laboratories from which lessons can be drawn on where, how and at what pace trees and forest ecosystems will respond to accelerating anthropogenic warming. Although research should aim at repeating the approach by including other tree species, it should also go beyond the assessment of how the tallest inhabitants of forests respond to climate change. Rather, long-lived shrubs and perennial herbs should be included in future work as well, as they have been shown to suffer – and sometimes even more – from the ongoing anthropogenic



**Figure 2.** Cross section of a *Pinus cembra* L. killed by the protruding ice of an advancing glacier: This tree, sampled at Gepatschferner in the Austrian Alps, shows a sharp decrease in ring widths between 1600 and 1640 CE. This significant drop in increment reflects cold microclimatic conditions prevailing next to the advancing glacier. After a period of relative recovery, the tree was finally killed by the glacier in 1679 CE and conserved in one of its Little Ice Age moraines [Credit: Kurt Nicolussi, used with permission].

warming and changes in snowmelt seasonality (Francon et al., 2020). By building such a network in comparable natural laboratories – which exist at many other periglacial sites in mountain environments across the globe – we would doubtlessly enhance our ability to study and predict the global-change biology of the future.

### 3. Conclusions and Outlook

Whereas trees growing under the influence of a glacier's microclimate can obviously serve as sentinels of change and analogs of anticipated changes outside the immediate periglacial setting, this study also points to the limited use of trees growing in (former) ice-margin forests for larger-scale climate reconstructions. In fact, research aimed at reconstructing glacier advances during the Little Ice Age (c. 1300–1900; Matthews & Briffa, 2005) has evidenced that trees standing in the way of an advancing glacier tend to show suppressed growth well before they are eventually killed by the protruding ice (Figure 2; Nicolussi et al., 2022). Like in the case presented by Gaglioti et al. (2022), these trees were functioning as natural thermometers and veridically recording microclimatic conditions during the growing season. Yet, their growth patterns differed sharply from those recorded in trees growing outside the reach of the cold, dense air masses flowing down the glacier and its margins. In a somewhat larger context, the findings of Gaglioti et al. (2022) therefore also call – albeit indirectly – for caution when it comes to the inclusion of subfossil trees from moraines or proglacial plains in dendroclimatic studies as their signals – especially during colder periods of the Little Ice Age and other cold episodes of the Holocene – might well capture local, microclimatic conditions while likely – and probably even strongly – overestimating cooling at regional or even larger spatial scales.

### Data Availability Statement

Data were not used, nor created for this research.

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