Glacier Boundary Layer Thermal Coupling and Nonlinear Warming Feedbacks

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Abstract

Mountain glaciers are considered one of the sentinels of climate change. Their response to atmospheric warming is usually supposed to be linear and spatially uniform. Recent observational and modelling studies indicate that the near-surface processes in the boundary layer of glaciers are a very strong control over glacier-atmosphere interactions and create partial thermal decoupling between glacier surface air temperatures and the outer atmosphere. This buffering effect results from due to katabatic wind and surface energy balance processes, which reduce glacier melt rates due to warming in the region, but, as glaciers thin, fragment, and recede, the buffering effect diminishes, leading to nonlinear warming feedbacks and sudden increases in melt rates. The review provides existing knowledge about the thermal coupling of glacier boundary layers (GBLs), the processes of decoupling and recoupling, and findings on the implications of the process on glacier mass-balance modelling. Understanding boundary layer dynamics is essential for improving projections of the glacier change, hydrological impacts, and climate interactions in a warming world.

Keywords: boundary layer, climate change, glacier microclimate, glacier–atmosphere coupling, katabatic winds, nonlinear feedbacks

Introduction

Glaciers are one of the most vulnerable elements of the Earth system and are generally considered an important indicator of climate change (Thakuri et al., 2014; Wang et al., 2026). They evolve in response to a complicated interaction between large-scale atmospheric forcing, regional meteorological variability, surface energy balance processes and ice dynamics within them. The response of glaciers to atmospheric warming is thus the key to the future projections of water, cryospheric hazards, and the sea-level rise contribution (Rather et al., 2026; Bolch et al; 2019; Edwards et al; 2021; Siegert et al; 2020; Thakuri et al; 2019).

Traditionally, temperature-index (degree-day), simplified forms of energy balance models have been used to model glacier melt and mass balance; these implicitly assume that near-surface air temperature at glaciers closely follows ambient atmospheric temperature at similar altitudes. Based on this assumption, glacier projections can be forced by results of a coarse-resolution climate model by treating melt as roughly linearly dependent on-air temperature (Hock, 2003; Pelicciotti et al., 2005). These techniques are computationally efficient, and have been able to reproduce the trends in long-term average mass balance fairly well, especially in regions where the data are sparse.

There is, however, a central simplification in this model of glaciation, which is that glaciers themselves are unimportant actors in atmospheric warming, but rather passive receivers instead of active contributors of near-surface climate conditions to which they are exposed. This is being questioned by an increasing amount of observational and theoretical evidence. In field experiments in various mountains, it has been determined that glaciers produce their own unique microclimates such as lower temperatures of the air near the surface, stagnant temperature inversion, altered turbulence regimes and altered heat and moisture exchanges relative to adjacent terrain with no ice (Oerlemans & Grisogono, 2002; Shea & Moore, 2010). These results show that the interactions between glaciers and the atmosphere are bilateral and dynamic as opposed to being forced by the upper hand.

The main feature of this interaction is the establishment of a glacier boundary layer that is supported by a substantial thermal gradient between a cold ice surface and the atmosphere above it (Nicholson et al., 2025; Groos et al., 2024; Goger, 2021). Glaciers surfaces are regularly limited in the melt period to close to 0 °C, whereas the free atmosphere can be a lot warmer. The gradient facilitates consistent stratification, and it results in the movement of cooler, heavier air downhill (katabatic winds), which inhibits the upward transfer of heat and restrained turbulent heat exchange (Goger et al., 2022; Mott et al., 2020). Consequently, reasonable and latent heat fluxes between the free atmosphere and the glacier surface are minimized. Temperature of the air near the surface of glaciers thus tends to warm slower than the air in the rest of the region, which forms a condition of partial thermal decoupling.

According to the recent research, it can be implied that this decoupling phenomenon is common and can significantly shield glaciers against global warming (Salerno et al., 2023; Shaw et al., 2025; Šeruga, 2025). The effectiveness of decoupling is based on the glacier geometry, surface properties and the synoptic forcing. The ability to maintain a strong boundary layer and strong or sustained glaciers having steep slopes is especially effective in maintaining the flow of katabatic circulation, and smaller or discontinuous glaciers have less potent cooling effects (Goger et al., 2022; Goger et al., 2024).

Notably, this buffering is not a lasting one (Shaw et al., 2025). New syntheses in the world show that the processes of the boundary layer of a glacier are dependent on the state and change when glaciers change in shape (Shaw et al., 2025; Sauter et al., 2026). As the glaciers get thinner, retreat, and fragment, they become shorter, their slope continuity reduces and their elevation range dwindles. These alterations decrease the fetch needed to accomplish the growth of katabatic wind and weaken the gravitational forcing responsible to maintain the downslope flow of cold air. Constant boundary layers are prone to erosion by the synoptic winds and convective mixing. When this happens, it leads to a process of thermal recoupling of the glaciers: temperatures at the near-surface air will start to more directly follow ambient atmospheric warming, sensitizing sensible heat flux and also causing glaciers to melt faster (Goger & Stiperski, 2024; Goger et al., 2024; Goger et al., 2025).

This buffered-recoupled change provides nonlinear feedbacks in glacier-climate interactions (Shaw et al., 2023; Shaw et al., 2024). Although glaciers can initially cool the atmosphere by cooling the boundary layer, the ultimate loss of this cooling can ultimately result in threshold-like boosts in melt sensitivity. This means that the rate of loss of glacier mass can increase even with linearly rising air temperature patterns, and attempts to assume that there is a linear relationship between temperature and melt. This has critical implications in prediction of the glacier change, timing of the peak water, hazard limits, and water resources in the long-term.

Although there is an increased appreciation of these processes, majority of the global and regional glacier models do not clearly describe state-dependent thermal coupling. Microclimatic buffering and its possible breakdown are seldom factored in terms of temperature-index schemes, or face-resolution climate-glacier integration schemes. Consequently, current estimates can be misleading on the scale and timing of the loss of the mass of glaciers, especially in late-stage recession.

In this regard, a systematic synthesis of such thermal coupling of boundary-layers in glaciers and its nonlinear implications is required. The purpose of the review is to synthesize prior knowledge on the physical processes determining glacier thermal coupling in glacier boundary layers, review the existing evidence on decoupling and variability, study the way glacier retreat can facilitate glacier thermal recoupling, and the implication of such processes to glacier mass-balance modeling and hydrological prediction. This review aims to elucidate the re-orienting of the glacier sensitivity to climate change by shifting glacier-atmosphere interactions and discover ways to make dynamic thermal couplings functional within predictive models.

Data and Methods

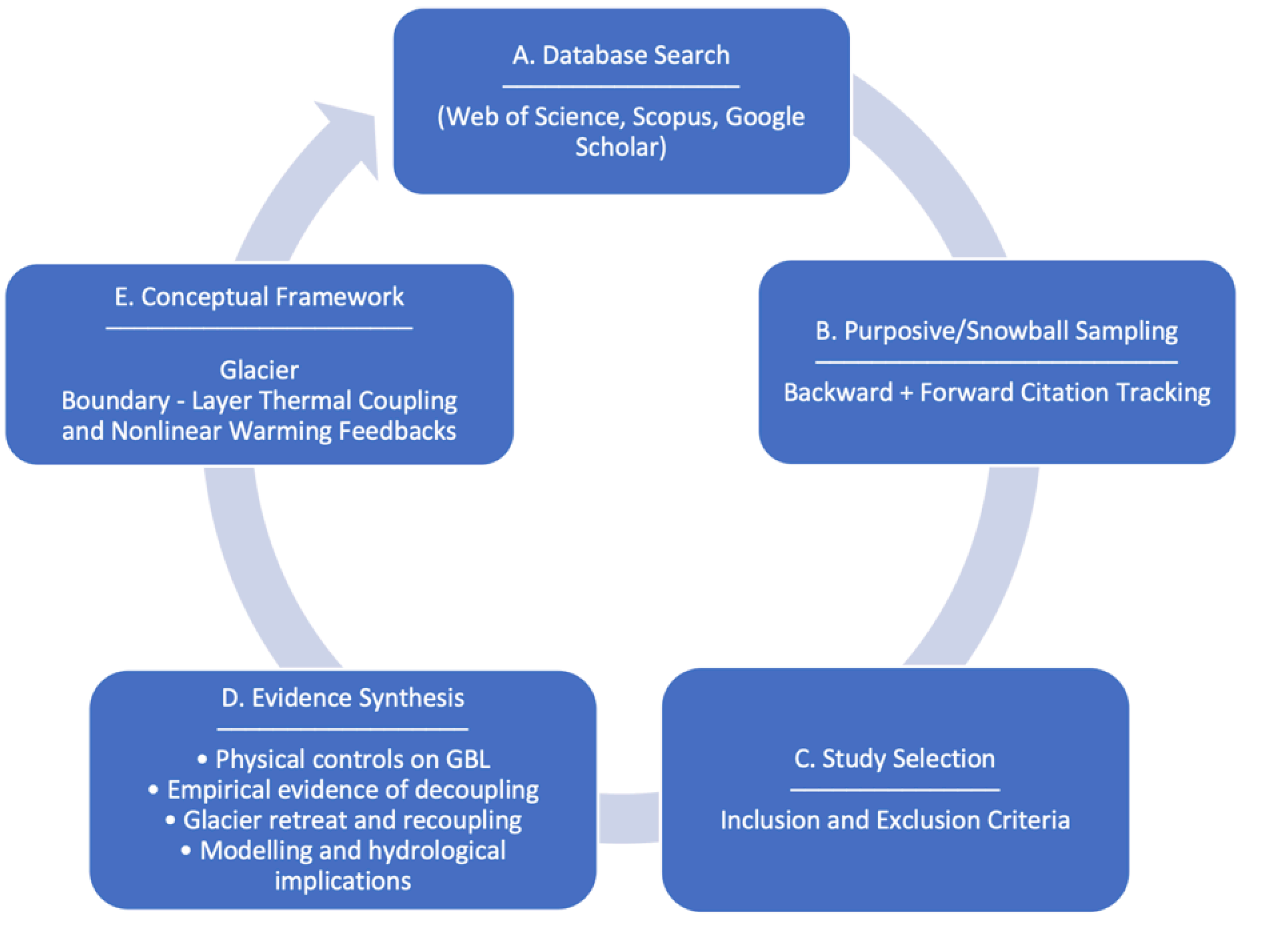
This review is based on a narrative synthesis of the available researches to study emerging evidence on the thermal coupling of the GBL and the nonlinear warming feedbacks. Instead of a formal systematic review, or meta-analysis, the task is to incorporate and review recent conceptual, observational and modelling work in fields that have not yet been coordinated in a single framework (Figure 1).

Literature Identification

Literature searches were conducted in January 2026 using Web of Science, Scopus, and Google Scholar. Search terms included combinations of “glacier boundary layer”, “glacier microclimate”, “thermal decoupling”, “katabatic winds”, “surface energy balance”, and “glacier–atmosphere coupling”. To ensure comprehensive coverage of foundational and recent contributions, a purposive and a snowball sampling approach (Johansson et al., 2025; Sherpa et al., 2019) was employed. This involved backward citation tracking of reference lists from key studies and review articles, as well as forward citation tracking of publications that cited these works. The literature search was conducted iteratively until the major conceptual, observational, and modelling studies relevant to glacier boundary-layer thermal coupling were identified.

Figure 1

Methodological steps of the study.



Literature Selection

Studies were included if they (i) investigated glacier boundary-layer dynamics, glacier microclimates, katabatic winds, or glacier–atmosphere interactions; (ii) employed field observations, remote sensing, numerical modelling, or theoretical analyses; and (iii) provided evidence relevant to thermal coupling, decoupling, or recoupling processes. Studies were excluded if they (i) focused exclusively on glacier mass-balance trends without examining near-surface atmospheric processes; (ii) lacked sufficient methodological information; or (iii) were not directly relevant to glacier boundary-layer dynamics.

The final selection included about 40 studies from a range of glacierized environments, including the European Alps, Himalaya, and other high-mountain regions. This diversity enabled the identification of both region-specific characteristics and broader patterns in glacier boundary-layer thermal coupling.

Because the objective of this study was to synthesize emerging understanding and conceptual developments in glacier boundary-layer thermal coupling, a narrative review framework was adopted rather than a formal systematic review or meta-analysis.

Analytical Framework

Thematic synthesis of selected studies was based on the following themes: (i) processes that control the formation and maintenance of the GBL, (ii) empirical evidence of thermal decoupling and its variability, (iii) dynamic changes in the coupling related to glacier retreat, and (iv) implications of the glacier melt to the glacier modelling and hydrological predictions. Empirical results were related to theoretical knowledge with conceptual models and simplified physical formulations.

Dynamics and Structure of Glacier Boundary Layer (GBL)

Definition of the GBL

The boundary layer of the atmosphere of glacier or the GBL is the section of the atmospheric boundary layer that is directly affected by the surface of the glacier and its unique thermal and radiative characteristics. In contrast to neighboring unglacial surfaces, glacier surfaces are in a state of persistently low temperatures, which are usually limited near 0 °C during periods of melting, with high albedo and vigorous long-wave radiative cooling. Moreover, they also have a relatively smooth surface roughness relative to vegetated or rocky terrains, which change the momentum exchange between them and the atmosphere. All these make the formation of a microclimatic regime that is very different than its surrounding. Field observations indicate that GBL thickness typically ranges 10–100 m, although values exceeding 150 m have occasionally been reported under weak synoptic forcing and strongly stable conditions (Oerlemans, 2010; Oerlemans & Grisogono, 2002). Structurally, it is described as being associated with intense near-surface inversions of temperatures, low turbulence kinetic energy, consistent downslope katabatic winds and low vertical mixing. The stable stratification thus inhibits the effectiveness of turbulent heat transfer as a whole between warmer overlying air to the glacier surface and this moderates surface energy exchange and surface sensitivity to atmospheric warming.

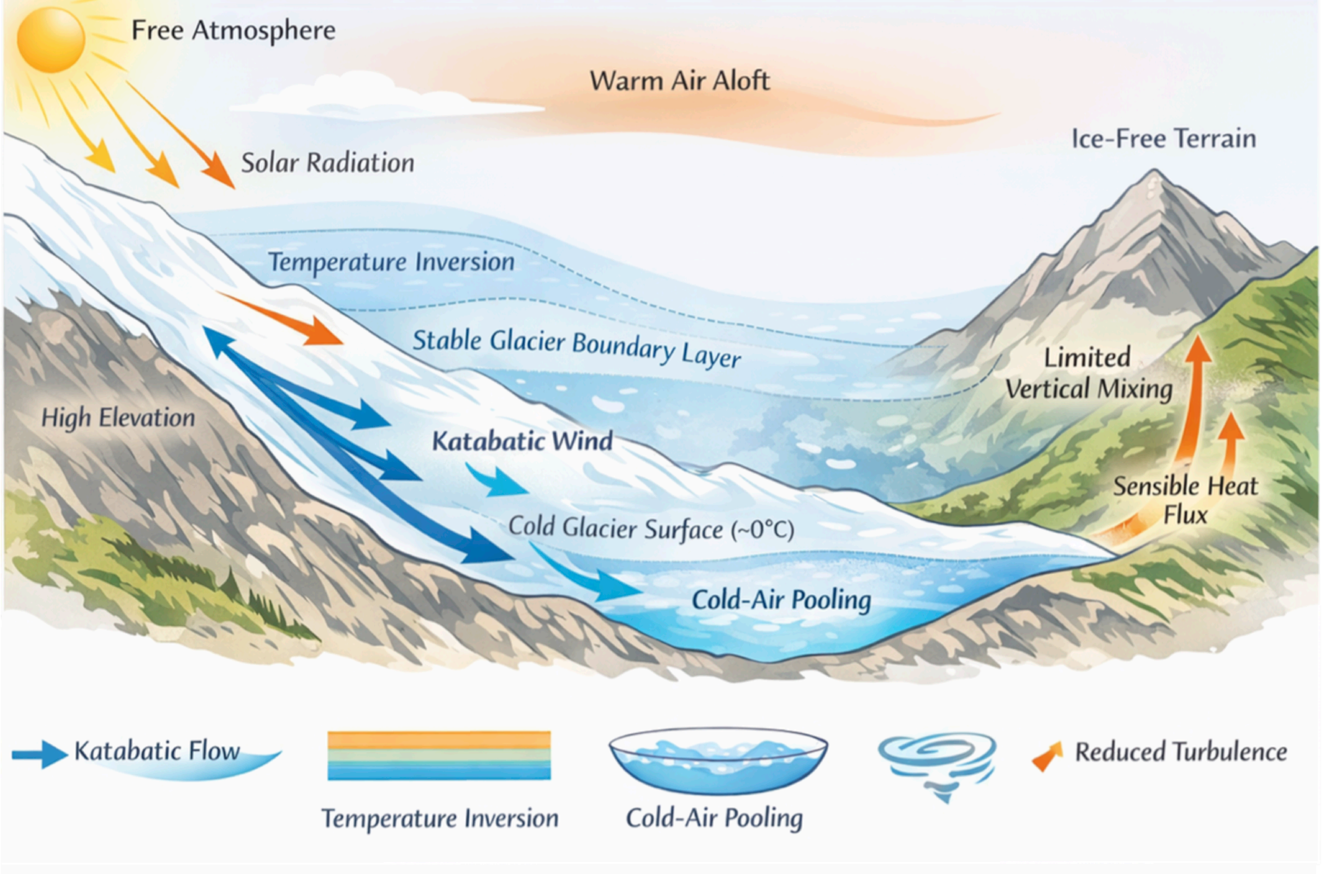
Katabatic Winds and Cold-Air Pooling

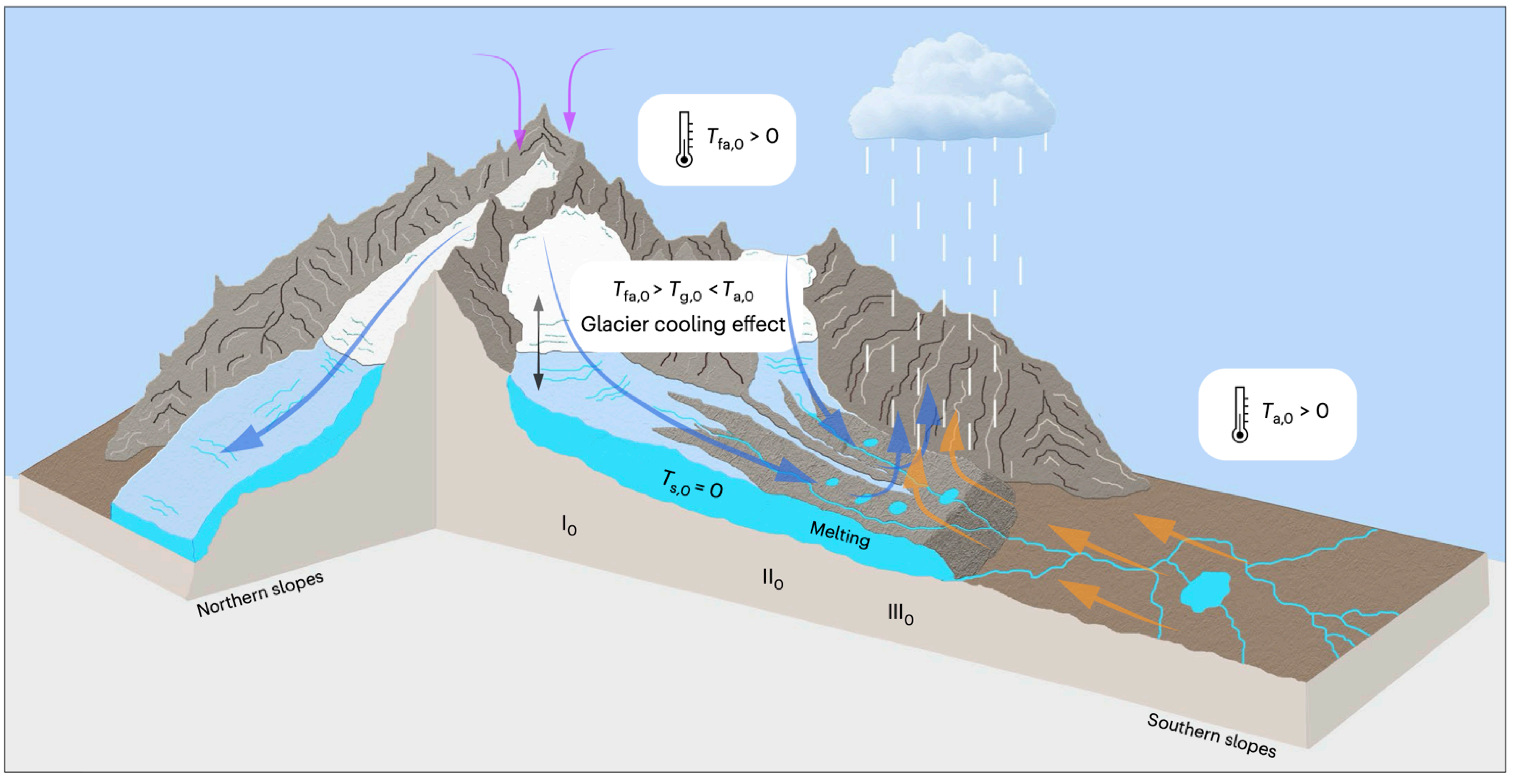
A characteristic dynamical process of the GBL is the presence of katabatic winds which play a primary role in controlling the glacier-atmosphere relations. These gravity-induced flows are formed when the air that is in direct contact with a cold glacier surface transfers heat via conduction and longwave radiations, becomes heavier than the surrounding air, and starts moving downwards due to the effect of gravity. Since surfaces on glaciers melt only seasonally (during the melt season), they serve as consistent cooling bodies in comparison with the free atmosphere, especially on warm and clear days. The ensuing temperature gradient creates a downslope-facing buoyancy force which maintains a shallow yet dynamically coherent wind system along the glacier surface.

Once initiated, the near-surface cooling is intensified by the feedback of several mechanisms with the help of katabatic winds (Salerno et al., 2023). This downward movement of air keeps bringing fresh cooled air of greater altitude downwards, so that a layer of air systematically colder than the surrounding air of the same altitude is kept off-glacier. It is a process that lowers the effective atmospheric temperature that occurs at the surface of the glacier compared to adjacent terrain that is not a glacier. Meanwhile, the cold-air stratification inhibits the vertical turbulent mixing of the air, which suppresses the entrapment of warmer air by the cold-air layer. Consequently, sensible heat flux to the surface is limited even during these situations of regional atmospheric warming.

Figure 2

Conceptual schematic of glacier boundary layer (GBL) processes, including katabatic wind, temperature inversion over ice, contrast with adjacent non-glacier terrain, and energy flux pathways.





Source: Salerno et al., 2023; Daly et al., 2009.

Katabatic circulation is usually accompanied by cold-air pooling (Daly et al., 2009), in concave glacier geometries, in overdeepenings, or in proglacial basins (Figure 2). Topographic depressions cause thick air in these environments, which further increases temperature inversion and increases the stability (Salerno et al., 2023). This type of pooling may result in persistent microclimatic cold spots, which are in part detached to regional synoptic variability (Daly et al., 2009). Katabatic advection and cold-air pooling combine to maintain a relatively stable layer of glacier boundary at which the boundary is largely resistant to external thermal perturbations.

Figure 3

Glaciers are sensitive indicator of the boundary layer temperature change.

Note: Photo by S. Thakuri from Mount Everest Region of Nepal.

Observations in the field (i.e., in a variety of glaciated areas such as the European Alps, the Himalaya, the tropical Andes, and margins of the Greenland Ice Sheet; Figure 3) have continuously shown that the katabatic winds prevail in near-surface meteorology during the melt season (Greuell & Böhm, 1998; Shea & Moore, 2010; Litt et al., 2015). Such studies indicate that the existence of the katabatic flow can also occur when moderate synoptic winds are present; however, the presence of strong large-scale winds can momentarily erode the GBL. Notably, the intensity and scale of the spatial coverage of the katabatic circulation is highly reliant on the length, slope, and continuity of the glaciers. Previous studies (Salerno et al., 2023; Shaw et al., 2025; Šeruga, 2025) shows that even if the world is warming, in the past 15 years the summer temperatures in the southern slope of the mountain, measured by the Pyramid Laboratory since 1994, have exerted a downward trend. Glaciers are warming more slowly than expected, but they are projected to warm faster in the future (Shaw et al., 2025). As surface gradients decrease due to glacier retreat and the shortening of surface gradients, the fetch needed to achieve full katabatic development is reduced, which may undermine this process of dynamically forced cooling (Salerno et al., 2023). This geometrical sensitivity offers an important connection between shrinkage of glaciers and changing thermal connectivity, which preconditions nonlinear responses of melting to be discussed later.

Mechanisms and Quantification of Thermal Decoupling

Decoupling Coefficient

Thermal decoupling can be expressed using a coupling coefficient (k):

$$k=(\Delta T_{glacier})/(\Delta T_{ambient})$$

where, $\Delta T_{glacier}$ is the change in near-surface air temperature over the glacier and $\Delta T_{ambient}$ is the change in free-air temperature outside the GBL

A value of $k=1$ implies full coupling and $k<1$ implies for partial decoupling. Shaw et al. (2025) reported median coupling coefficients (k) ranging from approximately 0.6 to 0.85 across glacierized regions, with interquartile ranges varying among climate regimes, indicating that glacier near-surface temperatures typically respond to only 60–85% of free-atmosphere warming.

Table 1

Summary on the previous empirical studies and their findings.

Study	Region/Site	Glacier Geometry	Method	Key Result
Greuell & Böhm (1998)	Alps	Valley glacier	AWS observations	Near-surface temperatures buffered relative to free atmosphere
Shea & Moore (2010)	Western Canada	Mountain glaciers	Distributed temperature modelling	Strong glacier cooling effect on local air temperatures
Salerno et al. (2023)	Everest region	Large valley glaciers	AWS + reanalysis	Persistent glacier-induced cooling and drying

Shaw et al. (2024)	Alpine glaciers	Various lengths/ slopes	Observations + modelling	Decoupling strength controlled by glacier geometry
Shaw et al. (2025)	Global synthesis	Multiple regions	Modelling synthesis	Median k ≈ 0.6–0.85; future recoupling increases warming sensitivity
Goger et al. (2025)	Hintereisferner, Austria	Retreating glacier	LES modelling	Surface changes weaken katabatic flow and increase recoupling

Surface Energy Balance and Boundary Layer Feedbacks

Glacier melt is governed by the surface energy balance (Asaoka et al., 2025; Oerlemans & Klok, 2002):

$$Q_M=Q_{SW}+Q_{LW}+Q_H+Q_{LE}+Q_G$$

where, Q_{SW} = net shortwave radiation, Q_{LW} = net longwave radiation, Q_H = sensible heat flux, Q_{LE} = latent heat flux, Q_G = ground (conductive) heat flux

Boundary layer processes primarily influence Q_H and Q_{LE} by limiting turbulent exchange. Reduced turbulence lowers heat transfer efficiency, effectively buffering melt despite rising ambient temperatures.

Controls on Decoupling Strength

Decoupling strength varies with i) Glacier length and slope, ii) Surface roughness and debris cover, iii) Synoptic wind strength, and iv) Humidity and cloud cover. Dry, high-elevation glaciers tend to exhibit stronger decoupling than maritime glaciers (Oerlemans, 2010).

Nonlinear Warming Feedbacks and Thermal Recoupling

Glacier Retreat and Boundary Layer Breakdown

The changes in the glacier lead to the breakdown of the boundary layer in the atmosphere as well as the layers of the glacier itself. With continued climatic warming, the geometry of glaciers is continually changing in a systematic way that has direct influence on the dynamics of the boundary layer. The length of glaciers becomes shorter, dips in the surface tend to be less continuous and the overall degree of elevation range reduces due to the disappearance of low-altitude tongues. Such geometrical variations decrease the fetch of the katabatic wind growth and decrease the gravitational force which enables the upkeep of downslope cold-air flow. Since katabatic circulation requires the length and slope of glaciers to be long enough to permit successively cooling and accelerating near-surface air, smaller glaciers cannot support a stable self-reinforcing boundary layer.

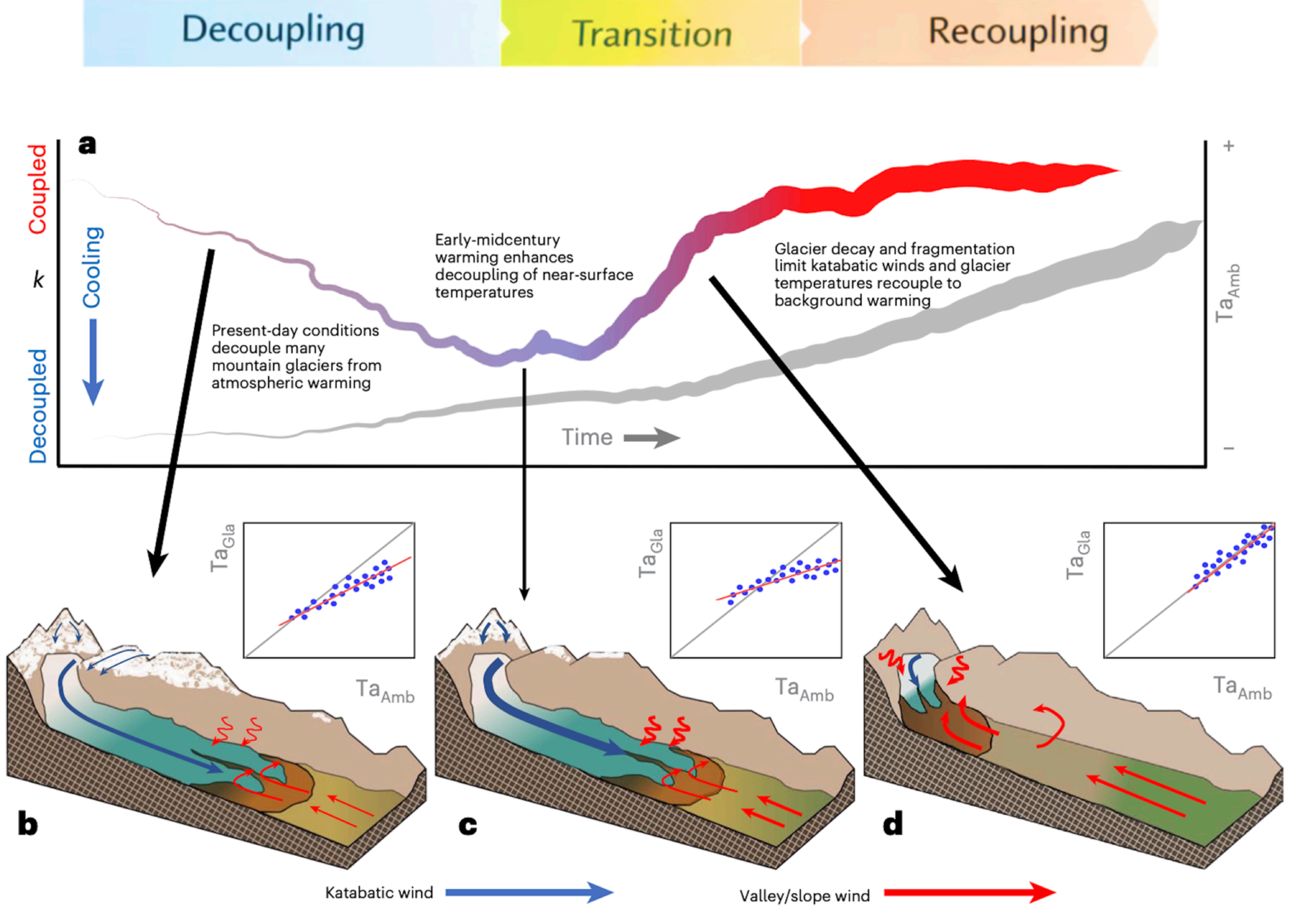
This in turn creates a thinner, more intermittent and more vulnerable GBL to erosion by synoptic scale winds and through convective mixing. Weakened katabatic strength decreases the stability of near-surface temperature inversion and increases the vertical movement with the free atmosphere above it. This changes the area of the glacier ice to warmer ambient air, a phenomenon known as the thermal recoupling (Figure 4). After recoupling, surface air temperature of the glaciers is more closely associated with the warming of the atmosphere in the region, which further increases the sensible heat flux and increases the rates of melting.

Nonlinear Acceleration of Melt

The process of moving to the recoupling state due to a resultant change in the thermal means undergoes a threshold-like behavior, with melt being sensitive to critical geometry loss which occurs at high rates. Although big glaciers can initially cool off the effects of atmospheric warming via a consistent boundary layer mechanism, the buffering effect at its core is steadily eroded as the glaciers retreat. When critical geometrical conditions are destroyed, e.g., there is not sufficient length available to develop through katabatic processes the boundary layer collapses quickly, not gradually. This change in structure yields nonlinear growth in melt sensitivity.

Figure 4

Nonlinear relationship between atmospheric warming and glacier melt, showing decoupling, transition, and recoupling phases.



Source: Shaw et al., 2025.

Box 1. A simplified illustration demonstrates the effect of recoupling. Consider a regional warming of +2 °C. Under partial thermal decoupling (k = 0.6), glacier near-surface air temperature increases by only 1.2 °C. Following thermal recoupling (k = 1.0), the same atmospheric warming produces a full 2 °C increase at the glacier surface. Assuming melt scales approximately linearly with near-surface temperature, recoupling would increase melt sensitivity by approximately 67% (2.0/1.2), even without additional atmospheric warming.

As a result, the mass-loss curves of glaciers could also show acceleration even with the smoothly or even linearly changing atmospheric temperature sequences. Melt response curves thus are found to be non-linear with regard to temperature-index, which is an indication of a state-dependent sensitivity dependent on changing glacier geometry. This non-linear behavior can be used to explain the accelerating rates in glacier mass loss in several mountain areas and emphasize the significance of considering the boundary layer dynamics in predictive glacier and hydrological models.

Implications for Glacier and Hydrological Modelling

This behaviour has drastic consequences. When, initially, the glaciers are the first to buffer the atmospheric warming, and then fail to do so, the conventional melt models can be defective in forecasting the ice loss at the late stage, the timing when the peaks of melting water are to be most important and the threshold-like responses of interest in hazard and water resource planning. Although it is relevant, GBL thermal coupling is still not well addressed in most regional-to-global glacier modelling systems and is seldom addressed directly during climate impacts evaluation.

Limitations of Temperature-Index Models

Temperature-index (degree-day) models continue to be popular in glacier and hydrological modelling as they are simple, have moderate data needs, and have strong empirical performance in a wide range of regions. Nonetheless, these models assume implicitly that there is a linear relationship between the air temperature and the melt, and the glacier surface is treated as completely coupled with atmospheric conditions (i.e., with a constant coefficient of sensitivity, $k = 1$). This hypothesis ignores the microclimatic buffering economic by means of GBL procedures and katabatic cooling.

Consequently, the indexes of temperature can distort the temporal dynamics of the melt sensitivity. Similarly, in the near term, glaciers that do not have enough length and slope to maintain stable boundary layers these models will underestimate the amount of thermal buffering and consequently overestimate melt rates. On the other hand, when the glaciers shrink and thermal recoupling takes place, the same models can not be effective to account the quick rise in the melt sensitivity concerned with breakdown in boundary layers. This may cause the underestimation of acceleration at the end of the century in the mass loss. The overall resultant effect is the distortion of the glacier response tracks especially in places where geometry thresholds have a high impact on boundary layer persistence. These prejudices are then transferred to hydrological projections and this influences the seasonal runoff timing, peak water occurrence, and long-term water availability.

Dynamic Coupling Parameterizations

To obtain better glacier projections, there is a need to have state-dependent coupling between the glacier surface and the atmosphere. Time-varying or geometry-dependent coupling coefficients that indicate the changing strength of katabatic circulation and boundary layer stability is among the promising ways to do so. As an example, the scaling of coupling parameters may be done to glacier length, slope, or range of elevation, so melt sensitivity may dynamically respond to changing glacial geometry. Alternative pathway is to simply treat turbulent heat exchange models with glacier-length-dependent or stability-sensitive transfer coefficients. These parameterizations would be more realistic in terms of the inhibition or amplification of sensible heat flux in stable versus recoupled conditions. In more complex models, such as coupled glacier atmosphere models at km or sub-km resolution can explicitly close off the katabatic flows and boundary layer transitions, and include the feedbacks that are overlooked by coarse-resolution climate models.

Glacier melt model can be corrected as $M=DDF*(kT)$, where k evolves with glacier geometry, DDF = degree day factor, and T = temperature.

Such parameterizations provide a computationally inexpensive way to represent glacier–atmosphere thermal coupling in temperature-index models while retaining the first-order effects of changing glacier geometry. The introduction of the dynamic thermal coupling into glacier and hydrological models is important. It will be able to make better projections of the mass balance of glaciers, better estimates of the seasonality of glaciers meltwater and timing of their peaks, and better estimates of hazard thresholds associated with glacier lake outburst floods and slope instability. The nonlinear coupling processes are hence critical in accounting to generate more physically consistent projections with further climate warming.

Regional and Global Implications

The processes of GBL do not only have implications on the mass balance of a single glacier, but also have a role to play in the hydrology of the region and the global climate feedbacks. Standoff or disruption of thermally decoupled conditions affect the time of maximum water and amount of maximum water since changes in melt sensitivity modify the seasonal water runoff. The level of thermal recoupling can be improved to hasten surface melt, facilitating the development and growth of supraglacial lakes and making glacier lake outburst floods (GLOFs) more probable. On larger scales, post-boundary layer erosion nonlinear acceleration of the melt can enhance glacier contributions of sea-level rise. Areas that host numerous small glaciers or fast disappearing glaciers like the tropical Andes and the European Alps can recouple earlier and suddenly lose compared to larger systems. Therefore, they are especially susceptible, where the previous breakdown of the boundary layers can lead to sudden and non-recovery mass loss in comparison to bigger and more stable glacier systems.

Conclusions and Future Perspectives

A control on glacier sensitivity to climate change is a relatively little known, but mandatory GBL thermal coupling. Although the glaciers have the capability of reducing atmospheric warming due to microclimate feedbacks, it is temporary. Through the production of steady stratification, katabatic winds and hindered turbulent exchange, glaciers may partially separate their surface air temperatures with overall atmospheric heating. This microclimatic buffering stabilizes the melting rates and postpones full manifestation of the regional rise in temperature at the ice surface, but this buffering mechanism is a temporal process in itself. The decreasing thickness, surface area, length of the glaciers erodes the boundary layer stability, continuity of the slope, and the elevation range of the glaciers strengthen and weaken the katabatic circulation. This thermal recoupling opens glacier surfaces to the direct effects of ambient warming, initiating nonlinear feedbacks to drive ice loss faster than realistic expectations dictated by linear dependencies with temperature. These dynamics are necessary to be included in glacier and hydrological models to generate plausible predictions of glacier change, and the resulting cascades of impacts on water resources, hazards and sea-level rise.

The major future research interests could be the extension of in-situ meteorological monitoring of the glaciers, systematic boundary layer profiling by use of UAVs (Unmanned Aerial

Vehicles), inclusion of microclimate mechanisms in regional and global models of glaciers, and closer associations between GBL processes and hazard and hydrological models.

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