

Rapid, heterogeneous retreat of lake-terminating Himalayan glaciers driven by local controls, not regional climate

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Abstract

Rising global temperatures are driving widespread mass loss across the Himalaya, threatening water security for ~ 800 million downstream residents. While proglacial lake expansion accelerates glacier mass loss, retreat trends remain highly heterogeneous and poorly understood. Here, we quantify monthly terminus position changes from 2017 to 2024 for 74 large Himalayan lake-terminating glaciers using high-resolution PlanetScope imagery. We identify a highly synchronous seasonal retreat pattern across the entire Himalayan arc, peaking in late summer, independent of regional precipitation regimes. This seasonal cycle correlates strongly with peak seasonal air temperatures. In contrast to this consistent seasonal cycle, the magnitude interannual retreat on individual glaciers is highly episodic and stochastic, exhibiting no distinct geographic gradient. We suggest that these interannual trajectories are governed by localised sensitivity to climate and velocity fluctuations, rather than baseline glacier size or topography. Our findings demonstrate that while broad trends can be applied at macro-scales, applying linear frontal retreat rates or constant calving values is not appropriate for modelling the evolution of individual lake-terminating glaciers. Thus, incorporating non-linear, episodic retreat into models is vital for forecasting future water supplies and the risks posed by expanding proglacial lakes in specific catchments.

Introduction

Rising global temperatures and shifting patterns of seasonal precipitation are driving widespread glacier mass loss across the Himalaya [1, 2]. However, highly variable mass loss trends among the region's ~ 20,000 glaciers, of which 10% are lake-terminating [3], complicate water supply and flood forecasting for ~ 800 million downstream residents [4]. Proglacial lake expansion disproportionately accelerates Himalayan glacier loss, increasing retreat rates by two to three times relative to land-terminating counterparts [5, 6]. This enhanced retreat is driven by increased buoyancy and reduced basal drag at the calving front, which triggers dynamic thinning, and retreat occurs via calving and subaqueous melt [7–9]. On large, expanding lakes, retreat can exceed 100s meters annually [9–13]. Thus, there is an urgent need to disentangle the controls on terminus retreat of lake-terminating glaciers, including the relative roles of individual, glacier-specific characteristics (e.g. lake evolutionary stage, subglacial bathymetry and glacier geometry), versus seasonal and annual scale climate forcing.

Measuring seasonal-scale changes in terminus position and their coincidence with seasonal climatic variables can offer vital clues to underlying controls, shown by previous work on Arctic tidewater glaciers [14–19]. However, the seasonal variability of terminus position has only been measured for a small subsample of Himalayan glaciers [20–22]. Consequently, the seasonality of retreat and its interaction with glacier-specific controls and climate forcing, remains largely unknown. It is also unclear how frontal positions are affected by changing ice velocities at both seasonal and interannual scales. Understanding these controls on retreat is of critical importance, as rapid terminus retreat and lake expansion directly impacts downstream water resource buffering and the risk posed by cryospheric hazards [23, 24].

Exploiting the recent development of high-resolution satellite platforms, we address this knowledge gap by measuring monthly terminus position changes from 2017 to 2024 for 74 large lake-terminating glaciers ($> 2 \text{ km}^2$) in the Himalaya, representing nearly all highly connected (Category 3) systems in the region (Fig. 1). Due to their size, these glaciers will likely have the greatest impact on downstream water resources and hazard, and their spatial distribution across diverse climatic zones allows us to examine underlying climatic and mechanical drivers of retreat at the Himalayan scale. To enable robust comparison between glaciers that differ by orders of magnitude in size, we normalise terminus change by each glacier's 2017 length and express it as a percentage change from this baseline. We also report the equivalent absolute change in metres to retain a physically meaningful measure of retreat or advance. Using 3 m resolution PlanetScope imagery [25], we extract monthly terminus position change rates to measure seasonal retreat and advance cycles. We pair this new dataset with a new monthly ice velocity product determined from high-resolution Planet imagery using feature tracking (A. Hyde et al., submitted) and ERA5-Land climate data [26] to assess the correlation between seasonal frontal position and seasonal changes in precipitation and temperature. These data are compared against potential topographic (e.g. aspect) and locational drivers (e.g. latitude) of observed frontal position change. This allows us, for the first time, to identify controls on seasonal-scale variations in frontal position for all large lake-terminating glaciers in the Himalaya and assess their correspondence with seasonal to interannual changes in ice velocities.

Results

Overall and Regional Trends

From 2017 to 2024, 90.5% (67) of the surveyed lake-terminating glaciers retreated, with the remaining 9.5% (7) staying relatively stable or advancing slightly (Fig. 1). Over this period, glacier length reduced by an average of 3.9% total, or 0.5% (34 m) per year. Across the entire dataset, the greatest average relative retreat occurred in 2022, with a mean reduction of 0.7% (41 m) (Fig. 1).

While the overall interannual retreat trend was remarkably consistent across the Himalaya, absolute and relative changes differed between regions (Fig. 2). Between 2017 and 2024, glaciers in the Central Himalaya experienced the greatest percentage retreat, with length reducing by 4.9% on average, compared to the Far West which had the lowest percentage reduction of 3.9% (Fig. 1, Fig. 2a-b). Conversely, absolute retreat was highest in the Far East, averaging 354 m (4.1%) of absolute retreat, compared to 199 m in the Far West (Supplementary Fig. 7). Average annual retreat rates were highest in the Central Himalaya ($0.58\% \text{ a}^{-1}$) and lowest in the Central East ($0.48\% \text{ a}^{-1}$) (Fig. 2c). Over the study period, the average annual retreat rate increased by 0.02% per year. However, this increase was regionally variable; the East experienced the greatest increase in its retreat rate (0.09% per year), whereas the rate of retreat in the Far East declined by 0.03% per year.

Despite regional variability in overall retreat trends, the seasonal timing of retreat was highly synchronous across the Himalaya (Fig. 3a-f). From January to March, glaciers exhibited a slight net

advance followed by a sizeable increase in net retreat from April and May onwards. Retreat peaked in August before rapidly reducing from October onwards. This August peak was synchronous with peak mean air temperatures (Fig. 3g). Within this overall seasonality, we observed some regional differences in the amplitude and duration of retreat, which corresponded to the length of the positive summer melt season. This regional behaviour can be broadly grouped into three zones:

Western Himalaya (Far West and Central West): These regions displayed the greatest seasonal amplitude with a sharp retreat peak concentrated in July and August. This aligns with rapid seasonal temperature transitions: spring warming and autumn cooling create a shorter, more intense window of positive summer temperatures (Fig. 3a, b).

Central to Eastern Himalaya (Central, Central East, and East): These regions exhibited a slightly broader peak in seasonal retreat: while retreat still generally peaked in July and August, elevated retreat rates were sustained over a wider window (June to September), mirroring a more prolonged peak in positive mean temperatures in these areas (Fig. 3c, d,

Far East

The Far East also peaked in summer, but exhibited the broadest peak in retreat, with elevated rates sustained from May through September (Fig. 3f). This extended retreat window directly corresponded to the region's longer duration of positive summer temperatures, which was driven by the lower minimum glacier elevations found here compared to the rest of the mountain range (Supplementary Table 1).

Individual Glacier Variability

Although cumulative retreat varied by region, we found no distinct west-east gradient in relative retreat rates. Instead, marked variations existed between individual, even neighbouring, lake-terminating glaciers (Fig. 4). For example, within the Central region, frontal position change ranged from + 0.5% (+ 18 m) (RGI60-15.09795) to -12.3% (-420 m) (Yanong glacier). Glaciers G087727E27878N and RGI60-15.10673 North in the Central East region illustrated extreme local heterogeneity; despite being 5 km apart under identical regional climates, they exhibited completely asynchronous frontal position fluctuations and sudden switches from retreat to advance (Supplementary Fig. 1–6), directly reflecting distinct, glacier-specific characteristics.

Over the study period, retreat rates for 67% of surveyed glaciers increased, indicated by clustering within the lower left quadrant of Fig. 5 (plotting median annual retreat against rate change). While the mean annual retreat varied substantially across this cohort (ranging from 0.02 to 1.7% a⁻¹), the majority experienced a consistent increase in retreat rate (between ~ 0 and 0.2% a⁻²). Furthermore, the greatest increases in retreat rate were observed at the glaciers that underwent the largest total percentage retreat (e.g., Longbasaba, Yanong, RGI60-15.10276). Thorthormi Glacier in the East Himalaya represented the most extreme case, experiencing both very high annual retreat rates and these rates accelerated markedly over the study period. It recorded both the greatest single-year retreat in 2022 (15.3%) and the

greatest single-year advance of the dataset in 2020 (+ 6.5%). Excluding Thorthormi, the largest single-year change was observed at Xiuke glacier in 2021 (-5.7%) in the Central Himalaya.

Conversely, a smaller subset of glaciers (24%) exhibited an overall decelerating retreat trend for the study period, plotting within the upper-left quadrant of Fig. 5. For example, while Dangpu and RGI60-13.00643 experienced high mean annual retreat rates (-0.6 to -1.1% a^{-1}), their overall retreat rates declined by 0.1 to 0.2% a^{-2} . Finally, advance occurred at only 9% of the surveyed glaciers (7 glaciers total). Of these advancing glaciers, the rate of advance slowed for 6 glaciers, while Coqung Glacier was the only glacier where the rate of advance increased over the study period (0.2% a^{-2}). Notably, there was no obvious pattern in the geographic distribution of advancing glaciers, although no advances were recorded in the Central West region (Fig. 4). Furthermore, unlike the distinct inter-annual variability observed in regional ice velocities (A. Hyde et al., submitted), we did not observe a single year or sub-period where retreat was particularly high across the study dataset or within individual regions (Fig. 4). Instead, there was marked temporal variability at individual glaciers.

Controls on Frontal Position Change

To identify controls on frontal position, we correlated retreat metrics against variables representing primary theoretical drivers of glacier dynamics: basal driving stress (ice thickness, slope, width), terminus buoyancy (lake area), and ablation (local climate). Topographic, locational, and baseline climatic parameters yielded no statistically significant correlations with frontal change after false discovery rate (FDR) correction (Fig. 6a; Supplementary Fig. 10). Instead, monthly-scale terminus fluctuations corresponded most strongly with concurrent climate and mean annual ice velocity.

Seasonal consistency (R), which measures the similarity in monthly terminus position change timing between years, exhibited a strong negative correlation with monthly temperature ($r = -0.57$, $p < 0.001$) and precipitation ($r = -0.38$, $p < 0.05$). Thus, when temperatures and/or precipitation in a given month were higher, the amount of retreat in that month differed more between years. Furthermore, a glacier's multi-year retreat trend correlated significantly with its average annual ice velocity ($r = -0.36$, $p < 0.05$; Fig. 6c). Faster flowing glaciers exhibited increasingly negative trends (accelerating retreat), whereas slower flowing glaciers exhibited reducing retreat rates.

To better understand the relationships between these highly collinear topographic, climatic, and dynamic variables, a Principal Component Analysis (PCA) was performed (Fig. 6b). The first two principal components explained a combined 41.1% of the total variance (PC1 = 22.2%; PC2 = 18.9%). The resulting biplot revealed a clear separation of drivers: Component 1 captured baseline physical dimensions and dynamics, grouping length, thickness, lake area, terminus width, and mean velocity together. In contrast, Component 2 captured climate sensitivity, location, and temporal behaviour, isolating mean elevation, monthly climate correlations, mean climate, and long-term trends. Mean velocity strongly aligning with geometric variables on Component 1 confirmed that baseline ice flow was fundamentally a product of

glacier size, operating independently of the climatic sensitivities and temporal trends dictating Component 2.

Discussion

Heterogeneity and Regional Dynamics

Our analysis revealed pronounced local heterogeneity in the magnitude and timing of interannual retreat of lake-terminating Himalayan glaciers, despite highly synchronous seasonal cycles and consistent regional-scale trends (Fig. 3a-f). Overall, lake-terminating glaciers retreated rapidly between 2017 and 2024 [5, 8], with retreat being highest in the central east and eastern regions and lowest in the far west and west, where the seasonal peak in retreat was the shortest (Fig. 2). However, when we assessed the overall trend or retreat magnitude for individual glaciers, there was no distinct West-East gradient in retreat (Fig. 2), unlike the clear spatial gradients observed in ice velocities (A. Hyde et al., submitted), this suggests that climate forcing alone cannot explain the behaviour of individual glaciers [3, 5, 6, 8], which we suggest are controlled by glacier-specific factors. Furthermore, we did not observe consistent phases of increased retreat across multiple proximal glaciers (Fig. 3), unlike for ice velocities (A. Hyde et al., submitted), suggesting the timing of retreat is also controlled by glacier-specific factors, rather than external climate forcing.

Seasonal Synchronicity and Climatic Correspondence

The highly synchronous July to September peak in seasonal retreat rates observed across the Himalaya (Fig. 3) suggests that peak summer air temperatures are a pan-Himalaya control. While glaciers in the East and Central Himalaya experienced this summer peak alongside intense monsoon-driven precipitation [27], glaciers in the Far West, which are predominantly sustained by winter westerlies [27, 28], still exhibited peak retreat during the same window. Because peak retreat timing remained uniform across fundamentally different precipitation regimes, precipitation timing alone cannot be the primary driver. Instead, the narrow summer temperature window of the Western Himalaya produced a shorter retreat peak (Fig. 3a), while the extended warm season in the Far East produced a prolonged retreat phase (Fig. 3f). This regional correspondence confirms that peak summer air temperatures dictate the broad seasonal retreat window. Conversely, during the winter and early spring (January to April), lower air and lake temperatures likely reduced surface melt and/or thermal erosion by lakes [29], resulting in the slight net advance observed across the dataset (Fig. 3g). However, lake temperature data is needed to fully confirm the role of lake versus air temperature controls.

Our correlation results also demonstrated that higher air temperatures ($r = -0.57$) and precipitation ($r = -0.38$) significantly reduced seasonal consistency, i.e. under warmer and/or wetter conditions, the magnitude of retreat in a given month varied more between years. We suggest this may result from the direct effects of warmer air temperatures and their indirect effects, via lake temperatures and/or lake ice, which together may promote greater retreat and provide the opportunity for feedbacks to develop with

local controls, such as bathymetry. Conversely, when air temperatures are colder, we expect retreat magnitudes to be reduced, resulting in lower variability.

The pronounced summer retreat cycle in our data shared similarities with the seasonal dynamics established at many Arctic tidewater glaciers, where late-summer retreat is driven by warm fjord waters and peaks in subglacial melt [16–19]. However, observing such a high level of synchronicity is highly unexpected, as High Mountain Asia possesses some of the most diverse macro-scale climates in the world [28, 30], suggesting a common, overarching air temperature control, likely mediated via lake warming. Because high-resolution seasonal frontal position data for lake-terminating glaciers in other regions (such as the European Alps) remains limited, determining whether this robust seasonal temperature dependence persists within other mountain ranges, such as the Andes or the rapidly retreating systems of the New Zealand Southern Alps and Patagonia [31–33] is an avenue for future investigation.

Retreat magnitude is decoupled from regional climate forcing

Our Principal Component Analysis (Fig. 6b) and correlation results demonstrated that long-term retreat magnitude did not correlate with baseline climate, surface velocity, or glacier geometry. Thus, while summer temperatures govern the seasonal timing of retreat, interannual changes in precipitation and temperature do not correspond to overall multi-year trajectories. This decoupling is highlighted by glaciers G087727E27878N and RGI60-15.10673 North located just 5 km apart exhibiting completely asynchronous frontal position changes despite a comparable timing of peak retreat (Supplementary Fig. 4). Thus, we suggest that the magnitude of interannual retreat is instead controlled by glacier-specific factors, most likely the glacial lake bathymetry and subglacial topography. Specifically, once a glacial lake has grown big enough, it can become decoupled from climate forcing and retreat can persist via a series of feedbacks between floatation, dynamic thinning, increased ice velocities and further retreat [5, 6, 9].

While regional ice velocities exhibited widespread interannual shifts, likely in response to basal water pressure [34, 35] and (A. Hyde et al., submitted), our dataset revealed that annual terminus retreat was highly variable between glaciers and years. Indeed, we did not observe any coherent high or low retreat years, between neighbouring glaciers, within regions or across the dataset as a whole (Fig. 3). We suggest that the timing of glacier retreat also depends on individual glacial lake bathymetry. This episodic retreat behaviour has been observed on individual lake-terminating glaciers elsewhere, including Patagonia [11, 33], Alaska [36] and New Zealand [32, 37], but we demonstrate that it is widespread and persistent across the Himalaya. Although direct subglacial bathymetric data remains sparse across the region, specific instances of extreme step-change retreat serve as classic morphological indicators of a terminus retreating into an overdeepening. Thorthormi Glacier provides the most extreme example of this, where we observed a retreat of 15.3% (1,040 m) in a single year (Supplementary Fig. 5) as the glacier retreated across an overdeepened lake. Direct, detailed

measurements of glacial lake topography are rare in the Himalaya, but are critical for determining future interannual retreat trajectories.

Broader Implications

This highly episodic retreat pattern has important implications for regional water security and hazard mitigation, because it makes determining the interannual patterns in water supplies challenging. Predictive mass-loss models often rely on broad regional climate averages and overall retreat patterns to forecast glacier evolution across the Himalaya [8, 38]. However, our findings highlight a fundamental distinction needed for future models: while the seasonal timing of retreat is temperature driven, the total magnitude of retreat for each year is glacier specific and decoupled from immediate climate forcing (Supplementary Fig. 1 to 6). A key component of this localised variability is calving. Because calving is a stochastic process that is difficult to accurately simulate [33, 39], large-scale models frequently manage computational complexity by parameterising frontal ablation with temporally constant retreat rates. While simplified parameterisations are often practically necessitated in marine-terminating environments (e.g., [40]), our findings demonstrate that assuming a constant retreat rate is unsuitable for modelling the trajectory of individual Himalayan lake-terminating glaciers. Furthermore, models need to incorporate the impact of lake bathymetry on glacier retreat, but detailed in-situ measurements are scarce among in the Himalayan and other high mountain regions [41]. Thus, collecting robust, detailed bathymetric and subglacial topographic data is critical to our ability to forecast the near future behaviour of lake-terminating outlet glaciers in the Himalaya.

Methodology

Data used

Orthorectified PlanetScope imagery between 2017 and 2024 was acquired from Planet Explorer (planet.com/explorer/). We removed images with cloud cover > 50%, sun elevations < 20°, lack of ground control. Prior to mapping retreat, all images were checked from one to the next for any shifts on areas of ground where no movement is expected in the short term (e.g. ridge crests and gullies), if any movement was observed, these images were removed.

Table 1
Data sources used in this study. * Indicates static dataset.

Dataset	Resolution	Time period	Source	Reference
Velocity	12 m	2017 to 2024	PlanetScope	This study
Thickness	25 m	2000 to 2019*	Model	[42]
Debris cover %	Vector	2013 to 2017	Landsat 8, Sentinel-2A/B	[43]
Topography	30 m	2000*	C-band Spaceborne Imaging Radar and X-Band Synthetic Aperture Radar	[44]
Aspect (northness)	Vector	2000 to 2017	Randolph Glacier Inventory 6.0	[45]
Mean glacier area, length and lake area	3 m	2017 to 2024	PlanetScope	This study
Climate	9 km	2017 to 2024	Model – ERA5-Land	[26]

Glacier selection and delineation

Glacial extents for the Himalaya were acquired from the Randolph Glacier Inventory (RGI 6.0) [45]. Glaciers were then filtered by proximity to lakes in ArcGIS using the 2018 Third Pole lakes mapped by Zhang and others [46]. Glaciers with an area $< 2\text{km}^2$ were then removed, as glaciers smaller than this are more susceptible to short-term temperature and precipitation and other stochastic local effects, making it difficult to generalise their dynamics at a regional scale [47].

Glacial lake intersects for 2017 were then manually confirmed and classified by level in ArcGIS using Planet imagery [25]. This classification followed the approach detailed by Steiner and others [48], based on a visual evaluation of the “connectivity level” of each lake and glacier.

- **Category 3:** lake terminating glaciers were classified as terminating in a lake $> 0.01\text{ km}^2$, with at least 50% of the terminus in contact with the lake.
- **Category 2:** lake terminating glaciers were classified as having $> 10\%$, but $< 50\%$ of the terminus in contact with the lake
- **Category 3:** lake terminating glaciers had less 10% contact with the lake, or the lakes were less than 0.01 km^2 .

We excluded category 1 lake-terminating glaciers that transitioned to category 2 before the end of the study. Glaciers classed as surging in the RGI 6.0 dataset were also excluded due to the outsized impact surging can have on glacier dynamics [49].

Front position mapping

We measured changes in glacier front positions using the commonly applied box method [15, 50–52]. This approach works by repeatedly digitising the ice front location within a fixed reference box of known width and length drawn parallel with ice flow and extending beyond the maximum and minimum front positions. Frontal position change is calculated by dividing the area of the reference box upstream of the digitised terminus by the width of the box. This method is ideal for lake terminating glaciers as unlike measurements along the glacier centreline position which can yield arbitrary results, it accounts for total retreat across the calving front [53].

We mapped terminus positions on a monthly frequency. Measurements closest to the 15th of each month were prioritised, however if the image quality for that first candidate was poor, the next closest data was chosen. Frozen lakes and snow cover in the pre-monsoon period sometimes prevented precise mapping of the terminus location; these months were therefore skipped. Georeferencing and manual digitisation can be considered the main source of error. Following a similar approach to Hill and others [52], we quantified average error for each by repeatedly mapping a 1000–500m long lakeshore 20 times in each region of interest. The resulting total mean errors for the six ROIs was 3.5 m.

Retreat time series analysis

To assess drivers of terminus position change and enable cross-regional comparison, cumulative retreat was standardised as a relative percentage of each glacier's 2017 baseline length. From this, we calculated both total net change (total distance retreated) and mean annual retreat rate (the average distance retreated per year, expressed in m a^{-1}). Retreat trend (m a^{-2}) was estimated using linear regression across the annual rates; because retreat is represented by negative values, a negative trend indicates an accelerating rate of retreat.

To isolate the seasonal timing of retreat from the absolute magnitude of retreat, we calculated a 'Normalised Retreat Intensity' for each glacier. Mean monthly retreat rates were min-max normalised on a scale from 0 to 1, where 0 represents maximum advance and 1 represents peak monthly retreat. Seasonal consistency (R) was quantified by fitting a sinusoidal function to the detrended cumulative retreat signal to extract the phase of maximum retreat. These annual phases were treated as unit vectors, where the magnitude of their vector mean ($0 \leq R \leq 1$) indicates the inter-annual stability of the seasonal cycle [54].

Potential forcing factors

We compared retreat metrics against a suite of topographic, dynamic, and climatic variables. Mean glacier elevations and slope were extracted from the SRTM 30m DEM [44], and ice thickness was extracted from Farinotti and others [42] at 50 m resolution. Glacier area, length, and terminus width (measured 100 m up glacier of the 2017 terminus) were manually digitised using January 2017 PlanetScope imagery. Lake area was measured for 2017 and updated to correspond with changes in terminus position.

To capture the characteristics of the ablation zone, we extracted data for median ice velocity, elevation, ice thickness, slope, and debris cover specifically for ice below the Equilibrium Line Altitude (ELA). The ELA was assumed to be the median altitude of each glacier [55]. These values were calculated by extracting the median value of all respective raster pixels falling within the RGI 6.0 glacier polygon below the ELA threshold.

For climatic forcing, we utilised ERA5-Land monthly averages for 2 m temperature and precipitation from January 2017 to December 2024 [26]. ERA5-Land outputs reliably represent observed meteorology in High Mountain Asia [56, 57]. Climate data was extracted from the 10 x 10 km grid cell corresponding to the centre point of each glacier.

Statistical framework and outlier exclusion

To disentangle the overlapping controls on terminus retreat and diagnose multi-collinearity, all static topography and baseline climate variables were integrated into a Principal Component Analysis (PCA). We then generated a cross-regional correlation matrix to evaluate direct relationships between predictors and retreat metrics, applying the Benjamini-Hochberg procedure to control the False Discovery Rate (FDR) [58]. Furthermore, to quantify the dynamic response of individual glaciers, we calculated their climate correspondence (Pearson r) by correlating exact-interval retreat rates against concurrent monthly climate anomalies and ice velocities.

To prevent extreme mass-loss events from artificially skewing the study-wide statistical relationships, we mapped retreat metrics to identify outliers exhibiting behaviour greater than two standard deviations from the regional mean. Only one glacier, Thorthormi Glacier, met this extreme criterion; it was consequently excluded from all study-wide PCA and correlation statistics, though retained for individual behavioural comparisons. Additionally, one other glacier (RGI60-13.26432) was omitted from specific topographic sampling due to the complexity of its ice margin making reliable data extraction challenging.

Declarations

Data availability

The PlanetScope satellite imagery used for velocity tracking is available via Planet Explorer (<https://planet.com/explorer>) subject to their licensing agreements. The glacier outlines are available from the Randolph Glacier Inventory (RGI 6.0). The climate data is available from the Copernicus Climate Change Service (ERA5-Land). The retreat timeseries for each glacier will be made available with this publication in the Figshare repository.

Code availability

The MATLAB scripts used for retreat mapping will be uploaded to the Figshare repository.

Author contributions

A.H., conceptualised the study, conducted the data processing, and wrote the original draft. R.C., S.A.D. contributed to the formal analysis and reviewing of the manuscript.

Competing interests

The authors declare no competing interests.

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Figures

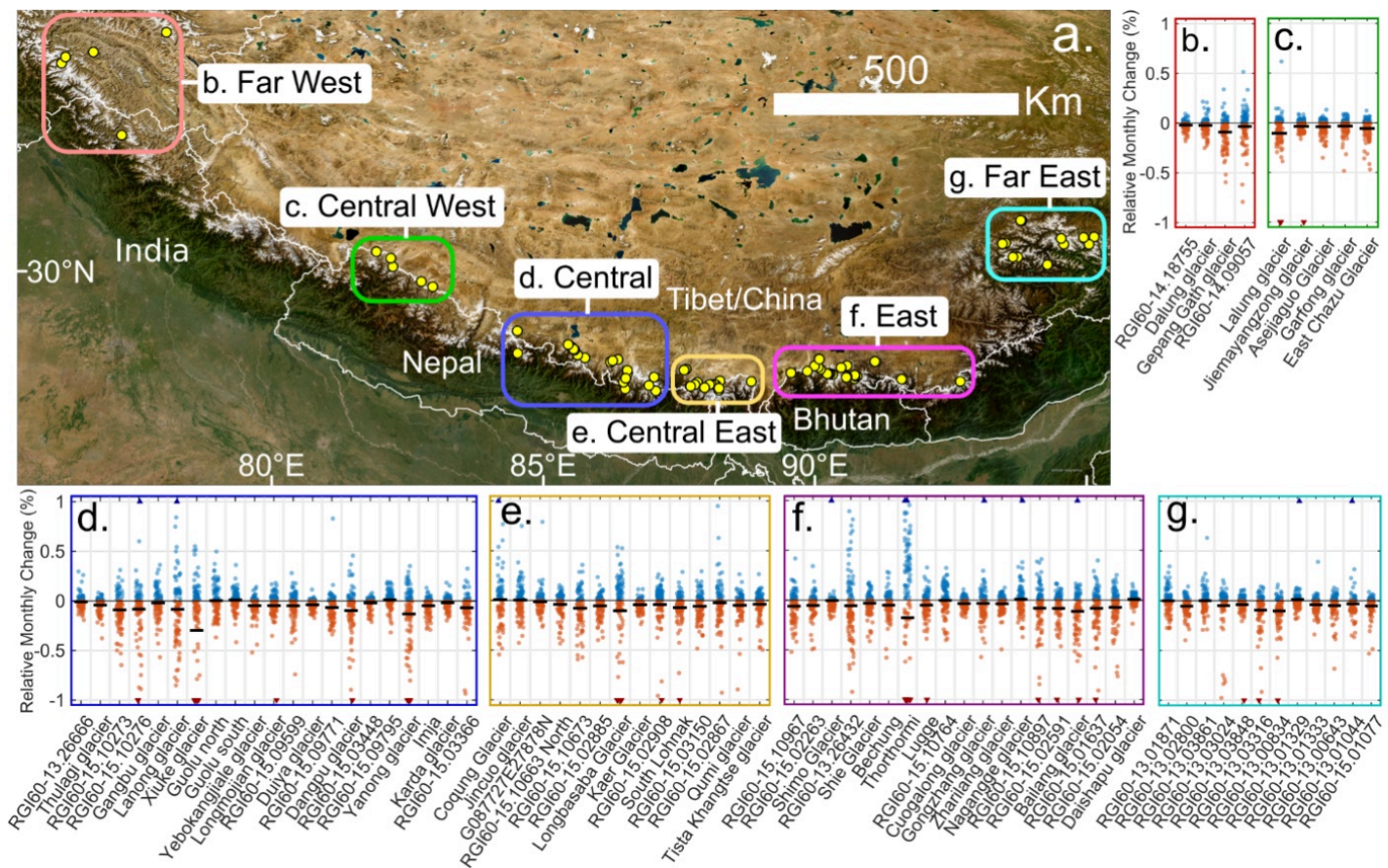


Figure 1

Distribution and monthly retreat rates of studied glaciers. **a**, Location of large Category 3 (>2 km²) lake-terminating glaciers and associated sub-regions across the Himalayan arc. **b–g**, Distribution of relative monthly changes by individual glacier from west to east across the Far West (**b**), Central West (**c**), Central (**d**), Central East (**e**), East (**f**), and Far East (**g**) regions. Data are cut off at -100 to +50 m per month, with mean change (2017 to 2024) indicated by black bars.

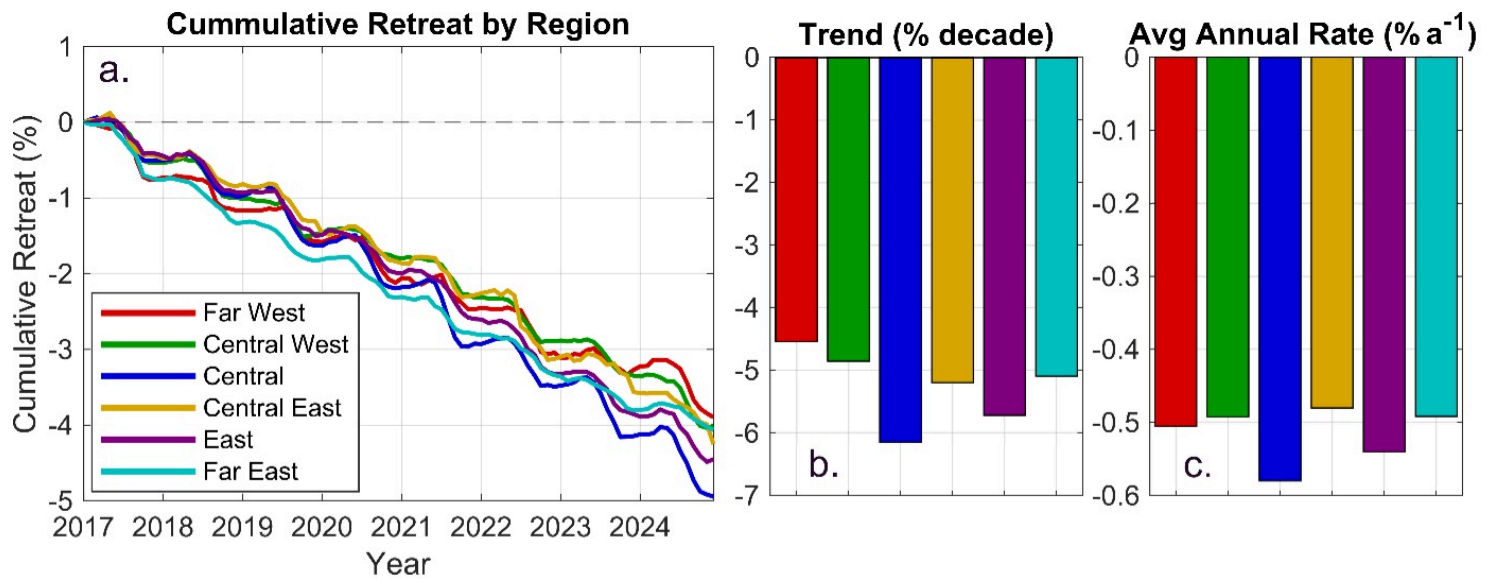


Figure 2

Regional retreat trends from 2017 to 2024. **a**, Average cumulative percentage change in terminus position relative to 2017 glacier length for the six study regions. **b**, Decadal terminus position change trends. **c**, Average annual rate of change over the study period. Regional colours in **b** and **c** correspond to the legend in **a**.

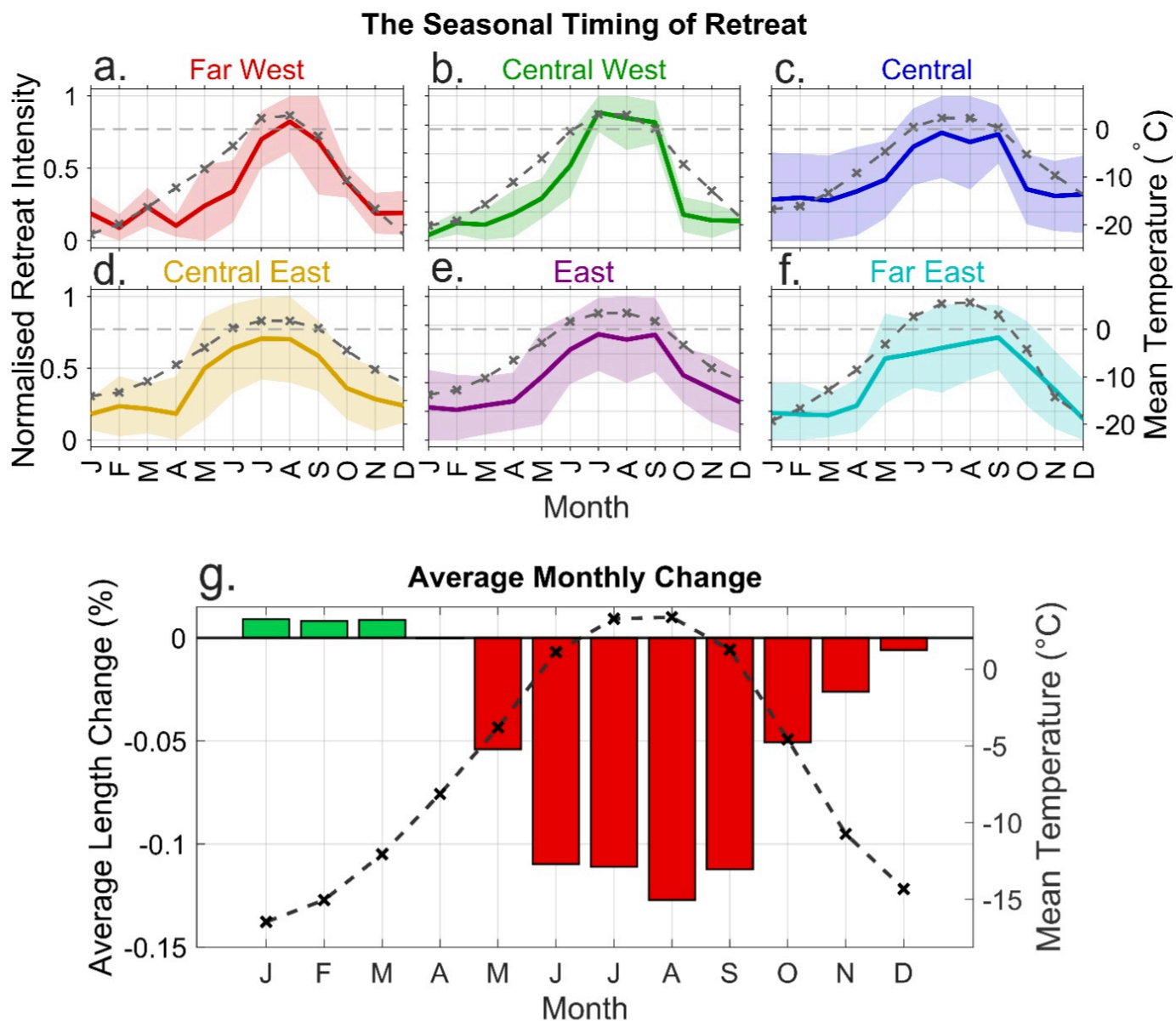


Figure 3

Seasonal retreat intensity and corresponding air temperatures. **a–f**, Normalised seasonal retreat intensity for Himalayan lake-terminating glaciers (2017–2024) across the Far West (**a**), Central West (**b**), Central (**c**), Central East (**d**), East (**e**), and Far East (**f**) regions. Monthly retreat rates are min-max normalised from 0 (maximum monthly advance) to 1 (maximum monthly retreat). Mean monthly temperature for each region is plotted on the right y-axis (black dashed line). Shaded error bands

indicate one standard deviation from the regional mean. **g**, Average absolute monthly terminus position change across all glaciers over the study period (green bars indicate advance, red bars indicate retreat), with mean monthly temperature for all regions plotted on the right y-axis.

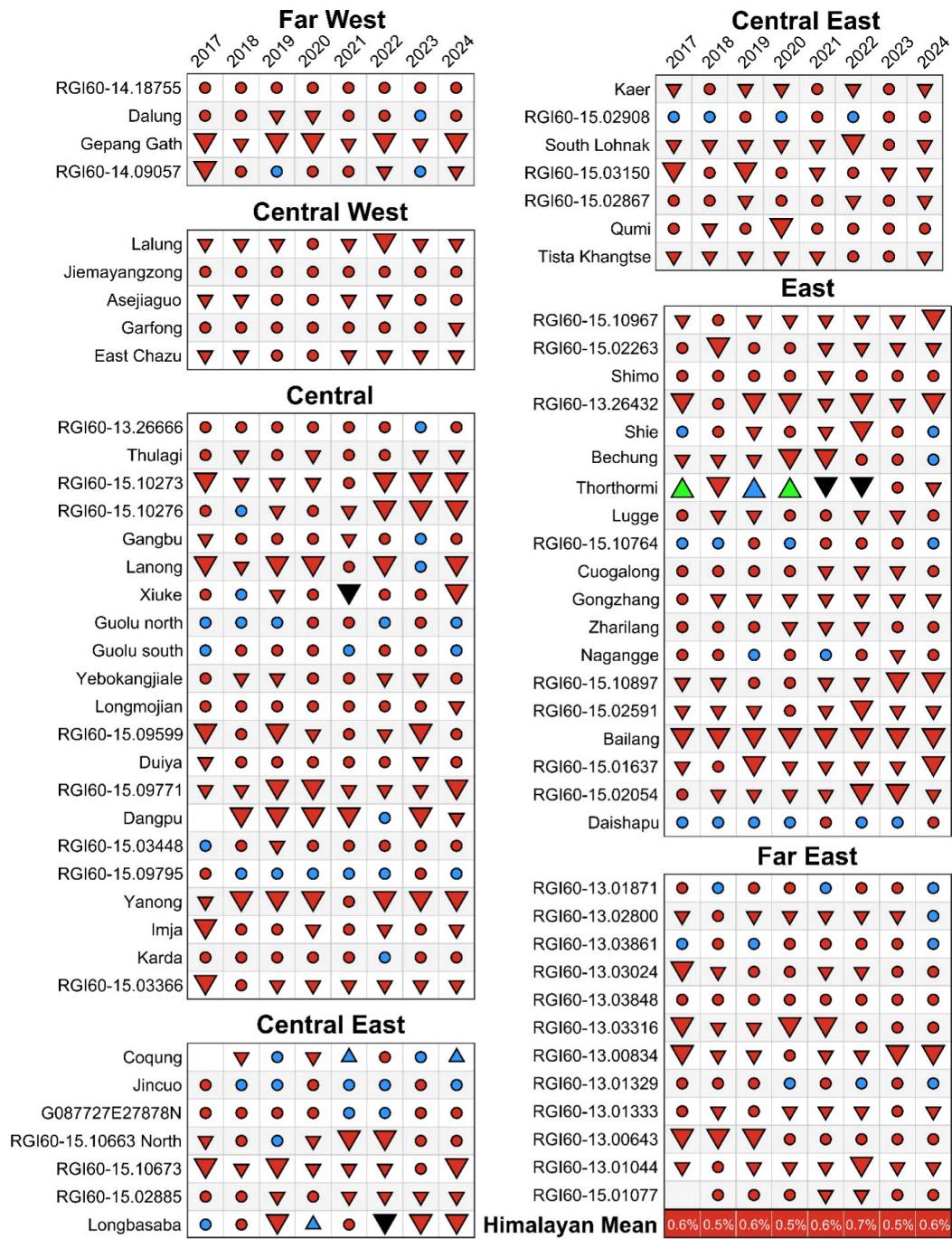


Figure 4

Annual changes in glacier front position (2017–2024). A visual matrix tracking relative changes as a percentage of baseline glacier length. Red markers denote retreat; blue markers denote advance. Circles indicate <0.5% change, small down-pointing triangles indicate between 0.5% and 5% change, and large down-pointing triangles indicate >5% change in relative glacier length. Extreme changes (>5%) are indicated by large green up-pointing triangles for advance, and black down-pointing triangles for retreat. Himalayan-wide averages (excluding Thorthormi) are included at the bottom.

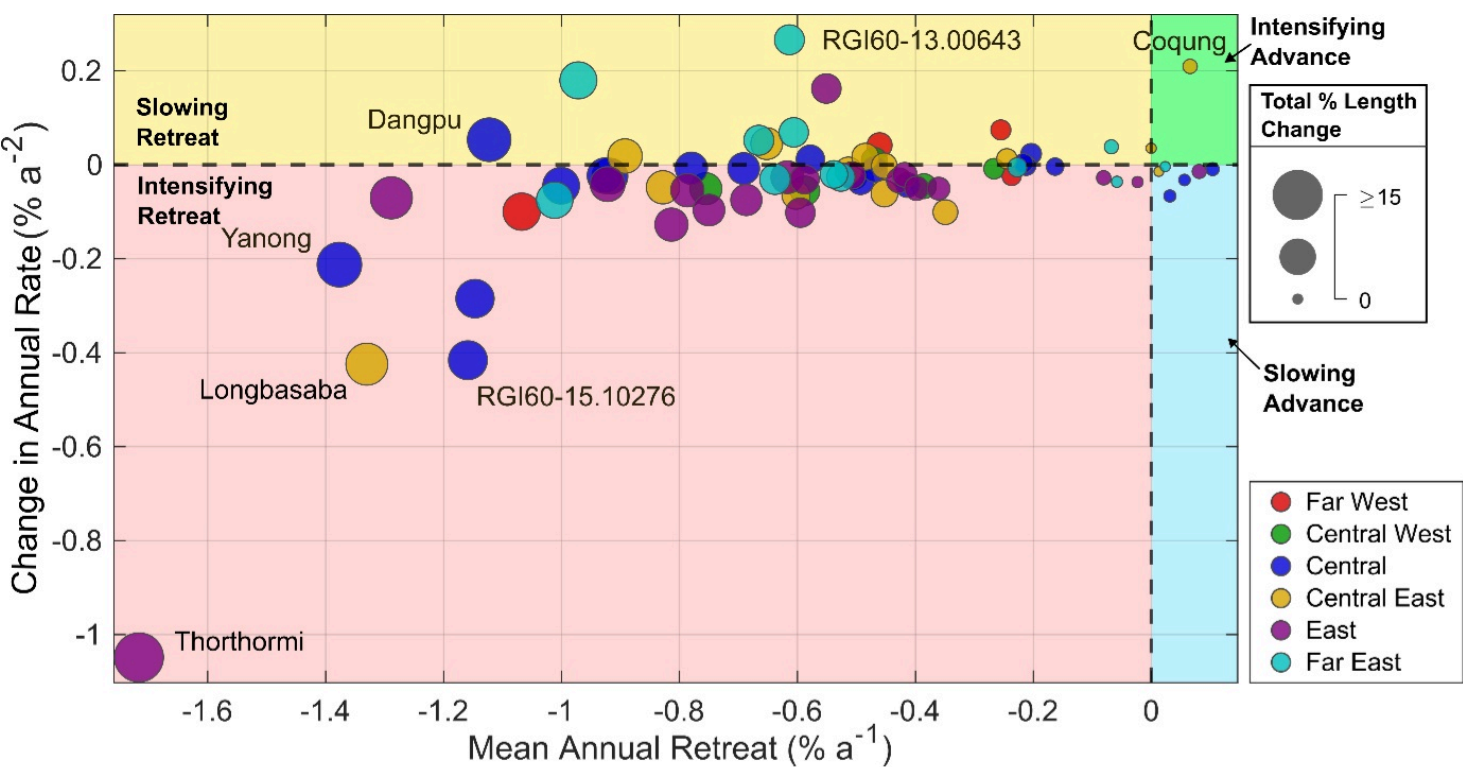


Figure 5

Retreat dynamics of individual glaciers. Bubble chart comparing mean annual retreat against acceleration from 2017 to 2024. Bubble size denotes total percentage length change over the study period. The horizontal dashed line denotes the zero-acceleration baseline; glaciers plotting below this line are actively accelerating in their retreat, while those above are decelerating. Notable outliers are individually labelled.

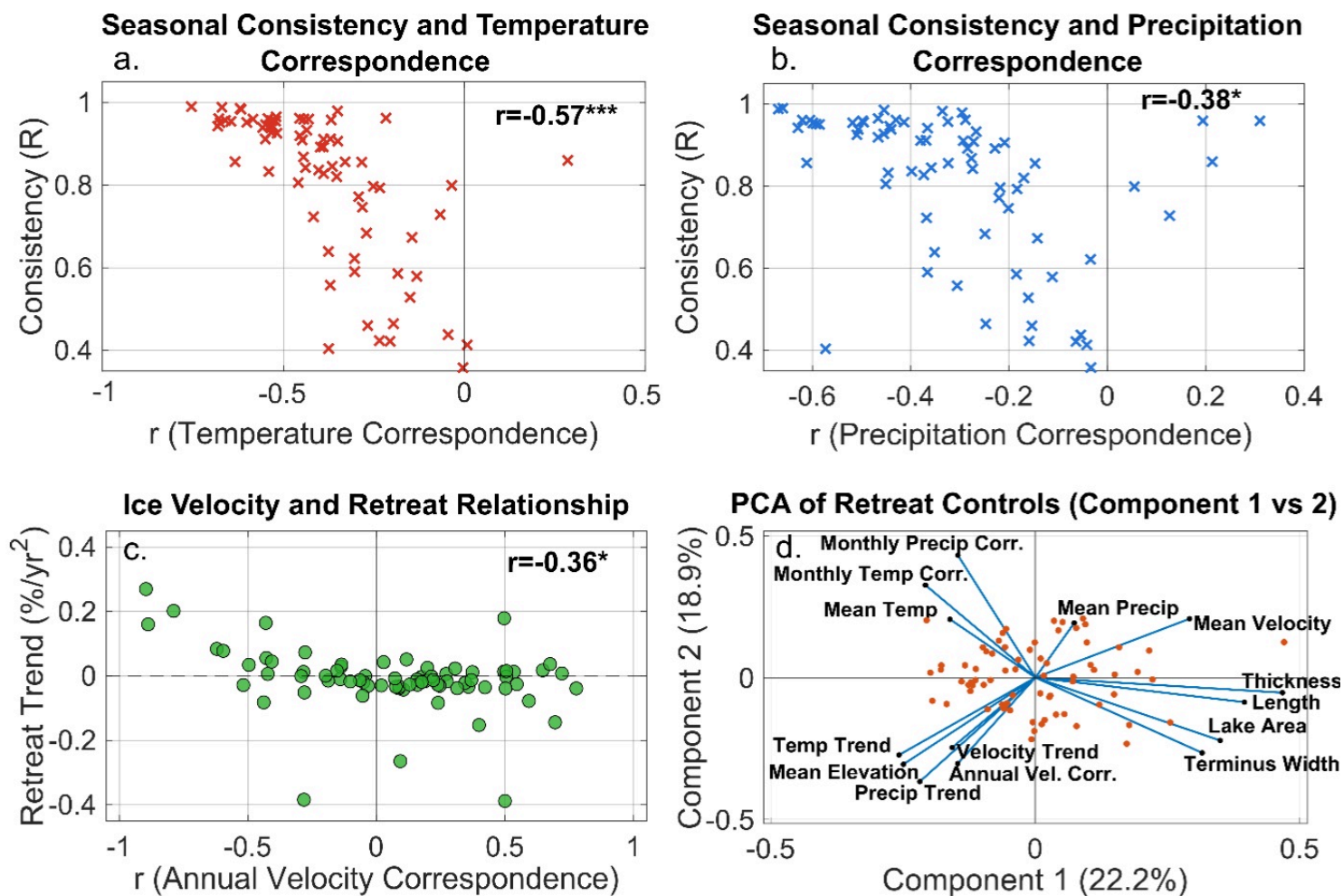


Figure 6

Climatic and dynamic controls on frontal position change. **a, b**, Scatter plots demonstrating the correlation between seasonal climate and the consistency of retreat timing between years. Seasonal consistency (R) is plotted against exact-interval monthly temperature (**a**, $r = -0.57^{***}$) and precipitation (**b**, $r = -0.38^*$) correspondence. **c**, Scatter plot illustrating the relationship between annual average ice velocity and overall retreat trend ($r = -0.36^*$). **d**, Principal Component Analysis (PCA) biplot of geomorphological, climatic, and dynamic controls on retreat. Orange markers represent individual glaciers (n=73); blue vectors indicate the direction and magnitude of variables relative to the principal components. Asterisks

denote statistical significance (* $p < 0.05$, *** $p < 0.001$) determined using Benjamini-Hochberg False Discovery Rate (FDR) correction.

Supplementary Files

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