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# Proximity to active volcanoes enhances glacier velocity

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Volcanic heating is predicted by theory to affect the velocity of nearby glaciers. However, conclusive studies on a large scale are lacking. Here, we conduct a global comparison of the velocities of glaciers near active volcanoes (i.e. within 5 km) and those located elsewhere ( > 5 km from an active volcano). Our findings show that, when considered over an annual scale (e.g. 2017-2018) and controlling for other factors, glaciers near volcanoes flow 46% faster than those located elsewhere (based on median values). This finding strongly suggests that volcanic heating impacts glacier velocity at a global scale, and supports the idea that glacier velocity monitoring could be a valuable indirect tool to help volcano monitoring and eruption prediction, particularly where volcanic heating (and therefore subglacial melt) intensifies months or years prior to eruptions.

Forecasting volcanic eruptions is fundamental to natural hazard management[1,2], and new and improved methods of achieving this are continually being developed. At present, this mostly involves monitoring volcanoes and their surroundings to identify early indicators of unrest, including ground deformation, degassing, changes in crater lakes, seismicity, and increased heat flow[3,4]. However, many volcanoes are located in remote areas where cost and logistical challenges prevent many or all associated monitoring methods from being continuously deployed. Glaciers, which are known to respond to volcanism (particularly associated thermal unrest) through changes in their dimensions[5–7], are currently an underexploited volcano monitoring tool, especially because remote monitoring of changes in the size and shape of glaciers on or near volcanoes can help provide early indicators of volcanic unrest and imminent eruptions[8]. This is also potentially true of glacier velocity (flow speed), which might fluctuate in response to volcanism because subglacial heating enhances basal ice melt, thereby lubricating the ice-bed interface[9–12], and is also theorised to change cold-based glacier thermal regimes to warm-based regimes[13]. Unfortunately, robust links between volcanism and changes in glacier velocity are currently lacking[5], and it has never been conclusively demonstrated if, or how, volcanic activity impacts glacier velocity. Before glacier velocity monitoring can be assessed as a useful indicator of volcanic activity, the relationship between glacier velocity and volcano proximity needs to be determined. In this study we integrate records of glacier dynamics and climate (for the ~215,000 glaciers in the Randolph Glacier Inventory (RGI) v. 6.0[14]) with worldwide mapping of glacierised volcanoes[15] to conduct the first global comparison of the velocities of glaciers near active volcanoes (i.e. within 5 km) and those located elsewhere ( > 5 km from an active volcano). We show that the median velocities of glaciers near active volcanoes are 46% greater than those of other glaciers and that, for glaciers within 5 km of an active volcano, velocities further increase with proximity to the volcano. These findings strongly suggest that volcanic heating is associated with enhanced glacier velocity at a global scale and support the idea that glacier velocity monitoring could be a valuable indirect tool to help volcano monitoring and eruption prediction, especially for remote volcanoes. This outcome has widespread implications because ~250 active volcanoes currently have glaciers within a 5 km radius (Fig. 1) and many of these volcanoes, particularly in South America, have sizable settlements and infrastructure nearby (e.g. ~7 million people currently live within 30 km of a glacierised, active volcano)[15].

## Results

Our dataset comprises 214,086 glaciers, of which 2729 are located within 5 km of an active volcano. The latter are distributed across a range of latitudes and longitudes, but primarily located in the Andes, western North America (including Alaska), Iceland and Kamchatka (Fig. 1, Supplementary Table 1). Comparison of global glacier velocities for the period 2017-2018[16,17] reveals that glaciers near active volcanoes have a median velocity of 11.44 $ma^{-1}$ (95% confidence interval: 10.90 to 12.04 $ma^{-1}$) compared to 5.20 $ma^{-1}$ (95% confidence interval: 5.18 to 5.23 $ma^{-1}$) for glaciers located elsewhere (Fig. 2a, Table 1). This pattern of faster flow for glaciers near volcanoes is observed in all RGI regions with active volcanoes, except for the Antarctic and Subantarctic region (Fig. 2b). Thus, glaciers near volcanoes flow more than twice as fast as other glaciers. However, other aspects, besides proximity to volcanoes, might independently affect glacier velocity.

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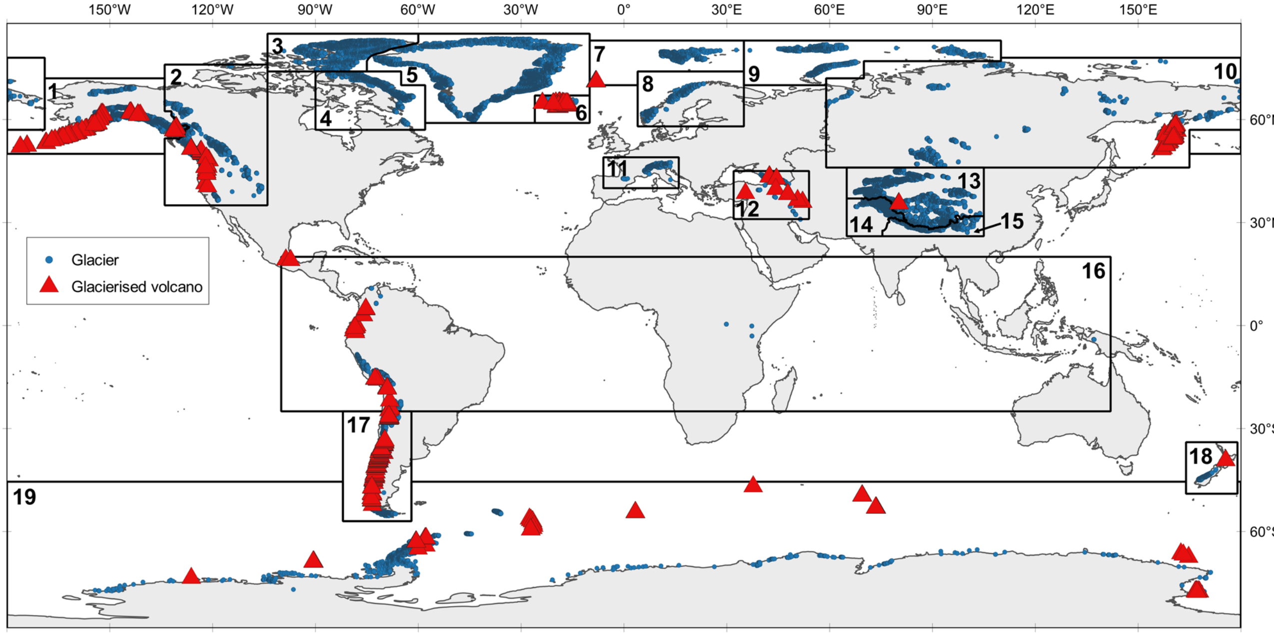


**Fig. 1 | Global distribution of glaciers and glacierised volcanoes (active volcanoes with glaciers within 5 km).** Numbers correspond to RGI regions: (1) Alaska; (2) Western Canada and USA; (3) Arctic Canada North; (4) Arctic Canada South; (5) Greenland Periphery; (6) Iceland; (7) Svalbard and Jan Mayen; (8) Scandinavia; (9) Russian Arctic; (10) North Asia; (11) Central Europe; (12) Caucasus and Middle East; (13) Central Asia; (14) South Asia West; (15) South Asia East; (16) Low Latitudes; (17) Southern Andes; (18) New Zealand; and (19) Antarctic and Subantarctic. Glacier points and RGI regions from RGI Consortium[14], glacierised volcanoes from Edwards et al.[15].

Our results show that glaciers near active volcanoes are typically larger (in area, thickness, and length), less steep, and often located at lower elevations, in warmer and wetter climates than other glaciers (Table 1, Supplementary Fig. 1). Linear modelling (using multiple linear regressions - see Methods) shows that being near an active volcano, ice thickness, and warmer and wetter climates all have a significant positive impact on glacier velocity, while glacier elevation has a significant negative impact (Table 2). When controlling for these factors, our model indicates that glaciers near active volcanoes flow 46% ($10^{0.164}$) faster than other glaciers (Table 2). Furthermore, within the subset of glaciers located near active volcanoes, linear mixed-effects modelling shows that, even when controlling for variations in glacier and volcano properties, glaciers closest to volcanoes (within 1 km) flow significantly faster than those further away (within 2.5-5.0 km), with median velocities of 13.35 $ma^{-1}$ (95% confidence interval: 12.33 – 14.47 $ma^{-1}$) and 10.26 $ma^{-1}$ (95% confidence interval: 9.43 – 10.90 $ma^{-1}$) respectively (Fig. 3, Table 3). Most other properties of volcanoes do not have significant impacts on glacier velocity (Table 3).

## Discussion

Based on data from 2017 to 2018, we present evidence that glaciers situated near active volcanoes flow faster than those located elsewhere (Fig. 2), and the closer these glaciers are to active volcanoes, the faster they flow (Fig. 3). Importantly, both these findings hold true when controlling for other influences on glacier velocity using linear modelling (Tables 2–3). We note that although absolute glacier latitude and glacier slope are not explicitly included in our models, their multicollinearity with variables that are included (median glacier elevation and median glacier thickness respectively - as detailed in the Methods), means that they also cannot fully explain the elevated velocities observed at glaciers near active volcanoes. We are also confident that these results are robust to the potential effects of terminus controls on glacier dynamics across a range terminus environments (Supplementary Note 1; Supplementary Table 2). We therefore conclude that these velocity differences are primarily a result of volcanic impacts on glaciers. Specifically, proximity to volcanoes most likely means higher volcanic geothermal flux or heat, which in turn triggers enhanced subglacial melt, increased basal water pressures, sliding and ice flow[9–12]. In instances where the volume of meltwater is sufficient to cause a subglacial flood, it has been suggested that glacier velocity can fall as an efficient subglacial drainage network develops[18]. Thus, glaciers located near active volcanoes have the potential to experience periods of both anomalously high and low velocities. However, our findings indicate that, when considered over an annual scale (e.g. 2017-2018), elevated velocity tends to dominate. The deviation of the Antarctic and Subantarctic RGI region from this global pattern is noticeable, and could be indicative of distinct glaciovolcanic processes, however the relative scarcity of velocity data (with only 29.1% of glaciers returning median velocity data, compared to a global average of 84.6%) means that the statistic from this region should be interpreted with caution.

There are several reasons we might expect elevated velocities for both cold-based and temperate (i.e., warm-based and polythermal) glaciers. Many glaciers globally are cold-based and often frozen to their beds, with very limited subglacial water flow[19]. These glaciers therefore experience very slow flow velocities because subglacial sliding is severely restricted or prevented entirely, with glacier flow largely or exclusively occurring through ice deformation. If such glaciers experience even minimal subglacial melt due to volcanic heating, this provides basal lubrication that is likely to trigger acceleration. In addition, because strain rates increase with higher ice temperatures[20], volcanic heating will also elevate rates of internal ice deformation. In contrast to cold-based glaciers, temperate glaciers often show a seasonal cycle in subglacial meltwater availability, and thus a seasonal cycle in their velocity. Fastest flow velocities typically occur in spring and early summer (when meltwater is abundant, and subglacial drainage channels are comparatively inefficient), slowing during late summer (when subglacial channels are sufficiently developed to efficiently evacuate subglacial water without triggering glacier acceleration), and remaining slow throughout winter (when meltwater is scarce, and glaciers may freeze to their beds)[21]. If such glaciers experience enhanced subglacial melt due to volcanic heating, they likely experience a modified version of this seasonal cycle. The reduction in glacier velocities during mid-late summer may occur earlier due to the comparatively rapid establishment of efficient subglacial drainage (a result of the combined impact of seasonally high air

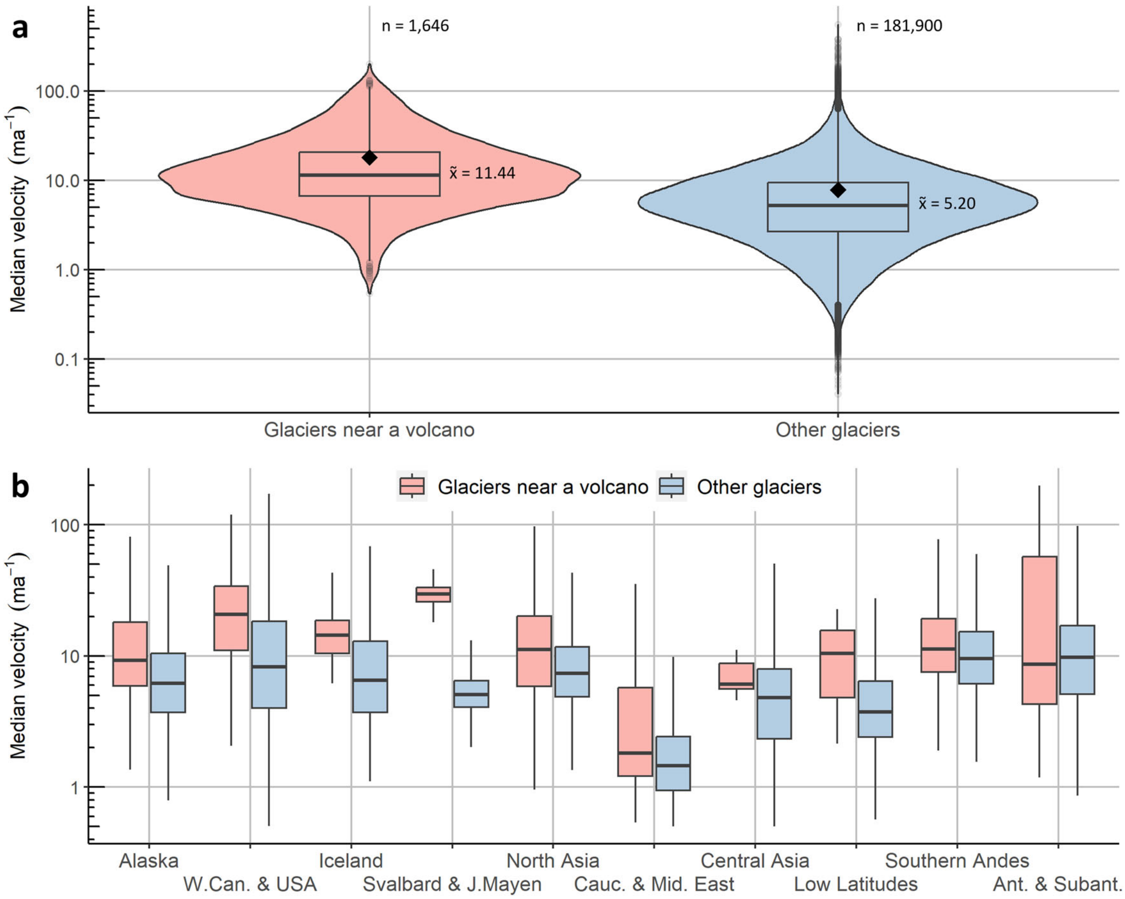


**Fig. 2 | Comparison of median glacier velocities ($\tilde{x}$) for glaciers located near active volcanoes (within 5 km) and those located elsewhere.** **a** global data; **b** global data categorised by RGI region (where RGI regions possess both glacier types). Box plots in (**a**) and (**b**) represent the median and interquartile range, and black diamonds and violin outlines in (**a**) represent the mean and the data distribution within each group respectively. For clarity, outliers are not plotted in (**b**).

**Table 1 | Median glacier properties for all glaciers in our dataset, and these data partitioned into glaciers located near an active volcano and glaciers located elsewhere**

| Glacier property | All glaciers | Glaciers near a volcano | Other glaciers | Cohen's d |
|---|---|---|---|---|
| n | 216876 | 2729 | 214147 | — |
| Absolute latitude (°) | 43.92 (47.94) | 46.85 (46.86) | 43.86 (47.95) | 0.07 |
| Area (km$^2$) | 0.25 (2.90) | 0.34 (7.79) | 0.25 (2.84) | 0.11 |
| Median elevation (m) | 3114 (3219) | 1995 (2346) | 3182 (3230) | 0.47 |
| Slope (°) | 23.7 (24.1) | 20.0 (20.4) | 23.8 (24.1) | 0.45 |
| Maximum surface flowline length (m) | 720 (1408) | 968 (2263) | 718 (1397) | 0.31 |
| Median velocity (ma$^{-1}$) | 5.24 (7.94) | 11.44 (18.09) | 5.20 (7.85) | 0.99 |
| Median thickness (m) | 31.28 (39.85) | 45.71 (56.74) | 31.19 (39.70) | 0.50 |
| Mean annual air temp. 2017-2018 (°C) | −5.7 (−5.7) | 2.1 (0.9) | −5.8 (−5.8) | 1.13 |
| Total annual precip. 2017-2018 (mm) | 995 (1304) | 1612 (1790) | 985 (1298) | 0.48 |

For comparison, mean values are presented in parentheses. Cohen's d is a measurement of the effect size (magnitude of difference) between two group means. Here the Cohen's d values represent the standardised magnitude of difference between the mean glacier properties for glaciers near a volcano and other glaciers, with higher values representing a greater degree of difference between the groups (units are standard deviations). For example, a Cohen's d of 0.5 indicates the difference in means between the groups is equivalent to half of the average standard deviation across both groups.

temperatures and volcanic heating). However, the key difference in seasonal velocities between glaciers near a volcano and other glaciers is likely to be curtailed velocity reductions during autumn, winter, and early spring, when velocity is normally low because the drainage system is closed. During these seasons, the sustained availability of volcanically triggered subglacial meltwater (which is seasonally/climatically independent) would typically allow for glaciers near volcanoes to maintain enhanced velocities. Thus, there are robust theoretical reasons to expect a global pattern whereby glaciers that experience sub-glacial volcanic heating (whether cold-based or temperate) flow faster than those that do not.

Overall, our findings indicate that proximity to active volcanoes enhances the velocities of glaciers at a global scale, most likely because of increased subglacial heating. This provides further support for the idea that glacier velocity can be used to monitor volcanic activity in cases where volcanic heating (and therefore subglacial melt) intensifies prior to eruptions[22,23]. In some cases, this may occur months to years prior[23], and

**Table 2 | Linear model (LM) results of independent controls on $\log_{10}$(median glacier velocity)**

| Independent variable | Estimate | 95% Confidence interval lower | 95% Confidence interval upper | Std. error | t value | p value |
|---|---|---|---|---|---|---|
| (Intercept) | 0.694 | 0.692 | 0.696 | 0.001 | 763.306 | <0.001 |
| **Glacier type: glacier near a volcano** | **0.164** | **0.145** | **0.183** | **0.010** | **16.991** | **<0.001** |
| **$\log_{10}$(Glacier thickness)** | **0.185** | **0.183** | **0.186** | **0.001** | **197.427** | **<0.001** |
| **Glacier elevation** | **−0.059** | **−0.061** | **−0.058** | **0.001** | **−61.544** | **<0.001** |
| **Climate PC** | **0.087** | **0.085** | **0.089** | **0.001** | **88.724** | **<0.001** |

Significant variables are highlighted in bold; $n = 177{,}816$; $R^2 = 0.24$; $p < 0.001$. The reference category for categorical variable 'glacier type' is other glacier (i.e. > 5 km from an active volcano).

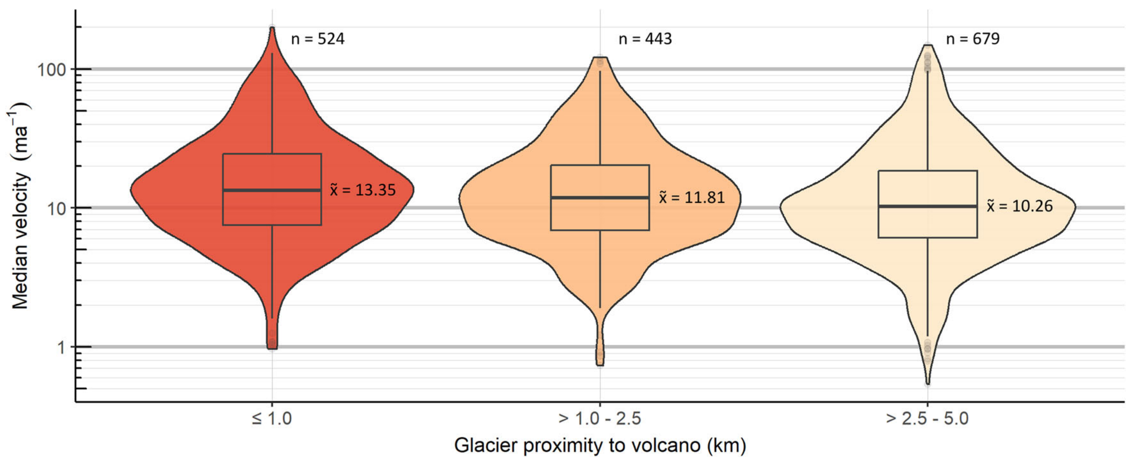


**Fig. 3 | Comparison of median glacier velocities ($\tilde{x}$) for glaciers located within 5 km of an active volcano.** Box plots represent the median and interquartile range, and violin outlines represent the data distribution within each group respectively.

should be reflected in elevated glacier velocities. This approach is likely to be particularly valuable where volcanic heat is difficult to measure (as might be the case for volcanoes with glaciers on them). The approach might also be useful for observing spatial and temporal variations in volcanic heat (even without an associated eruption), particularly when combined with the monitoring of changing glacier dimensions and elevations[7,8]. Our results also have broader implications for understanding whether future volcanic activity within the West Antarctic Ice Sheet could enhance its present climate-induced destabilisation[24–26], and are an important caveat when using changes at glaciers near volcanoes (≤5 km) as direct global warming proxies. In this research, glacier median velocity has provided a convenient and representative parameter for comparison to other glacier properties at the catchment scale. However, neither velocity nor the impacts of volcanic heating will be uniform across a given glacier, thus future research should also consider the specific distribution of velocities within glaciers relative to the location of likely geothermal hotspots. Furthermore, a temporal assessment of changes in glacier velocity at seasonal and multi-annual scales would advance the understanding of mechanisms underpinning the influence of volcanism on glacier velocity, particularly given the increasing availability of high-temporal resolution velocity datasets (e.g. ITS_LIVE[27]). Here, we have demonstrated that glacier velocities respond to volcanic heat as a general, global rule. The next step is to investigate how sensitive glaciers are, and how rapidly they respond, to volcanic activity so that their potential use as a monitoring tool can be fully evaluated.

## Methods

### Glacier, volcano and climate database

A database of glacier, glacierised volcano and climate properties was developed by integrating multiple sources (Supplementary Table 3). Glacier polygons, glacier classifications and measurements of glacier geometry were acquired from the RGI v.6.0[14]. Glacierised volcano locations and classifications were sourced from Edwards et al.[15] and supplemented with additional variables from the Smithsonian Global Volcanism Program Holocene Volcano List[28]. Mean annual air temperature and total annual precipitation at each glacier were extracted from ECMWF ERA5 reanalysis data[29] for the periods 1991-2020 and 2017-2018 using the glacier centroids in the RGI. Specifically, temperature and precipitation measurements for 98.4% of RGI glaciers were extracted from the ERA5 Land dataset (0.1° × 0.1° grids; ~9 km spatial resolution), with data for the remaining predominately island and/or coastal glaciers sourced from the ERA Global dataset (0.25° × 0.25° grids; ~30 km spatial resolution). Differences between the 1991–2020 and 2017–2018 climate variables were small, with effect sizes (Cohen's d) of 0.05 and 0.03 for temperature and precipitation respectively. Thus, the 2017–2018 climate variables were considered representative of the wider 1991–2020 period, and therefore adopted in the further analyses to ensure temporal consistency with the glacier velocity and thickness datasets.

### Glacier surface velocity and ice thickness measurements

Global glacier surface velocity and ice thickness maps for 2017–2018 were sourced from Millan et al.[16] (posted at 50 m horizontal spacing, with expected velocity accuracies of ≤ 10 $ma^{-1}$ and ice thickness uncertainties of ~30%), and supplemented with averaged 2017 and 2018 MEaSUREs surface velocity mosaics for Peripheral Glaciers and Ice Caps (PGICs) in Greenland[17] (posted at 200 m horizontal spacing, with estimated accuracies of typically <5 $ma^{-1}$). A single measurement of velocity and thickness for each glacier in the database was calculated in QGIS v.3.22.8 by overlaying the respective velocity and thickness raster maps with the RGI glacier polygons, then applying zonal statistics to determine the median value within each polygon. To minimise the effect of outliers, velocity and/or thickness values were omitted from the final database where glacier polygons overlaid fewer than three pixels (affecting 10,047 glaciers).

**Table 3 | Linear mixed-effects model (LMM) results of independent controls on $\log_{10}$(median glacier velocity) for glaciers near an active volcano**

| Independent variable | Estimate | 95% Confidence interval | | Std. error | t value | p value |
|---|---|---|---|---|---|---|
| | | lower | upper | | | |
| (Intercept) | 1.072 | 1.022 | 1.121 | 0.026 | 40.461 | <0.001 |
| **Glacier thickness** | **0.228** | **0.209** | **0.247** | **0.010** | **22.983** | **<0.001** |
| Glacier elevation | −0.012 | −0.045 | 0.027 | 0.019 | −0.618 | 0.537 |
| **Climate PC** | **0.088** | **0.051** | **0.127** | **0.020** | **4.353** | **<0.001** |
| Volcano type: Shield | 0.128 | −0.007 | 0.266 | 0.073 | 1.752 | 0.083 |
| Volcano type: Complex | 0.034 | −0.204 | 0.266 | 0.126 | 0.272 | 0.786 |
| Volcano type: Caldera | 0.041 | −0.117 | 0.195 | 0.083 | 0.487 | 0.627 |
| Volcano type: Pyroclastic Cone | −0.060 | −0.224 | 0.107 | 0.089 | −0.674 | 0.502 |
| **Volcano type: Subglacial** | **−0.415** | **−0.619** | **−0.198** | **0.112** | **−3.709** | **<0.001** |
| Volcano type: Volcanic Field | 0.100 | −0.129 | 0.328 | 0.122 | 0.824 | 0.412 |
| Tectonic setting: Subduct. Zone (intermed. crust 15-25 km) | 0.063 | −0.226 | 0.356 | 0.156 | 0.406 | 0.685 |
| Tectonic setting: Rift Zone (oceanic crust <15 km) | 0.074 | −0.060 | 0.208 | 0.072 | 1.028 | 0.306 |
| Tectonic setting: Intraplate (continental crust > 25 km) | 0.056 | −0.116 | 0.216 | 0.089 | 0.628 | 0.531 |
| Tectonic setting: Intraplate (oceanic crust <15 km) | 0.181 | −0.093 | 0.459 | 0.149 | 1.217 | 0.227 |
| Number of volcanoes within 5 km of glacier: 2 | −0.003 | −0.076 | 0.066 | 0.036 | −0.085 | 0.932 |
| Number of volcanoes within 5 km of glacier: 3 | 0.161 | −0.034 | 0.342 | 0.097 | 1.662 | 0.097 |
| Glacier proximity to volcano: > 1.0 − 2.5 km | −0.014 | −0.048 | 0.022 | 0.018 | −0.773 | 0.440 |
| **Glacier proximity to volcano: > 2.5 − 5.0 km** | **−0.065** | **−0.098** | **−0.028** | **0.018** | **−3.591** | **<0.001** |
| Number of Holocene eruptions | 0.004 | −0.027 | 0.035 | 0.017 | 0.256 | 0.799 |

Significant variables are highlighted in bold; $n$ = 1,600; $R^2m$ = 0.37; $R^2c$ = 0.61. Reference categories for categorical variables are: 'volcano type' = stratovolcano; 'tectonic setting' = subduction zone (continental crust > 25 km); 'number of volcanoes within 5 km of glacier' = 1; 'glacier proximity to volcano' = ≤ 1 km.

## Data cleaning

To improve the standardisation and accuracy of the database, a number of glaciers were excluded from our analysis, including: 489 glaciers that only possess indicative or estimated geometry in the RGI; 957 PGICs that are strongly connected to the Greenland Ice Sheet (and thus have velocities, thicknesses and geometries that may be unrepresentative of local climatic conditions and topography); and 1344 glaciers with observed, probable or possible evidence of surging (and thus with potentially unrepresentative velocities during the 2017–2018 study period) as classified in Sevestre and Benn (2015)[30]. Our final database comprised 214,086 glaciers (98.7% of those listed in the RGI v.6.0), of which 84.6% returned a velocity measurement and 87.5% returned a thickness measurement.

## Statistical analyses

The database was analysed using descriptive and multivariate statistics in R v.4.2.1 to address three objectives: (i) to compare the properties of glaciers near an active volcano and other glaciers globally for the period 2017–2018, (ii) to investigate the extent of geometric, volcanic and climatic controls on glacier velocities, and (iii) to investigate relationships between glacierised volcano properties and the velocities of glaciers near volcanoes. Specifically, linear modelling, using multiple linear regressions, was employed for objectives (ii) and (iii) to isolate the effect of individual variables on glacier velocity, whilst holding the other variables in the model constant.

A linear model (LM) was developed to address objective (ii) and fitted with $\log_{10}$(median glacier velocity) as the dependent variable ($n$ = 177,816). Potential independent variables were standardised, then tested for multicollinearity prior to model fitting using Pearson's correlation coefficient (for numeric variables) or variance inflation factors (for categorial variables). Two pairs of variables (absolute glacier latitude and median glacier elevation, and glacier slope and median glacier thickness) failed to meet this assumption ($|r| > \pm 0.7$)[31], displaying strong negative correlations (r = −0.92 and −0.87 respectively). Consequently, absolute glacier latitude and glacier slope were excluded from the LM. Mean annual air temperature and total annual precipitation also correlated strongly (r = 0.93). Therefore, principal component analysis was used to create a new, unitless variable 'climate principal component' (climate PC) for the LM. The climate PC explained 91.5% of the variability in both temperature and precipitation variables, with higher numeric values representing warmer, wetter climates and lower numeric values representing colder, drier climates. The LM was thus parameterised: $\log_{10}$(median glacier velocity) = $\beta_0 + (\beta_1 \times$ glacier type$) + (\beta_2 \times \log_{10}$(median glacier thickness)$) + (\beta_3 \times$ median glacier elevation$) + (\beta_4 \times$ climate PC); where $\beta_0$ represents the intercept, $\beta_1$-$\beta_4$ are coefficients of the independent variables, and 'glacier type' is a binary categorical variable indicating whether a glacier is 'near a volcano' or 'other' (Table 2). Following model fitting, testing of the LM residuals for normality and heteroscedasticity showed that they were heavy-tailed. To investigate the impact of outliers on model fit, a robust linear model (RLM) was fitted with the same variables[32]. The similarity of the respective LM and RLM coefficients (see estimates in Supplementary Table 4) illustrated that the outliers had a very limited effect on the fit of the LM, consequently the outputs of the LM are presented in the results.

To address objective (iii) a linear mixed-effects model (LMM) was developed for glaciers near a volcano only, using the same approach and fitted using the lme4 package[33], with $\log_{10}$(median glacier velocity) as the dependent variable ($n$ = 1,600). The repeated sampling of glaciers situated on the same volcano was controlled in the LMM by including an additional numerical volcano identifier as a random effect. The LMM was thus parameterised: $\log_{10}$(median glacier velocity) $= \beta_0 + (\beta_1 \times$ median glacier thickness$) + (\beta_2 \times$ median glacier elevation$) + (\beta_3 \times$ climate PC$) + (\beta_4 \times$ volcano type$) + (\beta_5 \times$ tectonic setting$) + (\beta_6 \times$ number of volcanoes within 5 km of glacier$) + (\beta_7 \times$ glacier proximity to volcano$) + (\beta_8 \times$ number of Holocene eruptions$) + b_{\text{volcano_number}}$; where $\beta_0$ represents the intercept, $\beta_1$-$\beta_8$ are coefficients of the independent variables, and $b_{\text{volcano\_number}}$ represents the random intercept for each unique volcano (Table 3). One glacier (RGI 60-01.08367) was subsequently removed from the fitted LMM due to an undue influence on overall model fit. Testing of the LMM residuals again showed that they were heavy-tailed, so a robust linear mixed-effects model (RLMM) was fitted with the same variables. The similarity of the respective LMM and RLMM coefficients (see estimates in Supplementary Table 5) illustrated that the outliers had a very limited effect on the fit of the LMM, consequently the outputs of the LMM are presented in the results. Note that for both the LM and LMM, $\log_{10}$(median glacier velocity) was used to correct for the inverse gaussian distribution of the independent variable, and in the LM $\log_{10}$(median glacier thickness) was used to improve model fit.

## Data availability

The database of glacier, glacierised volcano and climate properties used in this study is archived at the NERC EDS UK Polar Data Centre: https://doi.org/10.5285/ae909122-b59f-4245-8ce9-f063f837fdf3.

## Code availability

The R code for the statistical analyses and figures presented in this study is available from GitHub: https://github.com/joemallalieu/glacier_velocities.

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## Author contributions

I.D.B., M.S., and J.M. conceptualised and designed the research and methodology. J.M. collated the glacier and volcano data, D.J.M. processed the climate data. J.M. conducted the GIS and statistical analyses. J.M. and

I.D.B. wrote the manuscript, with editorial contributions from M.S., D.J.M., E.S., B.R.E., and M.D.M. Funding for this research was acquired by I.D.B., E.S., B.R.E. and M.S.

## Competing interests
The authors declare no competing interests.

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