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Icy thermometers: quantifying the impact of volcanic heat on glacier elevation

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ABSTRACT

We present a continent-wide study of 600 glaciers located on and near 37 ice-clad volcanoes in South America, that demonstrates glacier sensitivity to volcanic heat. We distinguish between 'volcanic-glaciers' (≤1 km from volcanic centres; n=74), and 'proximal glaciers' (1-15 km; n=526) and calculate their equilibrium line altitudes (ELA). For each ice-clad volcano we compare the ELAs of its volcanic-glaciers to those of its proximal glaciers which shows that the ELAs of the former are higher than the ELAs of the latter. ΔELA_{mean}, defined as the offset between the mean ELA of the volcanic-glaciers and that of the proximal glaciers, is calculated for each ice-clad volcano. ΔELA_{mean} is positive for 92% of the 37 volcanoes, and a quantitative relationship between ΔELA_{mean} and volcanic thermal anomaly is established. Results highlight the impact of volcanic heat on glacier elevation; emphasise the need to exclude glaciers on, or near, volcanoes from glacier-climate investigations; and demonstrate the first-order potential for glaciers as 'volcanic thermometers'. Volcanic-glacier monitoring could contribute to our understanding of magmatic and thermal activity, with changes in glacier geometries potentially reflecting long-term fluctuations in volcanic heat and unrest.

INTRODUCTION

Volcanic eruptions are a natural socio-economic hazard with devastating consequences, including the displacement of communities; damage to businesses and infrastructure; disruption of air traffic; and loss of human life (Loughlin et al., 2015). A major challenge in the management of such hazards is the identification and monitoring of

precursors to forthcoming volcanic eruptions. The measurement of thermal anomalies is one such technique, with some volcanoes exhibiting signs of thermal unrest for several years prior to an eruptive event (Reath et al., 2019; Girona et al., 2021). Although thermal anomalies may be detected using remote sensing methods, glaciers on volcanoes may mask the thermal anomalies, impacting monitoring efforts.

While glaciers on volcanoes are considered a major risk (Tuffen, 2010; Edwards et al., 2020)and a hindrance to obtaining accurate temperature measurements, they are likely to be affected by volcanic heat (Barr et al., 2018). If the impact of volcanic heat on glaciers can be demonstrated and quantified, this could help improve magmatic system dynamics models and be used as a novel tool to monitor long-term changes in the thermal state of ice-covered volcanoes, which may otherwise be obscured from most conventional remote monitoring systems. Mapping of volcanic-glaciers using geospatial tools can be used to analyse the interplay between glacier geometries, glacier equilibrium line altitudes (ELA), and volcanic activity (Rivera et al., 2006; Rivera and Bown, 2013; Renithaler et al., 2019). This is the first large continental-scale analysis and quantitative assessment of the potential link between glacier geometries and volcanic heat.

METHODS

This study focuses on the Andes (**Fig. 1**), where many volcanoes have glaciers within 1 km (volcanic-glaciers), and between 1 and 15 km (proximal glaciers) from their centre and importantly, maximum thermal anomaly measurements are available for some of these volcanoes (Reath et al., 2019). We assume that a volcanic-glacier (located on a volcano) will likely experience a basal melt rate significantly higher than a proximal glacier (not on a volcano) (**Fig. 2**). To assess this effect, we could look at metrics such as the minimum, median or average glacier elevation for volcanic- vs. proximal glaciers. However, these can be impacted significantly by the local topography, so we calculate a different metric, the glacier ELA, using the Area Altitude Balance Ratio (AABR) method. This metric accounts for glacier geometry via the hypsometry (i.e. the distribution of the surface area with altitude) and recognises that the surface accumulation and ablation gradients differ (Rea 2009). The ELA is the point on the glacier where the surface mass balance, measured over one year, is zero i.e., accumulation (snowfall) equals ablation (snow melt/sublimation), and can be measured in the field via repeated (time-consuming and logistically-challenging) observations. Calculating ELAs using the AABR is a good proxy for measured ELA (Oien et al., 2021), provided glaciers are clean (no debris cover) terrestrially terminating (not in water) and basal melt contributes a negligible component of the overall mass balance.

For volcanic-glaciers, where the basal melt rate may be significant in the overall mass balance, the calculated ELAs (hereafter ELAs) are not a good proxy for the measured ELA but they nonetheless represent an ideal metric to characterise the elevation of the glaciers taking into account their hypsometry. By calculating the AABR ELAs for volcanic- vs. proximal glaciers we can identify the potential impact of volcanic heat on glacier geometries i.e., we expect the ELA for volcanic-glaciers to be higher than the ELA for the proximal glaciers. We also make the reasonable assumption that: the ELAs of the proximal glaciers are comparable within a restricted geographical area (i.e., a 15 km radius), as they will experience a similar climate (Sagredo et al., 2014); and that the ELA of the volcanic-glaciers is a function of both climate and the volcanic heat that drives additional ice loss (Jóhannesson et al., 2020). In this continent-scale study, we combine worldwide glacier (RGI 6.0) and volcano (GVP 2013) inventories to identify 37 Andean, Holocene volcanoes, which host glaciers on (volcanic) and near them (proximal). Water-terminating and debris covered glaciers are excluded, as are glaciers <0.1 km^2, to limit the effect of complex glacier dynamics and niche micro-climates. We calculate ELAs for 74 volcanic-glaciers and 526 proximal glaciers (Supplemental Material, **Table. S1**) distributed latitudinally from 5°N to 41°S along the Andes (**Fig. 1**). For each selected volcano, we assess how ELA varies with distance from the volcano and calculate the difference in mean ELA between the volcanic-glaciers and proximal glaciers (i.e., ΔELA_{mean}) (**Fig. 2**). Glacier ΔELA_{mean} is then compared with ASTER-based volcano temperature anomalies (Reath et al., 2019), acquired by the NASA Terra satellite, for 13 of the 37 ice-clad volcanoes (Supplemental Material, **Table. S2)**. We also compare ΔELA_{mean} with climate data from WorldClimVersion 2 (Fick and Hijmans, 2017). Full methodological details are provided in the Supplemental Material.

RESULTS AND DISCUSSION

ΔELA_{mean}: Assessing the impact of volcanic heat on glaciers.

Results highlight that 469 (89%) of the 526 proximal glaciers are characterised by an ELA lower than the mean ELA of the nearby volcanic-glaciers. For 50% of these, a statistically significant correlation ($r^2 > 0.50$, at $p < 0.05$) is established between glacier ELA and distance from the volcano centre (**Fig. 2**). For example, proximal glacier ELAs gradually decrease away from the volcano by as much as 655 m for Copahue volcano (Chile-Argentina), from an ELA of 2807 m on the volcanic-glacier to 2152 m on a proximal glacier located 8.46 km away ($r^2 = 0.87$) (**Fig. 2c&d**). Weaker relationships between glacier ELA and distance from the volcano (**Table. S1**) are rarely found and might be due to local microclimate (e.g., aspect/orientation of slope (Evans, 2006) or shading) and/or volcanogenic (e.g., offset

magma reservoirs (Lerner et al., 2020)) factors.

We use the ΔELA_{mean} to investigate how glaciers are affected by the volcano heat i.e. measured thermal anomalies. For 92% of the ice-clad volcanoes (**Fig. 2a, Table. S1**) the ΔELA_{mean} is positive (i.e., the mean ELA of volcanic-glaciers is higher than for the proximal glaciers), with a mean ΔELA_{mean} of 229 m and a median of 187 m. Given the relatively short distances considered (<15 km) and the large number (n = 600) of glaciers analysed (comprising different slope aspects, etc.), local climate variations cannot be invoked to explain our results. Instead, we take this as a strong indication that the offset in ELA between proximal and volcanic-glaciers is controlled primarily by the volcanic heat source.

How does volcanic heat affect glacier elevation?

To demonstrate a quantitative, empirical relationship between glaciers and volcanoes, continuous volcanic heat measurements covering a temporal interval longer than the glacier response times would have been ideal, but these are not available. Instead, Reath et al. (2019) provide direct observations of volcano maximum thermal anomalies, recorded between 2000 and 2018, which were obtained from Terra satellite data for 88 volcanoes in Central and South America, including some of the volcanoes analysed above. For 13 (Supplemental Material **Table. S2**) of the original 37 Holocene ice-clad volcanoes it was possible to analyse the correlation between the mean volcano maximum thermal anomaly (*mean* δT_{max}) and ΔELA_{mean}, to establish a first-order quantitative assessment of glacier elevation sensitivity to volcanic thermal state. Our results demonstrate a strong, positive relationship ($r^2 = 0.72$, $p < 0.001$) between *mean* δT_{max} and ΔELA_{mean} (**Fig. 3**), with $\delta T_{max} = 0.22 \cdot \Delta ELA_{mean} - 25.90$ and a slope uncertainty of ±0.04 (at 95% confidence level). For example, on the quiescent Falso Azufre (Chile-Argentina), Parinacota (Chile-Bolivia) and Pular (Chile) volcanoes, the ΔELA_{mean} is relatively low (133-156 m) as is *mean* δT_{max} (3.7-5.7°C). However, on the presently active Copahue (Chile-Argentina) and Villarrica (Chile) volcanoes, both the ΔELA_{mean} and *mean* δT_{max} are much higher (**Fig. 3**), with values ranging between 252-270 m and 35.9-44.7°C, respectively. This provides confidence that volcanic-glacier geometries respond to increased volcanic heat. The response time of a glacier to a surface mass balance perturbation related to climate can be approximated as a function of the ice thickness and ablation rate at the terminus (Paterson, 1994) such that, for a 50-100 m thick glacier with an ablation rate at the terminus of 5 ma^{-1} (reasonable values for the glaciers under consideration here) it is ~10-20 years. An ablation rate increased to 10 ma^{-1}, due to enhanced basal melt, would likely reduce the response time to 5-10 years.

Although the exact response time of glaciers to volcanic-induced enhanced basal melt is not known, the strong relationship between *mean* δT_{max} and ΔELA_{mean} is evidence that volcanic heat does enhance glacier basal melt, resulting in smaller volcanic-glaciers located at higher elevations, with concomitantly higher ELAs than for their proximal glaciers. This is particularly encouraging given that we used the maximum thermal anomaly and not a continuous measurement. These results indicate that the ΔELA_{mean} could be used as a first-order approximation, over reasonable timescales e.g. 5-10 years, for identifying changes in volcanic heat output and contribute to monitoring ice-clad volcanoes, particularly where the presence of glacial ice may otherwise obstruct or complicate the volcano thermal signature.

Variation of ΔELA_{mean} with climatic region

The Andes are characterised by three distinct mega-climatic zones(Garreaud et al., 2009; Sagredo and Lowell, 2012), corresponding well with the Northern, Central and Southern Volcanic Zones (Tilling, 2009) (**Fig**. **1**), and the climate influence on glacier ELAs along the Andes is well documented (Vuille et al., 2008; Rabatel et al., 2013; Braun et al., 2019). In principle, it is possible that climate also affects ΔELA_{mean} and could limit its applicability as a proxy for volcano thermal activity. However, the correlation between ΔELA_{mean} and total annual precipitation (P_{tot}) is very weak ($r^2 = 0.05$; $p = 0.164$) as is that for mean annual air temperature (T_{mean}) ($r^2 = 0.10$ and $p = 0.06$) (**Fig. 4**).

Given the lack of correlation between ΔELA_{mean} and climate, we conclude that, while the ELA of volcanic- and proximal glaciers are, respectively, in-part and fully controlled by climate, the ΔELA_{mean} is little impacted by variations therein. For example, the substantial decrease in volcanic-glacier ELAs (from an average of 6021 m to 2983 m) when migrating from the dry subtropical Andes of Peru and northern Chile (P_{tot} of 115 to 757 mm, and T_{mean} of -9.48 to -2.38°C) in the CVZ (15.52 to 27.20°S), to the warmer and wetter semi-arid regions along the border of Chile and Argentina (P_{tot} of 495 to 1652 mm, and T_{mean} of -7.98 to 3.99 °C) in the SVZ (34.16 to 40.97°S), is likely due to climate. Significantly, the ΔELA_{mean} remains consistent throughout these volcanic zones (an average of 209 m from Peru and northern Chile to an average of 182 m across the Chile-Argentine border).

Uncertainties

ELAs have a computational accuracy of 5 m (Pellitero et al., 2015). An ~5% gross geometry error for the Southern Andes (region 17) for RGI 6.0 glacier outlines, due to the erroneous inclusion of seasonal glacier-peripheral snow and transient ice, was reported by Pfeffer et al. (2014). Our exclusion of glaciers <0.1 km^2 will have reduced the

likelihood of including some erroneously mapped snow patches and seasonal ice cover. While re-mapping all 600 glaciers would have been unfeasible, we re-mapped outlines for the 13 volcanoes with a record of δT_{max}, also to align the temporal observation of δT_{max} with that of the glacier extent (supplemental material).

The algorithm for calculating ASTER derived temperatures is accurate to ±1–2 °C (Abrams, 2000). Magma vent and tectonic structures could be complex (Garcia et al., 2019), and hence GVP points can underestimate the extent and location of volcanic activity (thus, glacio-volcanic interactions). However, a volcano by volcano (field based) analysis of the magmatic geometry and geothermal heat flux was beyond the scope of this project.

CONCLUSIONS

In this study, we analysed 74 volcanic-glaciers and 526 proximal glaciers. For most locations the ELA of proximal glaciers is lower than that of the volcanic-glaciers, with a tendency for proximal glacier ELAs to decrease with distance from the volcanic centre. For 92% of the 37 ice-clad volcanoes the difference in mean ELA between the volcanic-and proximal glaciers (i.e., the ΔELA_{mean}) is positive. For a subset (13) of these 37 volcanoes, a strong, positive correlation was identified between ΔELA_{mean} and observed volcano maximum temperature anomalies (i.e., *mean* δT_{max}).

These results indicate that volcanic heat alters glacier geometries, which we have highlighted using calculated ELAs, through what is assumed to be enhanced basal melting. Volcanic-glaciers tend to be confined to higher elevations and so have a higher ELAs, relative to their proximal glacier neighbours. For this reason, glaciers located on, or near, Holocene volcanoes should be excluded from studies assessing the impact of recent or ongoing climate forcing on glacier dynamics and elevation. Conversely, and importantly, this study shows that ΔELA_{mean} can be used as a first-order approximation for volcanic thermal anomalies i.e., high ΔELA_{mean} means high volcanic heat. Monitoring ΔELA_{mean} for glacio-volcanic complexes may help identify changes in the thermal state of a volcano and could provide a long-term (e.g., 5-10 years) indication of increased/renewed activity that can be used to improve our understanding of magma dynamics, identify volcanoes of concern, and help assess future periods of volcanic unrest.

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FIGURE CAPTIONS

Fig. 1| Study area. Distribution of the 37 Holocene ice-clad volcanoes (**Table. S1**) within three distinct volcanic zones (NVZ: Northern Volcanic Zone; CVZ = Central Volcanic Zone; SVZ = Southern Volcanic Zone) (Tilling, 2009). Those labelled in red depict the locations of the 13 volcanoes with measured volcanic maximum thermal anomalies.

Fig. 2| volcanic influence on glacier elevation. **a,** A conceptual view of an ice-clad volcano. The increased volcanic heat induces basal melt which confines the volcanic-glaciers to higher elevations. **b,** Ice-clad volcano ΔELA_{mean}**,** i.e. the offset between the mean ELA of the volcanic-glaciers and that of the proximal glaciers. **c,** Effects of distance from the volcanic centre on ELAs showing a decrease with distance from the Copahue volcano. **d,** A scatterplot of ELAs and distance from volcanic centre for the 15 glaciers surrounding Copahue volcano ($r^2 = 0.87$). Data marker colours are from (c) and the yellow vertical line separates volcanic- and proximal glaciers.

Fig. 3| Relationship between ΔELA_{mean} and measured volcanic geothermal heat (*mean* δT_{max}). Means of maximum volcanic temperature anomalies (*mean* δT_{max}) above the background (**Table. S2**) between 2000 and 2018 based on ASTER values (AVTOD) plotted against ΔELA_{mean}**,** .

Fig. 4| Influence of atmospheric temperature and precipitation on ΔELA_{mean}. Correlation between ΔELA_{mean} and climatic variables (**a**: mean annual temperature; **b**:mean annual precipitation) between 1970 and 2000, demonstrating that climate has little influence on ΔELA_{mean}..

Figure 1

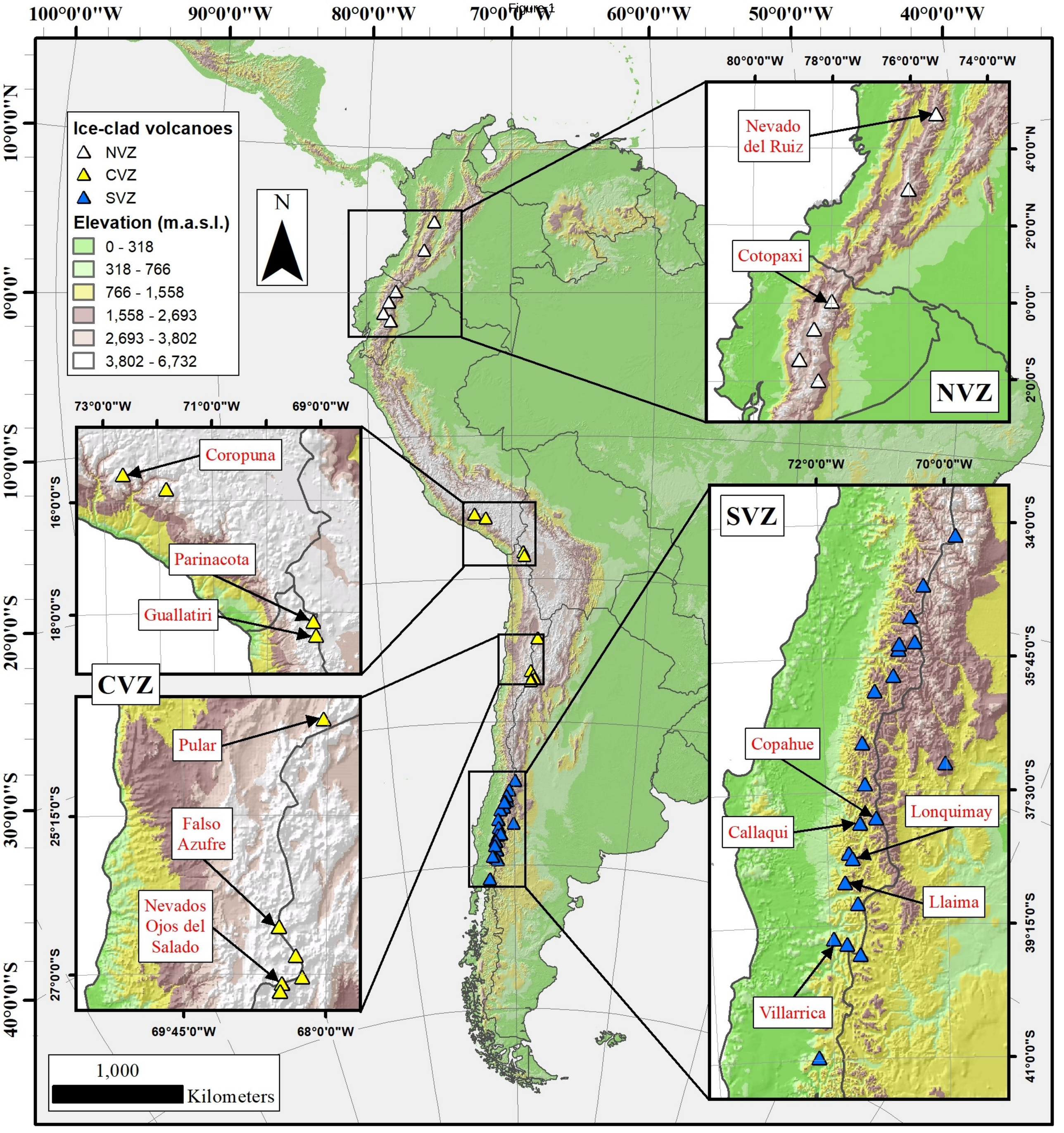

Ice-clad volcanoes
NVZ
CVZ
SVZ
Elevation (m.a.s.l.)
0 - 318
318 - 766
766 - 1,558
1,558 - 2,693
2,693 - 3,802
3,802 - 6,732
N
1,000
Kilometers
Nevado del Ruiz
Cotopaxi
NVZ
Coropuna
Parinacota
Guallatiri
CVZ
Pular
Falso Azufre
Nevados Ojos del Salado
SVZ
Copahue
Callaqui
Lonquimay
Llaima
Villarrica

Figure 2

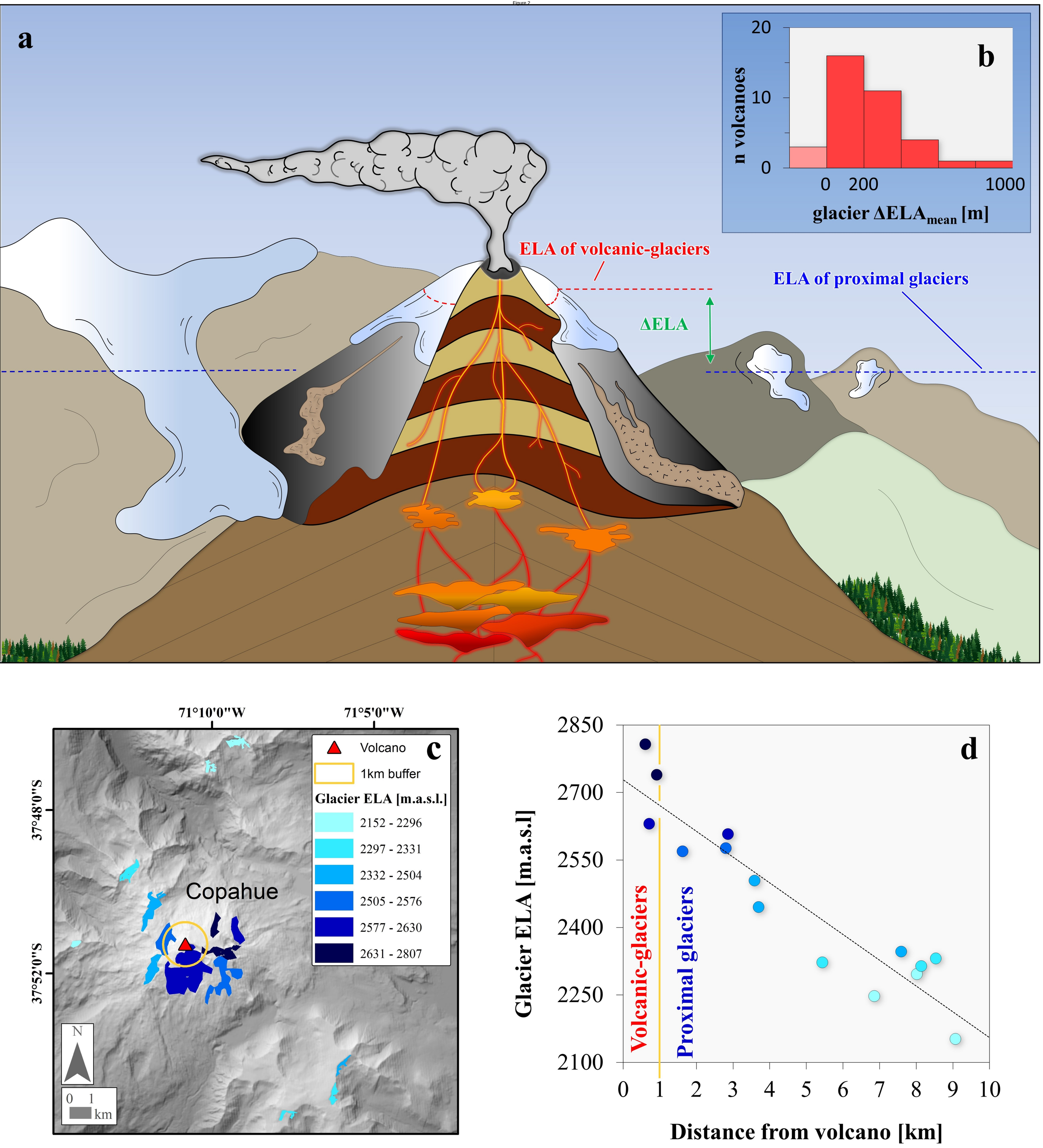

a
ELA of volcanic-glaciers
ELA of proximal glaciers
ΔELA
b
n volcanoes
20
10
0
0
200
1000
glacier ΔELA$_{mean}$ [m]
c
Volcano
1km buffer
Glacier ELA [m.a.s.l.]
2152 - 2296
2297 - 2331
2332 - 2504
2505 - 2576
2577 - 2630
2631 - 2807
Copahue
71°10'0"W
71°5'0"W
37°48'0"S
37°52'0"S
N
0 1
km
d
Glacier ELA [m.a.s.l]
2850
2700
2550
2400
2250
2100
Volcanic-glaciers
Proximal glaciers
0 1 2 3 4 5 6 7 8 9 10
Distance from volcano [km]

Figure 3

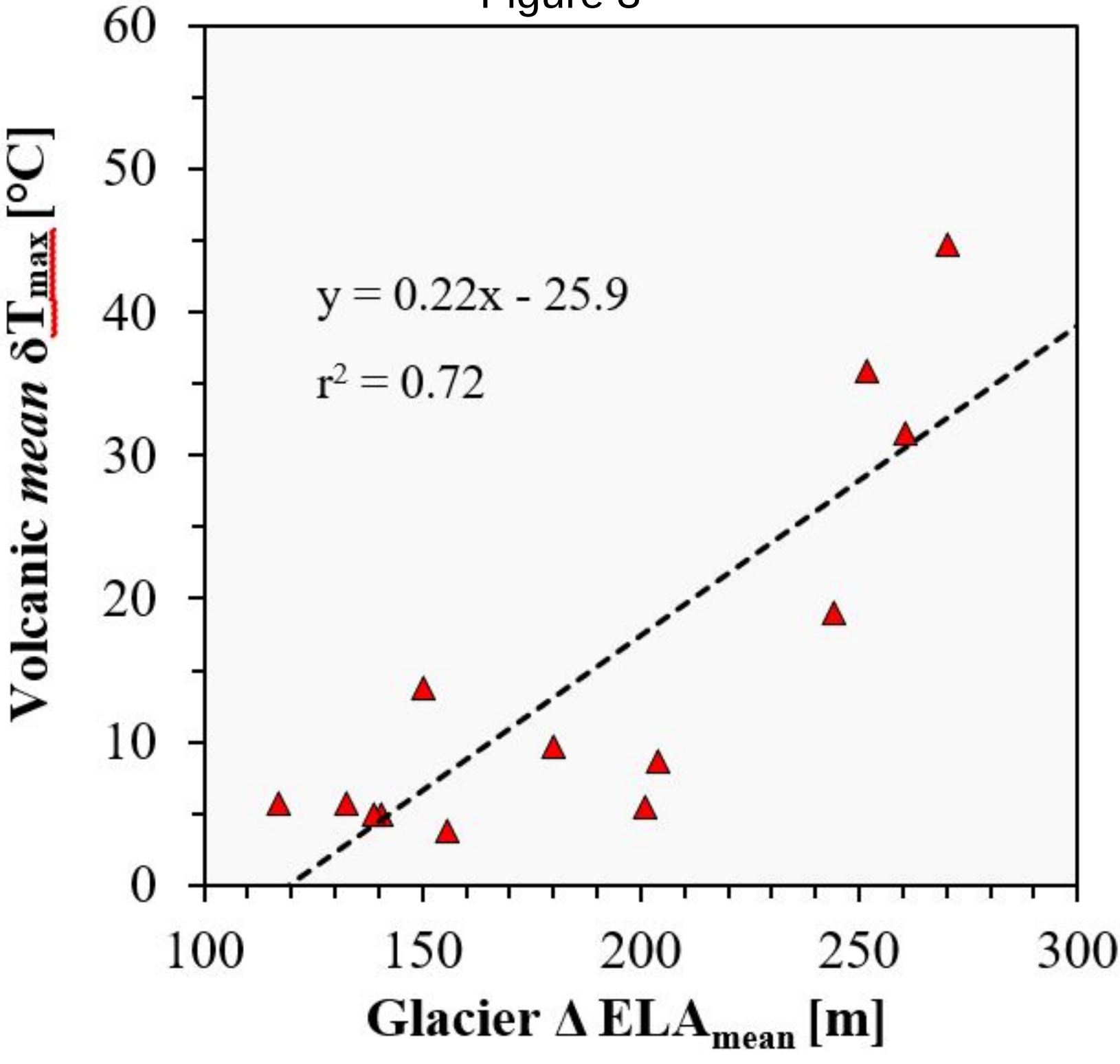
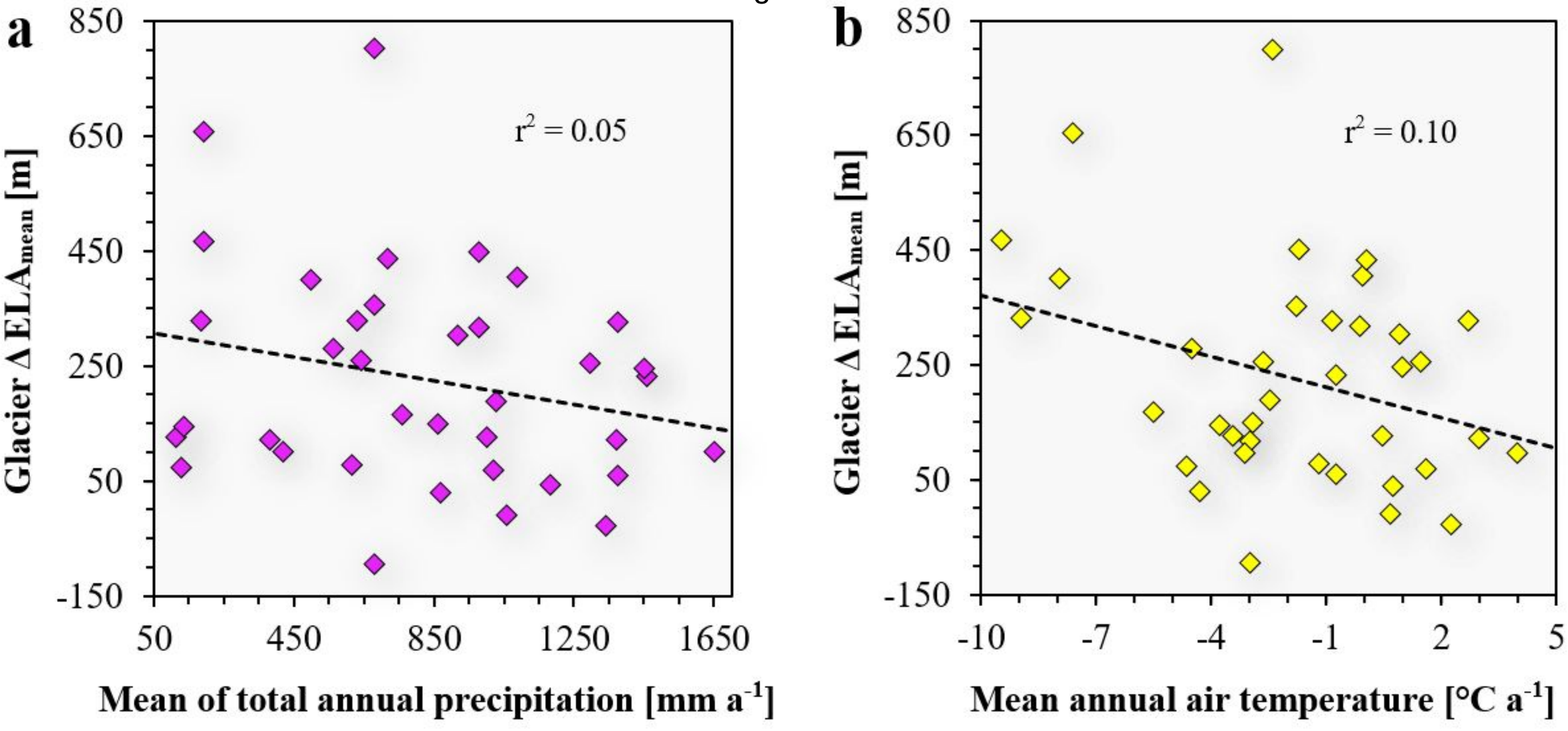

60
50
40
30
20
10
0
100
150
200
250
300
y = 0.22x - 25.9
r² = 0.72
Volcanic mean δT_max [°C]
Glacier Δ ELA_mean [m]

Figure 4


a
b
850
650
450
250
50
-150
Glacier Δ ELA$_{mean}$ [m]
$r^2 = 0.05$
$r^2 = 0.10$
50
450
850
1250
1650
-10
-7
-4
-1
2
5
Mean of total annual precipitation [mm a^{-1}]
Mean annual air temperature [°C a^{-1}]