Global and Planetary Change 229 (2023) 104242

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Pre-industrial Holocene glacier variability in the tropical Andes as context for anthropogenically driven ice retreat

Nathan D. Stansell [a,*], Mark B. Abbott [b], Maximiliano Bezada Diaz [c], Joseph M. Licciardi [d], Bryan G. Mark [e], Pratigya J. Polissar [f], Donald T. Rodbell [g], Tal Y. Shutkin [e]

[a] Department of Earth, Atmosphere and Environment, Northern Illinois University, United States of America
[b] Department of Geology and Environmental Science, University of Pittsburgh, United States of America
[c] Minnesota Geological Survey, University of Minnesota, United States of America
[d] Earth Sciences, University of New Hampshire, United States of America
[e] BPCRC and Department of Geography, The Ohio State University, United States of America
[f] Ocean Sciences, University of California, Santa Cruz, United States of America
[g] Geosciences Department, Union College, United States of America

ARTICLE INFO

Editor: Dr. Howard Falcon-Lang

Keywords:
South America
Early Holocene
Neoglacial
Medieval Climate Anomaly
Little Ice Age

ABSTRACT

Disentangling the timing and pattern of past glacier change in the tropics provides important perspectives for the future health of the Andean cryosphere. Here we review Holocene paleo-glacial records from the northern and southern tropical Andes to provide context for the loss of glacial ice since the late 20th century. The available archives indicate that glaciers advanced and retreated multiple times during the Holocene with notable shifts during the last millennium. However, the available records of glaciation from the northern and southern Andes depict contrasting climate conditions across the tropics through the early, middle and late Holocene, including during the Medieval Climate Anomaly (MCA). There is clearer evidence of widespread Little Ice Age (LIA) glacier advances throughout the region, however, there were significant, centennial-scale lags in the timing of southern tropical glaciation relative to the onset of cooling in the Northern Hemisphere. Notwithstanding age uncertainty, the combined regional paleoclimate records suggest the MCA in the tropical Andes was somewhat warmer and drier than the LIA, but not warmer than today. In contrast, the vast majority of Andean glaciers appear to be rapidly and uniformly retreating since the late 20th century in response to anthropogenic warming.

1. Introduction

There is mounting evidence that recent glacial variability across the tropical Andes cannot be explained by natural climate variability and ice dynamics alone (Byers, 2000; Francou et al., 2003; López-Moreno et al., 2014; Seehaus et al., 2019; Thompson et al., 2011), with rapid and accelerated ice loss now appearing to be largely anthropogenically driven (e.g., Stuart-Smith et al., 2021). Given the recent attention to past and present South American glacial variability (Davies et al., 2023), it is timely to revisit the available published records to consider the pattern and causes of Holocene climate changes in tropical Andean regions (i.e., over the last ~12,000 calendar years before present, or BP). In particular, the last ~1000 years of ice margin variability, with relatively well-documented climate fluctuations, should be compared to the accelerated glacier mass loss that has occurred since the mid-20th century (Coudrain et al., 2005; Schauwecker et al., 2014; Vuille et al., 2018).

Despite a lack of robust evidence, some have suggested that the Medieval Climate Anomaly (MCA; 950–1250 CE, or 1000 to 700 BP) was a period when the vast majority of terrestrial sites in South America experienced uniformly warmer conditions (Lüning et al., 2019), and that modern glacial retreat partly represents a recovery from an exceptionally cold Little Ice Age (LIA; 1400–1850 CE, or 550 to 100 BP) (Lüning et al., 2022). Further, they argue that the offset of ~0.8 °C between recent and pre-industrial temperature values should be ascribed more to natural causes than what is commonly used by the Intergovernmental Panel on Climate Change (IPCC) and others (Lüning and Vahrenholt, 2017). Instead, these authors suggest that the baseline for evaluating contemporary glacier loss should lie somewhere between the warm MCA and cold LIA (Lüning et al., 2022). This assessment would suggest there was a coherent pattern of both glacial variability and temperature

* Corresponding author.
E-mail address: nstansell@niu.edu (N.D. Stansell).

https://doi.org/10.1016/j.gloplacha.2023.104242
Received 22 June 2023; Received in revised form 6 September 2023; Accepted 11 September 2023
Available online 17 September 2023
0921-8181/

changes across the Andes in the paleo-records over the last millennium, which is unlikely because local internal climate variability should overcompensate any external forcing through that interval (Goosse et al., 2005). Moreover, the assertions by Lüning et al. would assume that temperature has been the dominant driver of glacial variability in the tropics during both the paleo-records and the modern, which does not fully consider the complex hydrological drivers of glacial mass-balance changes. Given the diverse ocean-atmospheric and glacial dynamic processes evident across the Andes today, we should expect the records of past glacial activity to also depict highly variable responses to pre-industrial Holocene climate changes. Here we review the available evidence of the timing and causes of tropical Andean Holocene glacial variability as a framework for evaluating the signal of recent glacier loss.

2. Background and discussion

2.1. Geographic setting and glacier mass balance regimes

The Andes stretch from the Northern Hemisphere tropics (12°N) to the sub-polar Southern Hemisphere (55°S) (Fig. 1), spanning a wide range of climate zones. Depending on location, Andean climates can exhibit little to no seasonality of temperature and precipitation, whereas other areas have highly contrasting winter and summer conditions (Sagredo et al., 2014). Hypsometry and aspect combine to drive sharp east-west gradients in precipitation and glacier elevation across the Andes (Hastenrath, 2009). As such, Andean glaciers have varying sensitivities to changes in the South America Summer Monsoon (SASM) with Atlantic Ocean connections, dynamics related to the Intertropical Convergence Zone (ITCZ), and Pacific Ocean influences such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (e.g., Vuille et al., 2008). Farther south, glacial mass balances are also largely dominated by ENSO, as well as the strength of Pacific Ocean

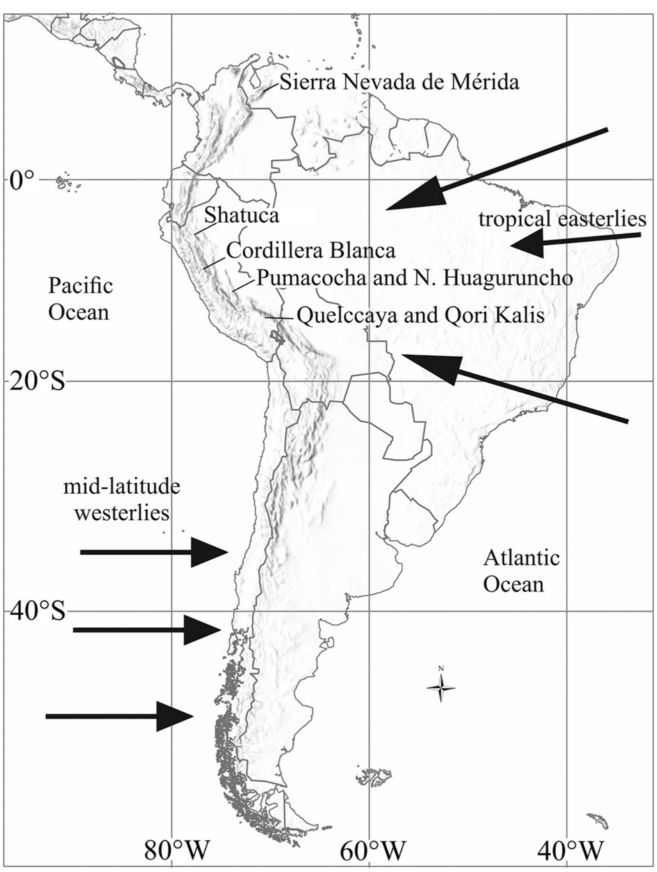


Fig. 1. Location map of sites mentioned in text.

westerlies, and the South Pacific Subtropical High (SPSH) (Aravena and Luckman, 2009; Garreaud et al., 2009; Price et al., 2022). Likewise, the Southern Annular Mode (SAM) in the Pacific affects the position and intensity of the westerlies, summer temperatures and rainfall distribution (Gillett et al., 2006; Reynhout et al., 2019).

While temperature is a primary forcing that drives glacier variability, hydroclimate is likely equally important in past and present Andean glacial variability. For example, the tropical highlands undergo greater diurnal than annual temperature variability. There is also a marked seasonality of precipitation (Hastenrath, 1985) that causes seasonal accumulation and year-round ablation (Kaser, 2001). During the wet season, maximum accumulation coincides with increased melt, whereas during the dry season, lower humidity enhances the role of sublimation, especially for the outer tropics (Wagnon et al., 1999a, 1999b; Winkler et al., 2009). For the humid inner tropics, like Venezuela, sublimation plays less of a role than for the outer tropics (Kaser, 2001). Moreover, the relative importance of hydrologic variables varies spatially and can shift through time, making the paleo-glacier records even more complex to interpret than today's ice margin fluctuations that can be directly compared to instrumental data (e.g., Francou et al., 1995).

2.2. Paleo-temperature data

Although temperature is a critical variable in paleoclimate studies, there is a lack of detailed temperature reconstructions spanning different climate zones across South America. One of the more detailed temperature reconstructions of the last millennium comes from southern South America (Neukom et al., 2011), although the authors of this study are careful to highlight a high degree of uncertainty in the temperature values for several centuries prior to the relatively cold LIA. The authors further note that the lack of high-resolution data imparts too much uncertainty in the records in the earlier part of the last millennium to make statistically robust comparisons to today. It is also unclear how these temperatures compare to the tropics. Moreover, as mentioned above, the climate of southern South America is highly influenced by the strength and position of westerlies, whereas glaciers in the tropical Andes are less influenced by high southern latitude modes of variability.

2.3. Last millennium tropical Andean climate change

Paleo-glacier studies can help fill the knowledge gap of past warming and cooling events, and these records indicate that the pattern of glacial variability across the northern and southern tropical Andes over the last millennium is indeed highly variable (Fig. 2). While other paleo-archives exist for the tropical Andes (e.g., Ledru et al., 2013; Rabatel et al., 2018), here we focus mostly on glacial sediment records that have been collected and analyzed using similar methods and dated with bracketing ^{210}Pb and ^{14}C ages. We also utilize sediment archives that can be directly compared to other nearby paleoclimate records. In brief, we interpret increases in clastic sediment flux and ice advances to be coeval during the Holocene (Stansell et al., 2013). In the Sierra Nevada de Mérida, Venezuela, the Lake Montos (Fig. 2A) and Lake Mucubají records (Fig. 2B) show little to no glacial activity during the MCA, followed by glacier advances during the LIA. In the eastern Cordillera of Peru, glaciers seem to have advanced during the MCA in the relatively wet Yanacocha valley at Nevado Huagurunccho (Fig. 2C), while at this same time ice retreated nearby in the more-precipitation-sensitive Queshque valley in the Cordillera Blanca of the western Cordillera (Fig. 2D). Similarly, the Qori Kalis dated glacial positions can be directly compared to the Quelccaya ice core record, suggesting local ice limits reached their maximum late-Holocene extent just prior to ~520 BP (Stroup et al., 2014).

Mounting evidence from the combined paleo-glacier records indicates that climate was spatially and temporally variable across the tropical Andes during the last millennium prior to the late 20th century. Most notably, the MCA was likely not a global temperature event

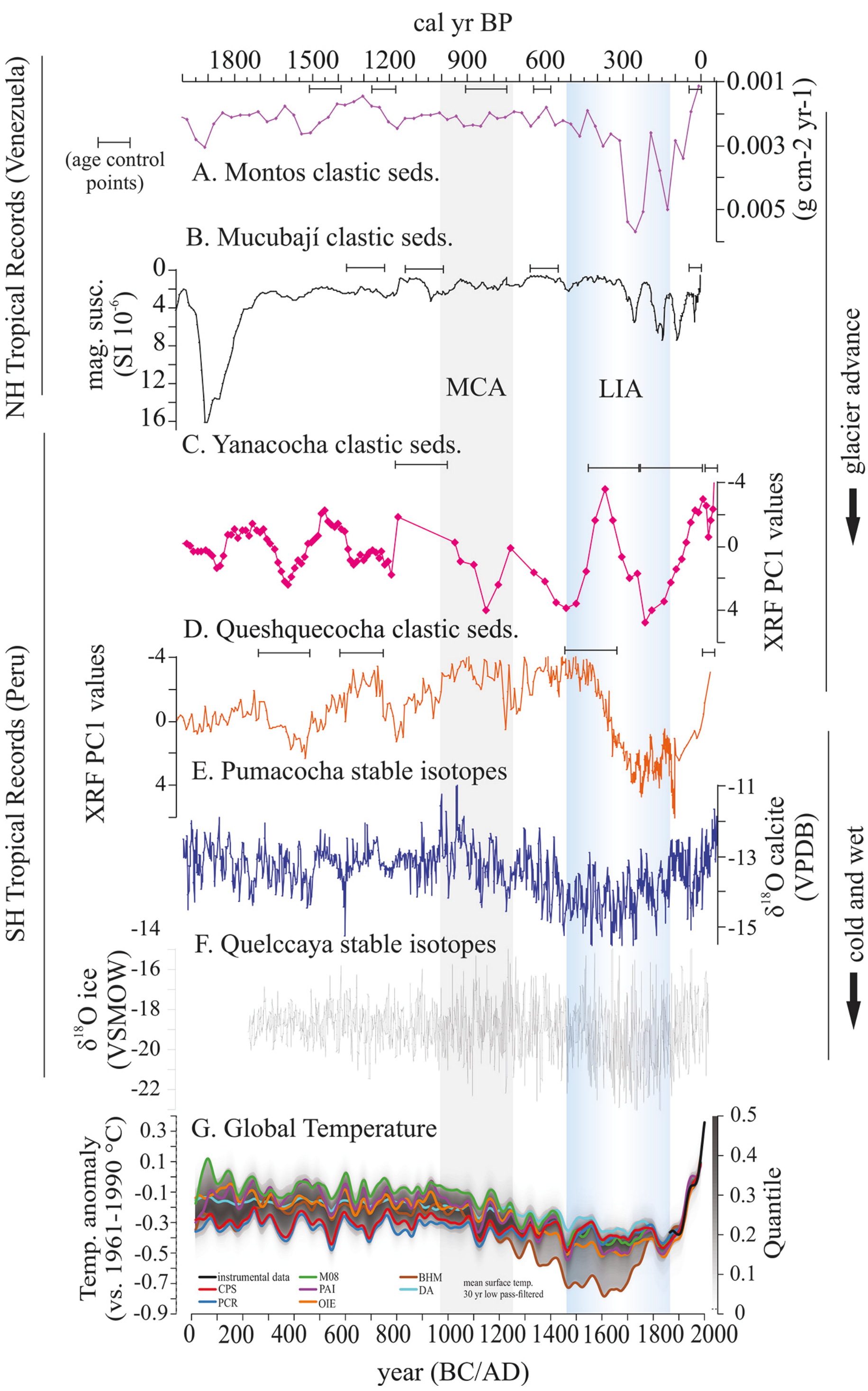


Fig. 2. Regional records from the northern tropical Andes of Venezuela (A,B) and southern tropical Andes of Peru (C—F). The Montos (A) and Mucubají (B) records show little to no glacial variability during the MCA, followed by evidence of ice advance during the LIA (Stansell et al., 2014). The Yanacocha (C) (Stansell et al., 2015) and Queshquecocha (D) (Stansell et al., 2017) records also show an inconsistent MCA pattern, followed by glacial advances during the latter stages of the LIA. The lake Pumacocha (E) (Bird et al., 2011) and Quelccaya ice core records (F) (Thompson et al., 2013) suggest colder and wetter conditions during the LIA. The Pages 2k Consortium (2017) temperature composite (G) indicates that while the MCA appears to be somewhat warmer and drier than the LIA that followed, the MCA does not stand out as a period of higher temperatures than today. The patterns of glacial variability in the northern and southern tropics likewise do not suggest a widespread and consistent pattern of MCA ice retreat. The methods present for the PAGES 2 k reconstruction include basic composite-plus-scaling (CPS), regression-based techniques (PCR, M08), linear methods (OIE, BHM) and techniques accounting for nonlinear relations between proxy values and temperature (PAI), or combine information from proxy data and climate models (DA).

(Bradley et al., 2003), as only ~40% of the planet experienced warming (Neukom et al., 2019). The combined stable isotope and accumulation records from the Quelccaya ice core (Fig. 2F) suggest the MCA was warmer than the LIA that followed. However, it is notable that the MCA was a time when both temperatures and hydroclimate were highly variable (Fig. 2E), underscoring the currently incomplete knowledge of glacier-based paleo-temperature estimates in South America (Thompson et al., 2013). If anything, hydrologic changes were more widespread than any substantial temperature shifts during Medieval times (Seager et al., 2007). Furthermore, composite global annual temperature reconstructions highlight a trend of progressively colder conditions through the MCA, not a pattern of persistent warming (Fig. 2G). Nevertheless, while detailed paleo-temperature syntheses are currently unavailable for the full spatial extent of the tropical Andes, it can be inferred from continuous records that the MCA was likely warmer than the LIA, but not warmer than today (Thompson et al., 2013).

While LIA cooling does appear to have been more regionally coherent than any apparent MCA conditions, the records presented here suggest that peak cooling in the southern tropical Andes lagged the onset of cooling in the northern tropical Andes and global average temperature composites (Fig. 2). For example, the onset of LIA cooling in Greenland occurred at ~1250 CE (700 BP) with culminations in the

1400s, early to middle 1700s and early middle 1800s (Kjær et al., 2022; Owens et al., 2017). The northern tropical Andes had ice advances with similar timing as cooling in Greenland (Polissar et al., 2006), whereas the clastic sediment and ice core records collectively suggest the onset of cooling in the southern tropical Andes (Fig. 2) occurred later than in Greenland, supporting the finding that Southern Hemisphere temperature changes generally lagged Northern Hemisphere cooling by around 2 centuries (Wanner et al., 2022). Dated ice positions in Peru suggest that glacial advances culminated in the southern tropical Andes between ~1500 CE and 1725 (Stansell et al., 2015; Stroup et al., 2014), generally corresponding to the latter LIA culminations in Greenland. Similar leads and lags have been noted for other regions outside Greenland (Neukom et al., 2019). Taken as a whole, cooling and warming events throughout the duration of the LIA do not appear to be registered globally (e.g., Neukom et al., 2019), nor was there a robust and synchronous pattern of glacial advances and retreats across the northern and southern tropics during the pre-industrial last millennium. This pattern is consistent with local internal climate variability overwhelming any externally forced temperature signal (Goosse et al., 2005).

Lastly, annual temperatures were likely colder than present-day in the Andes during the bulk of the last millennium. Although summer temperatures in parts of the Northern Hemisphere might have reached near-historical levels at times during the last ~2000 years (Büntgen et al., 2020), the PAGES 2k global temperature reconstructions suggest mean annual values did not exceed modern levels (Neukom et al., 2022). As noted above, the annual perspective is critical for tropical glacier mass-balance studies as ablation occurs year-round. While volcanic and solar forcing likely helped drive the pattern of LIA climate change across the Northern Hemisphere and tropics (Büntgen et al., 2020; Steinman et al., 2022), it is improbable that the prevalent trend of glacier recession in recent decades merely represents a return to pre-LIA conditions. Moreover, the study of Stroup et al. (2014) shows that industrial-era ice retreat greatly exceeds any variability that occurred over several centuries prior (Stuart-Smith et al., 2023).

2.4. Holocene perspective

Paleo-records document that glaciers were sometimes more, and often times less extensive than LIA limits in the tropical Andes since the end of the late glacial. Here we produced stacked clastic sediment records from the available published datasets following the method of Rodbell et al. (2008). These stacked clastic sediment records for the Venezuelan Andes (Fig. 3C) suggest a deglacial phase in Venezuela from ~10,000 to 8000 BP for valleys with headwalls higher than ~4400 m asl. This occurred soon after an extensive ice cap existed in Venezuela in the early Holocene (Stansell et al., 2005). For Peru, stacked lake sediment records combined with dated moraine positions (Fig. 3) indicate that glacial activity was relatively muted at the start of the early Holocene followed by ice advances and/or stillstands later in the early Holocene (after ~11,000 BP). It is also apparent from other dated records that alpine glaciers in parts of the tropical Andes experienced significant stillstands and/or advances during the early Holocene (Licciardi et al., 2009; Jomelli et al., 2022).

Insolation had contrasting patterns between the northern and southern tropics during the Holocene that likely impacted hydroclimate and glacier dynamics (Fig. 3). However, orbital forcing alone cannot explain the Holocene pattern of temperature and precipitation shifts during the Holocene, especially considering the synchronous nature of millennial-scale hydroclimate changes across the northern and southern tropical Andes (Polissar et al., 2013). In general, the Lake Pumacocha (Fig. 3G) and Huascarán ice core (Fig. 3H) records suggest an overall trend of colder and/or wetter conditions and a strengthening of the SASM while summer insolation increased in the southern tropics through the Holocene. Notably, the Shatuca cave record (Fig. 3F) has higher resolution than Lake Pumacocha and Huascarán, and when compared to glacial sediment records, suggests the glacial pattern partly responded to higher frequency hydroclimate variability driven by ocean-atmospheric changes.

Regardless of whether temperature or precipitation played a more prominent role in ice margin variability, the longer-term records provide perspective that LIA glaciation events are not isolated anomalies during the last ~12,000 years. Even when invoking a substantial (~25%) increase in precipitation, comprehensive glacier modeling suggests temperatures were ~ 3.0 to 2.8 °C colder in the southern tropical Andes during the early Holocene at ~10,800 and 9400 BP when glaciers exceeded LIA limits multiple times (Stansell et al., 2022). Considering temperature estimates for the LIA were ~ 1.1 °C colder in the southern tropical Andes (Autin et al., 2023), these directly dated early Holocene ice positions in multiple valleys run contrary to the claim by Lüning et al. (2022) that besides the so-called 8.2 ka event, the LIA was the coldest phase of the last ~10,000 years. It is also noteworthy that although the 8.2 ka event was associated with a strong, ~160 year-long cooling in Greenland (Thomas et al., 2007), there is no clear indication of this event in the paleoclimate records from the tropical Andes.

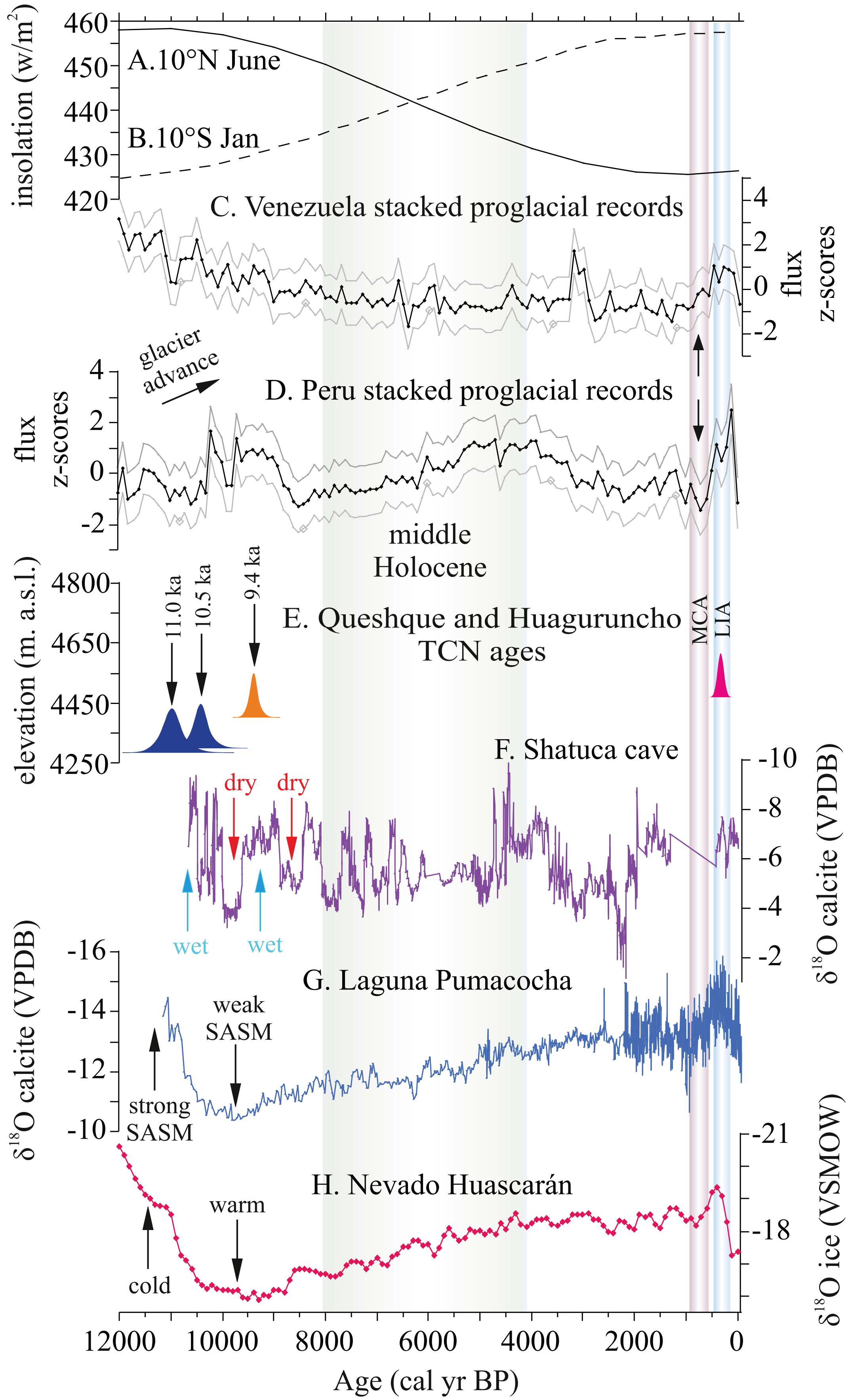
The middle Holocene pattern of glaciation in the tropics is less clear than for the early and late Holocene. However, it appears that glaciers were present at times after ~6000 BP, at least in the central Andes. For example, multiple proglacial sediment records in the southern tropical Andes show increased clastic sediment flux during the middle Holocene (e.g., Rodbell et al., 2009; Stansell et al., 2013). The clastic sediment records presented here (Fig. 3D) also suggest small-scale ice advances during the middle Holocene. Moreover, the Quelccaya ice cap provides perhaps the most striking evidence of middle Holocene ice advance in the southern tropical Andes, as plants buried by ice until recently are radiocarbon dated to ~5200 BP (Buffen et al., 2009). There were also periods of reduced ice cover in both hemispheres that lasted up to several millennia during the middle and late Holocene (Stansell et al., 2014, 2013). As noted above, insolation forcing and hydroclimate patterns across the Andes were quite different during the early, middle and late Holocene (Fig. 3), making it difficult to compare the causes of modern warming to these shifting boundary conditions. Nevertheless, the paleoclimate record highlights that LIA glaciers were not necessarily extraordinary in a longer-term perspective because it was commonplace to have periodic, and sometimes persistent ice in the tropical Andes at times during the last ~12,000 years.

3. Conclusions

Developing more records to better characterize the varied pattern of paleo-glacial activity across the Andes should be a high-priority of the paleoclimate community because it will help elucidate the complex drivers of shifting oceanic-atmospheric conditions on a range of timescales. However, based on the available evidence, there is neither an apparent nor consistent baseline ice position during the pre-industrial last millennium for comparison to today's scenario of uniform ice retreat. Instead, given the precedent of highly variable patterns of glacial variability through space and time over the Holocene, it is remarkable that the vast majority of tropical Andean glaciers are now retreating (Braun and Bezada, 2013; Ramírez et al., 2020; Schauwecker et al., 2017). This trend of ice loss is crucial to recognize as anthropogenic influences have become the pervasive signal driving the pattern of glacier retreat in recent decades (e.g., Gillett et al., 2021; Marzeion et al., 2014; Roe et al., 2021; St. George, 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



(caption on next page)

Fig. 3. Holocene records. Northern and southern tropical summer insolation (A,B) (Berger and Loutre, 1991). Stacked proglacial clastic sediment flux records with +/- 1 standard deviation values from Venezuela (C) are from lakes Montos and Mucubají (Stansell et al., 2014). Stacked records with +/- 1 standard deviation values from Peru (D) are from lakes Queshquecocha, Huarmicocha, Jahuacocha, Lutacocha (Stansell et al., 2013) and Yanacocha (Stansell et al., 2015). A composite of cosmogenic ages from Nevado Huaguruncho (Stansell et al., 2015) and the Queshque valley (Stansell et al., 2017) in Peru (E). The Shatuca cave (F) (Bustamante et al., 2016) and Lake Pumacocha (G) (Bird et al., 2011) records of southern tropical Andean hydroclimate and the Nevado Huacarán ice core record (H) (Thompson et al., 1995).

Data availability

The original and stacked clastic sediment data produced for this paper are available online at https://www.ncei.noaa.gov/access/paleo-search/study/38459.

Acknowledgements

This project was supported by the US National Science Foundation (EAR-1003711, EAR-1003780, EAR-1344476 and EAR-2002541).

References

Aravena, J.C., Luckman, B.H., 2009. Spatio-temporal rainfall patterns in southern South America. Int. J. Climatol. 29 (14), 2106–2120.

Autin, P., Sicart, J.E., Rabatel, A., Hock, R., Jomelli, V., 2023. Climate reconstruction of the Little Ice Age maximum extent of the tropical Zongo Glacier using a distributed energy balance model. Compt. Rendus Geosci. 355 (S1), 1–18.

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quat. Sci. Rev. 10, 297–317.

Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D., Rosenmeier, M.F., 2011. A 2,300-year-long annually resolved record of the south American summer monsoon from the Peruvian Andes. P. Natl. Acad. Sci. 108 (21), 8583–8588. https://doi.org/10.1073/pnas.1003719108.

Bradley, R.S., Hughes, M.K., Diaz, H.F., 2003. Climate in medieval time. Science 302 (5644), 404–405.

Braun, C., Bezada, M., 2013. The history and disappearance of glaciers in Venezuela. J. Lat. Amer. Geog. 12 (2), 85–124.

Buffen, A.M., Thompson, L.G., Mosley-Thompson, E., Huh, K.I., 2009. Recently exposed vegetation reveals Holocene changes in the extent of the Quelccaya Ice Cap, Peru. Quat. Res. 72 (2), 157.

Büntgen, U., Arseneault, D., Boucher, É., Churakova, O.V., Gennaretti, F., Crivellaro, A., Hughes, M.K., Kirdyanov, A.V., Klippel, L., Krusic, P.J., 2020. Prominent role of volcanism in Common Era climate variability and human history. Dendrochronologia 64, 125757.

Bustamante, M.G., Cruz, F.W., Vuille, M., Apaéstegui, J., Strikis, N., Panizo, G., Novello, F.V., Deininger, M., Sifeddine, A., Cheng, H., Moquet, J.S., Guyot, J.L., Santos, R.V., Segura, H., Edwards, R.L., 2016. Holocene changes in monsoon precipitation in the Andes of NE Peru based on $\delta^{18}O$ speleothem records. Quat. Sci. Rev. 146, 274–287. https://doi.org/10.1016/j.quascirev.2016.05.023.

Byers, A.C., 2000. Contemporary landscape change in the Huascarán National Park and buffer zone, Cordillera Blanca, Peru. Mt. Res. Dev. 20 (1), 52–63.

Coudrain, A., Francou, B., Kundzewicz, Z.W., 2005. Glacier shrinkage in the Andes and consequences for water resources. Hydrol. Sci. J. 50 (6), 925–932.

Davies, B., Bendle, J., Glasser, F., García, J.-L., Kaplan, M., 2023. Glaciation and climate change in the Andean Cordillera. Front. Earth Sci. 11, 1129795.

Francou, B., Ribstein, P., Saravia, R., Tiriau, E., 1995. Monthly balance and water discharge of an inter-tropical glacier: Zongo Glacier, Cordillera real, Boliva, 16°S. J. Glaciol. 41, 61–67.

Francou, B., Vuille, M., Wagnon, P., Mendoza, J., Sicart, J., 2003. Tropical climate change recorded by a glacier in the Central Andes during the last decades of the twentieth century: Chacaltay, Bolivia, 16°. J. Geophys. Res. 108 (D5), 4154.

Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day south american climate. Palaeogeogr. Palaeocl. 281 (3–4), 180–195.

Gillett, N.P., Kell, T.D., Jones, P.D., 2006. Regional climate impacts of the Southern Annular Mode. Geophys. Res. Lett. 33 (23), L23704 https://doi.org/10.1029/2006GL027721.

Gillett, N.P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G.C., Knutti, R., Gastineau, G., John, J.G., Li, L., Nazarenko, L., 2021. Constraining human contributions to observed warming since the pre-industrial period. Nat. Clim. Chang. 11 (3), 207–212.

Goosse, H., Renssen, H., Timmermann, A., Bradley, R.S., 2005. Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. Quat. Sci. Rev. 24 (12–13), 1345–1360.

Hastenrath, S., 1985. Climate and Circulation of the Tropics. C. Reidel Publishing Company, Dordrecht, 455 pp.

Hastenrath, S., 2009. Past glaciation in the tropics. Quat. Sci. Rev. 28 (9-10), 790.

Jomelli, V., Swingedouw, D., Vuille, M., Favier, V., Goehring, B., Shakun, J., Braucher, R., Schimmelpfennig, I., Menviel, L., Rabatel, A., 2022. In-phase millennial-scale glacier changes in the tropics and North Atlantic regions during the Holocene. Nat. Commun. 13 (1), 1–11.

Kaser, G., 2001. Glacier-climate interaction at low latitudes. J. Glaciol. 47 (157), 195–204.

Kjær, K.H., Bjørk, A.A., Kjeldsen, K.K., Hansen, E.S., Andresen, C.S., Siggaard-Andersen, M.-L., Khan, S.A., Søndergaard, A.S., Colgan, W., Schomacker, A., 2022. Glacier response to the Little Ice Age during the Neoglacial cooling in Greenland. Earth Sci. Rev. 227, 103984.

Ledru, M.-P., Jomelli, V., Samaniego, P., Vuille, M., Hidalgo, S., Herrera, M., Ceron, C., 2013. The medieval climate anomaly and the Little Ice Age in the eastern Ecuadorian Andes. Clim. Past 9 (1), 307–321.

Licciardi, J.M., Schaefer, J.M., Taggart, J.R., Lund, D.C., 2009. Holocene glacier fluctuations in the Peruvian Andes indicate northern climate linkages. Science 325 (5948), 1677–1679. https://doi.org/10.1126/science.1175010.

López-Moreno, J.I., Fontaneda, S., Bazo, J., Revuelto, J., Azorin-Molina, C., Valero-Garcés, B., Morán-Tejeda, E., Vicente-Serrano, S.M., Zubieta, R., Alejo-Cochachín, J., 2014. Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. Glob. Planet. Chang. 112, 1–11.

Lüning, S., Vahrenholt, F., 2017. Paleoclimatological context and reference level of the 2 C and 1.5 C Paris Agreement long-term temperature limits. Front. Earth Sci. 5, 104.

Lüning, S., Gałka, M., Bamonte, F.P., Rodríguez, F.G., Vahrenholt, F., 2019. The medieval climate anomaly in South America. Quat. Int. 508, 70–87.

Lüning, S., Gałka, M., Bamonte, F.P., García-Rodríguez, F., Vahrenholt, F., 2022. Attribution of modern Andean glacier mass loss requires successful hindcast of pre-industrial glacier changes. J. S. Am. Earth Sci. 104024.

Marzeion, B., Cogley, J.G., Richter, K., Parkes, D., 2014. Attribution of global glacier mass loss to anthropogenic and natural causes. Science 345 (6199), 919–921.

Neukom, R., Luterbacher, J., Villalba, R., Küttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.-C., Black, D.E., 2011. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. Clim. Dyn. 37, 35–51.

Neukom, R., Steiger, N., Gómez-Navarro, J.J., Wang, J., Werner, J.P., 2019. No evidence for globally coherent warm and cold periods over the preindustrial Common Era. Nature 571 (7766), 550–554.

Neukom, R., Steiger, N., Kaufman, D., Grosjean, M., 2022. Inconsistent comparison of temperature reconstructions over the Common Era. Dendrochronologia 74, 125965.

Owens, M.J., Lockwood, M., Hawkins, E., Usoskin, I., Jones, G.S., Barnard, L., Schurer, A., Fasullo, J., 2017. The Maunder minimum and the Little Ice Age: an update from recent reconstructions and climate simulations. J. Space Weather Spac. 7, A33.

Pages 2k Consortium, 2017. A global multiproxy database for temperature reconstructions of the Common Era. Sci. Data 4.

Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., Bradley, R.S., 2006. Solar modulation of Little Ice Age climate in the tropical Andes. P. Natl. Acad. Sci. 103 (24), 8937–8942. https://doi.org/10.1073/pnas.0603118103.

Polissar, P.J., Abbott, M.B., Wolfe, A.P., Vuille, M., Bezada, M., 2013. Synchronous interhemispheric Holocene climate trends in the tropical Andes. P. Natl. Acad. Sci. 110, 14551–14556. https://doi.org/10.1073/pnas.1219681110.

Price, B.N., Stansell, N.D., Fernández, A., Licciardi, J.M., Lesnek, A.J., Muñoz, A., Sorensen, M.K., Jaque Castillo, E., Shutkin, T., Ciocca, I., 2022. Chlorine-36 surface exposure dating of late holocene moraines and glacial mass balance modeling, Monte Sierra Nevada, South-Central Chilean Andes (38° S). Front. Earth Sci. 10, 848652.

Rabatel, A., Ceballos, J.L., Micheletti, N., Jordan, E., Braitmeier, M., González, J., Mölg, N., Ménégoz, M., Huggel, C., Zemp, M., 2018. Toward an imminent extinction of Colombian glaciers? Geografiska Ann.: Ser. A Phys. Geogr. 100 (1), 75–95.

Ramírez, N., Melfo, A., Resler, L.M., Llambí, L.D., 2020. The end of the eternal snows: Integrative mapping of 100 years of glacier retreat in the Venezuelan Andes. Arct. Antarct. Alp. Res. 52 (1), 563–581. https://doi.org/10.1080/15230430.2020.1822728.

Reynhout, S.A., Sagredo, E.A., Kaplan, M.R., Aravena, J.C., Martini, M.A., Moreno, P.I., Rojas, M., Schwartz, R., Schaefer, J.M., 2019. Holocene glacier fluctuations in Patagonia are modulated by summer insolation intensity and paced by Southern Annular Mode-like variability. Quat. Sci. Rev. 220, 178–187.

Rodbell, D.T., Seltzer, G.O., Mark, B.G., Smith, J.A., Abbott, M.B., 2008. Clastic sediment flux to tropical Andean lakes: records of glaciation and soil erosion. Quat. Sci. Rev. 27 (15–16), 1612–1626.

Rodbell, D.T., Smith, J.A., Mark, B.G., 2009. Glaciation in the Andes during the late Glacial and Holocene. Quat. Sci. Rev. 28 (21−22), 2165–2212.

Roe, G.H., Christian, J.E., Marzeion, B., 2021. On the attribution of industrial-era glacier mass loss to anthropogenic climate change. Cryosphere 15 (4), 1889–1905.

Sagredo, E.A., Rupper, S., Lowell, T.V., 2014. Sensitivities of the equilibrium line altitude to temperature and precipitation changes along the Andes. Quat. Res. 81 (2), 355–366. https://doi.org/10.1016/j.yqres.2014.01.008.

Schauwecker, S., Rohrer, M., Acuña, D., Cochachin, A., Dávila, L., Frey, H., Giráldez, C., Gómez, J., Huggel, C., Jacques-Coper, M., 2014. Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited. Glob. Planet. Chang. 119, 85–97.

Schauwecker, S., Rohrer, M., Huggel, C., Endries, J., Montoya, N., Neukom, R., Perry, B., Salzmann, N., Schwarb, M., Suarez, W., 2017. The freezing level in the tropical Andes, Peru: an indicator for present and future glacier extents. J. Geophys. Res.-Atmos. 122 (10), 5172–5189.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., Cook, E., 2007. Blueprints for medieval hydroclimate. Quat. Sci. Rev. 26 (19–21), 2322–2336.

Seehaus, T., Malz, P., Sommer, C., Lippl, S., Cochachin, A., Braun, M., 2019. Changes of the tropical glaciers throughout Peru between 2000 and 2016 – mass balance and area fluctuations. Cryosphere 13 (10), 2537–2556. https://doi.org/10.5194/tc-13-2537-2019.

St. George, S., 2019. The Aberrant Global Synchrony of Present-Day Warming. Nature Publishing Group UK London.

Stansell, N.D., Abbott, M.B., Polissar, P.J., Wolfe, A.P., Bezada, M., Rull, V., 2005. Late Quaternary deglacial history of the Mérida Andes, Venezuela. J. Quat. Sci. 20 (7–8), 801–812. https://doi.org/10.1002/jqs.973.

Stansell, N.D., Rodbell, D.T., Abbott, M.B., Mark, B.G., 2013. Proglacial lake sediment records of Holocene climate change in the western Cordillera of Peru. Quat. Sci. Rev. 70 (0), 1–14. https://doi.org/10.1016/j.quascirev.2013.03.003.

Stansell, N.D., Polissar, P.J., Abbott, M.B., Bezada, M., Steinman, B.A., Braun, C., 2014. Proglacial lake sediment records reveal Holocene climate changes in the Venezuelan Andes. Quat. Sci. Rev. 89 (0), 44–55. https://doi.org/10.1016/j.quascirev.2014.01.021.

Stansell, N.D., Rodbell, D.T., Licciardi, J.M., Sedlak, C.M., Schweinsberg, A.D., Huss, E. G., Delgado, G.M., Zimmerman, S.H., Finkel, R.C., 2015. Late Glacial and Holocene glacier fluctuations at Nevado Huaguruncho in the Eastern Cordillera of the Peruvian Andes. Geology 43 (8), 747–750. https://doi.org/10.1130/g36735.1.

Stansell, N.D., Licciardi, J.M., Rodbell, D.T., Mark, B.G., 2017. Tropical Ocean-atmospheric forcing of late Glacial and Holocene glacier fluctuations in the Cordillera Blanca, Peru. Geophys. Res. Lett. 44 (9), 4176–4185. https://doi.org/10.1002/2016GL072408.

Stansell, N.D., Mark, B.G., Licciardi, J.M., Rodbell, D.T., Fairman, J.G., Schoessow, F.S., Shutkin, T.Y., Sorensen, M., 2022. Energy mass balance and flow modeling of early Holocene glaciers in the Queshque valley, Cordillera Blanca, Peru. Quat. Sci. Rev. 281, 107414. https://doi.org/10.1016/j.quascirev.2022.107414.

Steinman, B.A., Stansell, N.D., Mann, M.E., Cooke, C.A., Abbott, M.B., Vuille, M., Bird, B. W., Lachniet, M.S., Fernandez, A., 2022. Interhemispheric antiphasing of neotropical precipitation during the past millennium. P. Natl. Acad. Sci. 119 (17), e2120015119.

Stroup, J.S., Kelly, M.A., Lowell, T.V., Applegate, P.J., Howley, J.A., 2014. Late Holocene fluctuations of Qori Kalis outlet glacier, Quelccaya Ice Cap, Peruvian Andes. Geology 42 (4), 347–350. https://doi.org/10.1130/g35245.1.

Stuart-Smith, R., Roe, G., Li, S., Allen, M., 2021. Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. Nat. Geosci. 14 (2), 85–90.

Stuart-Smith, R., Roe, G., Li, S., Allen, M., 2023. Comment on 'Attribution of Modern Andean Glacier Mass loss Requires successful Hindcast of Pre-Industrial Glacier changes' by Sebastian Lüning et al. J. S. Am. Earth Sci. 16, 104024.

Thomas, E.R., Wolff, E.W., Mulvaney, R., Steffensen, J.P., Johnsen, S.J., Arrowsmith, C., White, J.W., Vaughn, B., Popp, T., 2007. The 8.2 ka event from Greenland ice cores. Quat. Sci. Rev. 26 (1-2), 70–81.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Brecher, H.H., 2011. Tropical glaciers, recorders and indicators of climate change, are disappearing globally. Ann. Glaciol. 52 (59), 23–34.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.-N., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K., 1995. Late glacial stage and holocene tropical ice core records from Huascarán, Peru. Science 269, 46–50.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Zagorodnov, V.S., Howat, I.M., Mikhalenko, V.N., Lin, P.N., 2013. Annually Resolved Ice Core Records of Tropical Climate Variability over the past ~1800 years. Science. https://doi.org/10.1126/science.1234210.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., Bradley, R.S., 2008. Climate change and tropical Andean glaciers: past, present and future. Earth Sci. Rev. 89 (3–4), 79–96.

Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., Soruco, A., Villacis, M., Yarleque, C., Timm, O.E., 2018. Rapid decline of snow and ice in the tropical Andes–Impacts, uncertainties and challenges ahead. Earth Sci. Rev. 176, 195–213.

Wagnon, P., Ribstein, P., Francou, B., Pouyaud, B., 1999a. Annual cycle of energy balance of Zongo glacier, Cordillera Real, Bolivia. J. Geophys. Res.-Atmos. 104 (D4), 3907–3923.

Wagnon, P., Ribstein, P., Kaser, G., Berton, P., 1999b. Energy balance and runoff seasonality of a Bolivian glacier. Glob. Planet. Chang. 22 (1–4), 49–58.

Wanner, H., Pfister, C., Neukom, R., 2022. The variable European Little Ice Age. Quat. Sci. Rev. 287, 107531. https://doi.org/10.1016/j.quascirev.2022.107531.

Winkler, M., Juen, I., Mölg, T., Wagnon, P., Gómez, J., Kaser, G., 2009. Measured and modelled sublimation on the tropical Glaciar Artesonraju, Perú. Cryosphere 3 (1), 21–30.