Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099897

Key Points:

- Mid-latitude glacier annual equilibrium line altitude corresponds to broad regions of atmospheric temperature
- Mid-latitude glacier annual equilibrium line altitude is sensitive to latitudinal shifts of the mid-latitude westerlies
- The influence of the westerlies on glaciers has important implications for interpreting past and predicting future climate change

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. C. Audet,
alexander.audet@nevada.unr.edu

Citation:

Audet, A. C., Putnam, A. E., Russell, J. L., Lorrey, A., Mackintosh, A., Anderson, B., & Denton, G. H. (2022). Correspondence among mid-latitude glacier equilibrium line altitudes, atmospheric temperatures, and westerly wind fields. *Geophysical Research Letters*, *49*, e2022GL099897. https://doi.org/10.1029/2022GL099897

Received 2 JUN 2022
Accepted 24 OCT 2022

Author Contributions:

Conceptualization: Alexander C. Audet, Aaron E. Putnam, Joellen L. Russell, George H. Denton
Data curation: Alexander C. Audet
Formal analysis: Alexander C. Audet
Funding acquisition: Aaron E. Putnam, Joellen L. Russell, George H. Denton
Investigation: Alexander C. Audet
Methodology: Alexander C. Audet, Joellen L. Russell, Andrew Lorrey

Correspondence Among Mid-Latitude Glacier Equilibrium Line Altitudes, Atmospheric Temperatures, and Westerly Wind Fields

Alexander C. Audet[1,2], Aaron E. Putnam[1], Joellen L. Russell[3], Andrew Lorrey[4], Andrew Mackintosh[5], Brian Anderson[6], and George H. Denton[1]

[1]School of Earth and Climate Sciences and Climate Change Institute, University of Maine, Orono, ME, USA, [2]Department of Geography, College of Science, University of Nevada Reno, Reno, NV, USA, [3]Department of Geosciences, University of Arizona, Tucson, AZ, USA, [4]National Institute of Water & Atmospheric Research Ltd, Auckland, New Zealand, [5]Securing Antarctica's Environmental Future, School of Earth, Atmosphere and Environment, Monash University, Clayton, VIC, Australia, [6]Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand

Abstract Mountain glaciers are highly sensitive to climate change. However, the extent to which glaciers capture regional to hemisphere-scale atmospheric processes remains uncertain, hindering paleoclimatic interpretations derived from moraine-based glacier reconstructions. Here, we evaluate how mid-latitude glacier systems monitor climate by comparing climate reanalysis products with glacier annual equilibrium line altitude (ELA) elevations from the antipodal Southern Alps of New Zealand and European Alps. We find significant regional and hemispheric correlations between glacier annual ELA and summer tropospheric temperatures. Annual ELA also exhibit positive correlations with the latitude of the westerly jets in both hemispheres. These results indicate that westerly wind-belt latitude modulates the proportion of cold versus warm air masses influencing these glacier systems. These results highlight the sensitivity of mid-latitude glaciers to atmospheric temperatures and circulation, with implications for interpreting moraine-based paleoclimate reconstructions. Combined impacts of ongoing tropospheric warming and poleward-shifting westerlies will likely accelerate recession of mid-latitude glaciers.

Plain Language Summary Mountain glaciers respond to climate change by gaining mass when the climate cools and losing mass when the climate warms. However, the extent to which these glacial fluctuations are reflective of local, regional, and hemispheric climate variations is less clear, hindering climatic interpretation of paleo-glacier reconstructions developed from glacial landforms. This study evaluates the climatic footprint monitored by antipodal mid-latitude glacier populations by comparing gridded reconstructions of global temperature and wind changes with glacier annual snowline elevations in the Southern Alps of New Zealand and annual equilibrium line altitude elevations in the European Alps. Our results indicate that (a) these glacier systems co-vary with atmospheric temperatures on regional and even hemispheric scales throughout all levels of the troposphere, and (b) the latitudes of the westerly wind belts are important for regulating the proportion of cold versus warm air masses influencing glacier mass-balance. Altogether, our results indicate that mid-latitude mountain glacier fluctuations reflect temperature changes integrated over large regions of the atmosphere. With ongoing climate change, the combination of global atmospheric warming and poleward-shifting westerlies is likely to accelerate recession of mid-latitude glaciers in both hemispheres.

1. Introduction

Mapped and dated glacial moraine sequences have been used extensively as a means of reconstructing past ambient climate conditions (e.g., Nogami, 1972; Oerlemans, 2005; Putnam et al., 2013; Reynhout et al., 2019). Better understanding of the spatial scales at which mountain glaciers are monitoring the climate system has implications for interpreting past climate dynamics on the basis of paleoglacier reconstructions (e.g., Mackintosh et al., 2017; Putnam et al., 2012), and can also help to define the density of glacial records required to accurately characterize atmospheric conditions in different parts of the world, both in the past and as a prerequisite for predicting future global changes.

In this study, we seek to determine the spatial scales at which glaciers in the Southern Alps of New Zealand monitor contemporary atmospheric temperatures and climate dynamics. Studies have suggested that historic

10.1029/2022GL099897

Project Administration: Aaron E. Putnam, George H. Denton
Supervision: Aaron E. Putnam, Joellen L. Russell
Validation: Alexander C. Audet, Aaron E. Putnam, Joellen L. Russell, Andrew Lorrey
Visualization: Alexander C. Audet
Writing – original draft: Alexander C. Audet
Writing – review & editing: Alexander C. Audet, Aaron E. Putnam, Joellen L. Russell, Andrew Lorrey, Andrew Mackintosh, Brian Anderson

snowline and fluctuation records from these glacial are reflective of hemispheric-scale climate teleconnections (Clare et al., 2002; Fitzharris et al., 2007; Tyson et al., 1997). We expanded the analysis to another antipodal mid-latitude mountain range, the Europeans Alps to test if the analysis could be extended to other sites around the world. We compared glacier annual snowline and annual equilibrium line altitudes (ELA) data from the Southern Alps of New Zealand and the European Alps with climate variables for atmospheric temperature and circulation from the ERA5 Reanalysis (Hersbach et al., 2020). We tested the robustness of our glacier-climate analysis by performing the same method using instrumental temperature time series from each of the study areas. Additionally, we correlated the glacier timeseries with climate indices to help determine the role of natural patterns of climate variability in glacier ELA change. On the basis of these analyses, we discuss the spatial scales at which mid-latitude glaciers can serve as reliable physical records of climatic change, with implications for deriving paleoclimatic interpretations from glacial geologic reconstructions of paleo-ELA changes.

2. Glaciers and Climate

Annual ELAs serve as annual proxies for glacier mass balance. On terrestrial glaciers, the ELA divides the upper "accumulation area" from the lower "ablation area" (Meier, 1962). Measurement of the annual ELA, relative to the long-term ELA, provides information about glacier mass balance. In general, an annual ELA that is higher than the long-term ELA represents a negative mass balance. Similarly, a lower annual ELA represents a positive mass balance. The glacier will not survive if the ELA is persistently higher than the maximum glacier elevation (Pelto, 2010). However, the annual ELA is only a proxy for mass balance. Whether the sign and magnitude of annual ELA changes matches the sign and magnitude of mass balance changes depends on many factors, including annual variations in the mass balance gradient, changes in glacier geometry, the difficulty of defining the long-term ELA, and the situation in which the annual ELA is above the maximum elevation of the glacier. However, over longer periods there is a strong correlation between mass balance and annual ELA (Cullen et al., 2017; Rabatel et al., 2013). By extension, a persistent increase (decrease) in the annual ELA will cause the glacier terminus to recede (advance), although the amount of advance or retreat for a particular mass-balance change depends on the particular dynamic response of each glacier, as well as its mass-balance history.

Annual ELA values have been recorded for over a century on many glaciers in the European Alps (Figure 1) based on mass-balance observations cataloged by the World Glacier Monitoring Service (WGMS ["Data Exploration," 2020; WGMS, 2017]; see Figures 1, 2c, and 2d). In the Southern Alps, annual snowlines have been annually observed for 51 index glaciers since C.E. 1978 using oblique aerial photography (Willsman et al., 2015; see Figures 1, 2a, and 2b). The process for ascribing the annual snowline estimate from the imagery is iterative and semi-qualitative and quantitative. There are three approaches used any given year depending on snowcover: digitization, interpolation, and snowpatch evaluation (See Text S2 in Supporting Information S1; Willsman & Macara, 2022). The errors associated with these processes are likely on the order of 0.1–10 m (Lorrey et al., 2022). Less than 5 m of this error is associated with periodic remapping as the glacial extents change. As there is little-to-no superimposed ice in the maritime Southern Alps, the annual snowlines measured here can be used as a proxy for the annual ELAs (Chinn, 1995; Clare et al., 2002). Therefore, we will use the term "annual ELA" for convenience when referring to both sets of measurements.

Southern Alps glaciers are particularly sensitive to changes in atmospheric temperature due to their steep mass-balance gradients (Anderson & Mackintosh, 2006; Anderson et al., 2010; Lorrey et al., 2022; Mackintosh et al., 2017; Oerlemans, 1997; Oerlemans & Fortuin, 1992). Northeasterly and northwesterly airflow modulate enhanced incursions of warm subtropical air masses from northerly quarters around New Zealand, driving negative glacier mass-balance (Chinn et al., 2012; Clare et al., 2002; Fitzharris et al., 1997, 2007; Hooker & Fitzharris, 1999; Mackintosh et al., 2017; Salinger et al., 2019; Tyson et al., 1997). Southwesterly airflow, in contrast, favors incursions of cold, subantarctic air masses, driving positive mass-balance.

Similar to the situation for Southern Alps glaciers, modeling and observational evidence demonstrates that European Alps glacier fluctuations are dominantly controlled by atmospheric temperature variations (Huss et al., 2010; Marzeion et al., 2012). Huss et al. (2010) found that regional modes of ocean-atmosphere temperature variability, such as the Atlantic Multidecadal Oscillation/Variability (AMO/AMV), can explain as much as 50% of glacier mass-balance variance in the European Alps over the last 100 years.

10.1029/2022GL099897

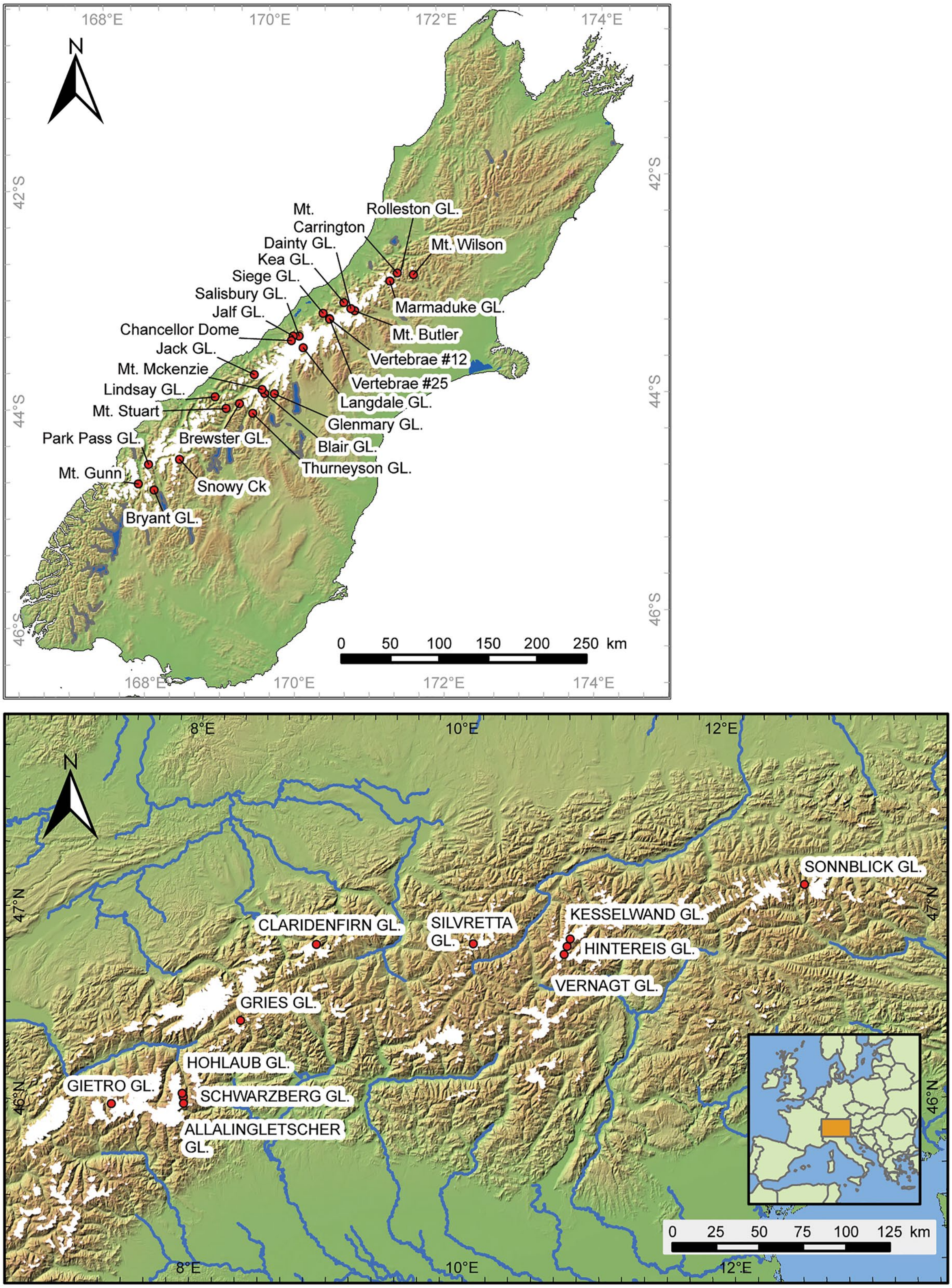

Figure 1.

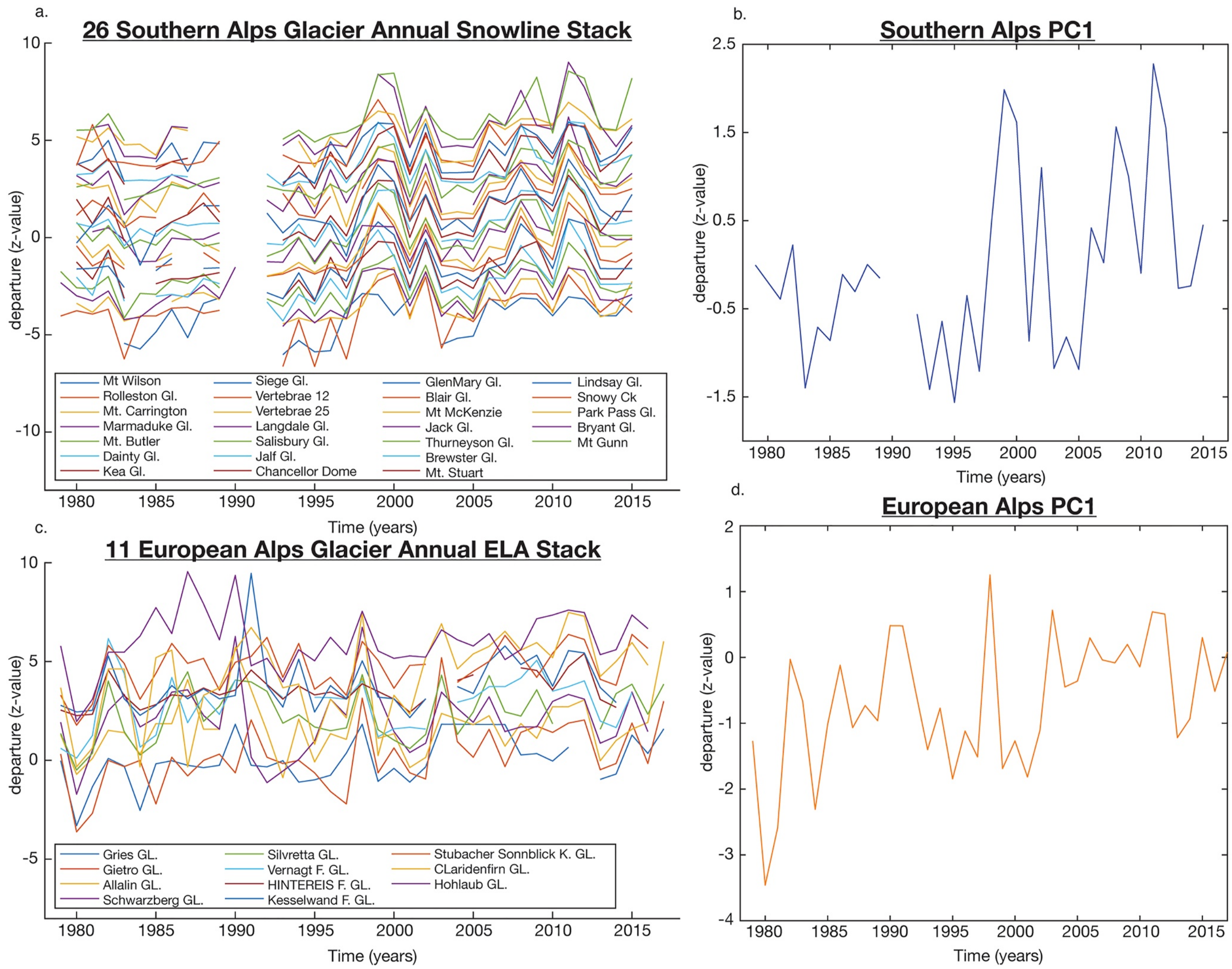

Figure 2. Stacked glacial records and the corresponding First Principal Components (PC1). (a) 26 Southern Alps glacier annual-snowline records separated vertically by 0.4 z-score increments for clarity (b) PC1 from the EOF analysis of the Southern Alps records (c) 11 European Alps annual ELA records, separated vertically by 0.6 z-score increments for clarity (d) PC1 of the EOF analysis of the European Alps records.

To determine correlations between glacier fluctuations and atmospheric climate changes, we analyzed European annual ELA and Southern Alps annual snowline datasets together with results from the fifth generation global climate reanalysis from the European Centre for Medium-Range Weather Forecast (ECMWF ERA5) (Hersbach et al., 2019, 2020). ERA5 has 0.25° horizontal grid spacing, with an average horizontal resolution of 31 km, and 37 levels with a vertical resolution of ~1,300 m. The temporal coverage of ERA5 extends from 1979 to present. We used the overlapping time span between the ERA5 and each respective glacier data set, and performed our analysis using the snowline series and each variable on 32 of the 37 pressure levels.

Figure 1. Maps illustrating the locations of the glaciers used in this study. (Top) South Island, New Zealand. Locations of 26 Southern Alps glaciers chosen for analysis are indicated with filled red circles. (Bottom) Locations of 11 European Alps glaciers selected for study are indicated by red circles. White patches show the glacier areas inventoried within the 2012 Randolph Glacier Inventory (RGI Consortium, 2017). The New Zealand base map features South Island digital elevation model (DEM) data (used with permission from Landcare Research New Zealand Limited). South Island hydrological polygons were obtained from the LINZ Data Service and licensed for reuse under CC BY 4.0. Background European DEM and river shapefiles are copyright of © European Union, Copernicus Land Monitoring Service 2020, European Environment Agency (EEA). European Location map is © EuroGeographics for the administrative boundaries.

3. Methods

Following the methodology of Lorrey et al. (2022), we selected a subset of the available glacier records that had at least 80% observational coverage. Twenty six of the fifty one Southern Alps measured glaciers fulfilled that criterion for the period 1979–2015, excluding the 1990–1991 interval when no official observations were made. In the European Alps using the same criteria, we selected 11 glaciers for the 1979 to 2017 timeframe. Years when the annual ELA surpassed the top of the glacier were excluded as the ELA could not be measured. We then standardized the data to a 10-year period, using that interval to represent the average equilibrium snowline altitude, and performed an empirical orthogonal function (EOF) analysis on each data set using the methodology of Russell and Wallace (2004; Figures S2 and S13 in Supporting Information S1). The selected 10-year average glacier periods spanned C.E. 2001–2010 for the Southern Alps and C.E. 2006–2015 for the European Alps (see Supporting Information S1). The results were not sensitive to the timeframe selected for the measurement base period. The first principal component (PC1) of each data set both in a non-detrended and detrended form (Supporting Information S1) were used for correlation analyses with climate reanalysis data.

Monthly averaged data from ERA5 were used to create yearly and seasonal time series by calculating the weighted average values from the three summer months in each hemisphere—June–August (JJA) in the Northern Hemisphere (NH) and December-February (DJF) in the Southern Hemisphere (SH). We then calculated the Pearson's correlation coefficient (r) between each climate reanalysis cell and PC1 of the Southern Alps and European glacial records to create a gridded map of climate correlation values. A Student's t-test was applied to mask all correlated cells outside of a 90% confidence interval. Results were still robust using a 95% confidence interval. The spatial pattern of correlations between glacier data PC1 time series and the ERA5 climate data was not sensitive to the methodology used to construct the snowline time series and showed significance in a Monte Carlo Analysis (see Supporting Information S1).

We repeated the analysis in autumn, winter and spring quarters (not shown), but the highest spatial correlation values were determined for the summer (i.e., ablation) seasons, followed closely by spring (March–May in the NH and September–November in the SH).

Instrumental temperature time series used for correlation analyses were from the New Zealand seven-station (NZ7S) record (Mullan et al., 2010) and the HISTALP monthly regional homogenized temperature time series for the European Alps (Auer et al., 2007; "HISTALP," 2012). We sourced the monthly NZ7S values for each station from the National Institute of Water and Atmospheric Research, and treated each region in the HISTALP series as a station in the analysis. The same period (1979–2015/2017) as the glacier correlation analysis described above was used, along with the same three-month summer averages: DJF for New Zealand and JJA for the European Alps. We prepared the instrumental record time series the same way as for the glacier time series, except that we did not standardize the data set for the whole analysis period (Figures S4 and S6 in Supporting Information S1). We then evaluated the instrumental PC1 against ERA5 variables.

4. Results

Results are summarized in Figure 3. The vertical structure of glacier-climate correlations is shown in Figure S9 (in Supporting Information S1) and described in Table S2. All reported correlations pass the student's t-test at 90% CL. Our results show that Southern Alps glacier annual snowlines covary strongly with summer atmospheric temperatures registered throughout much of the mid-latitudes of the SH (Figure 3a and Figure S9a in Supporting Information S1), aligning with the latitudinal belt of the summertime mid-latitude austral westerlies (Figure S3 in Supporting Information S1). In addition to temperature, the results show a strong relationship between annual ELA and wind strength, with high (low) annual ELA corresponding to increased (decreased) wind speeds to the south of New Zealand, and decreased (increased) wind speeds to the north of New Zealand.

Similar to the Southern Alps, European Alps glacier annual ELAs also covary with regional mid-latitude summer atmospheric temperatures (Figure 3c and Figure S9c in Supporting Information S1) in the upwind North Atlantic region. There are also correlations with the region straddling tropical and subtropical latitudes (Figure 3c and Figure S9c in Supporting Information S1). Regional European Alps annual ELA correlations with mid-latitude temperatures correspond with the zone of the boreal summer westerly windfield (Figure S3 in Supporting Information S1).

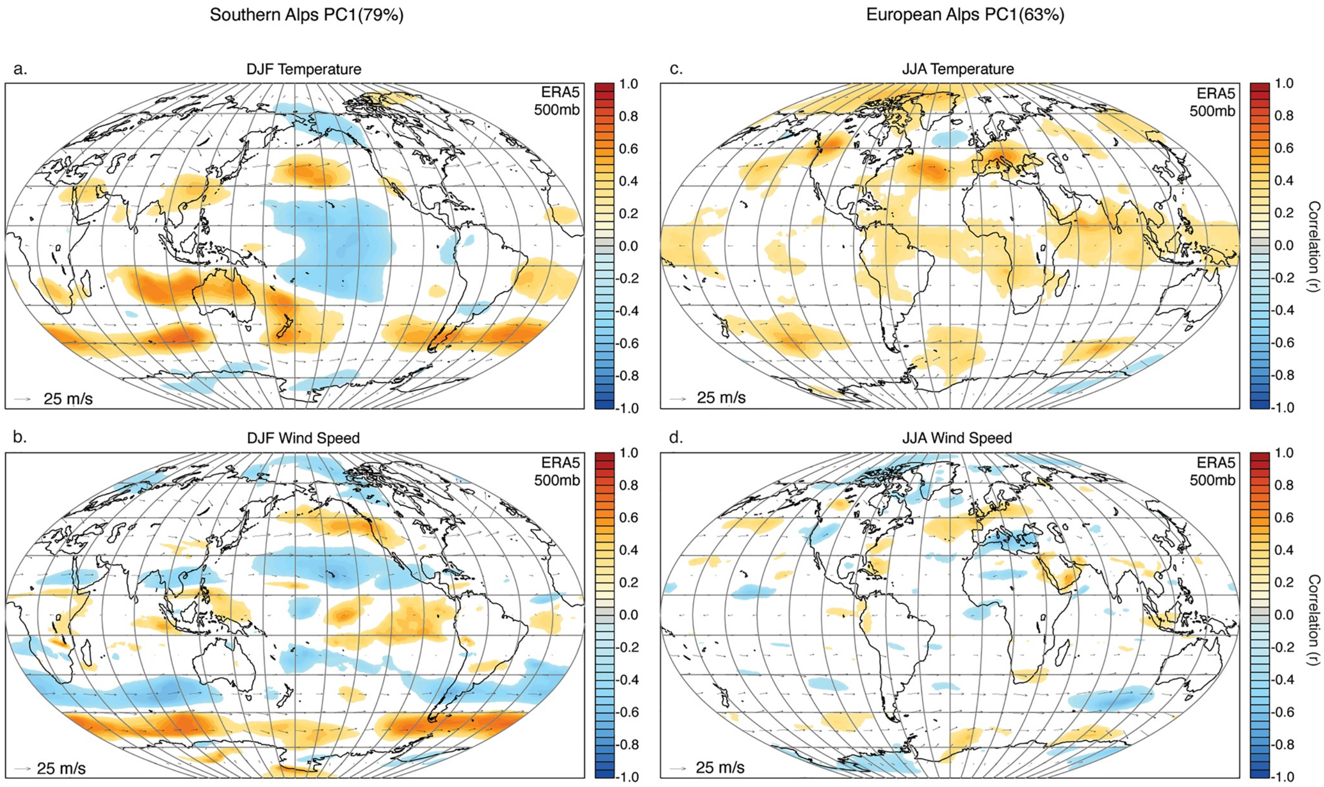

Figure 3. Maps showing correlations among glacier PC1s and ERA5 variables at CL = 90% for the 1979–2015 timeframe. Correlation between the New Zealand PC1 annual snowline time series and austral summer reanalysis temperature (a) and wind speeds (b) at 500 mb. Correlation between the European Alps PC1 annual ELA time series and northern summer reanalysis temperature (c) and wind speeds (d) at 500 mb. Overlying arrows indicate wind speed magnitude and direction (scale arrows, inset).

European Alps annual ELA correspond with regional bands of mid-latitude winds speed, with relatively high annual ELAs corresponding increased (decreased) wind speeds to the north (south) of the European Alps in (Figure 3d and Figure S9d in Supporting Information S1).

Correlation values determined from comparing annual ELAs with climate-mode indices are given in Table 1. Among the indices evaluated, Southern Alps annual snowlines exhibit the strongest correlation with the DJF Southern Annular Mode index (SAM; $r = 0.516$, $p = 0.05$, $n = 35$, 1979–2015). European Alps annual ELAs show the strongest correlation with the JJA Pacific-North American Pattern (PNA) ($r = 0.482$, $p = 0.05$, $n = 39$, 1979–2017). Other significant correlations among Southern Alps/European Alps annual ELAs and climate indices are reported in Table 1.

Finally, when regressed against ERA5-derived temperatures and wind speeds, instrumental temperature time series from the Southern and European Alps reveal spatial patterns that were nearly identical to results from the glacier regressions. NZ7S records covaried with circumpolar bands of mid-latitude temperature and wind speed (Figures S5a and S5b in Supporting Information S1). And, much as we found for European annual ELA, HISTALP temperatures similarly covaried with regional temperatures over the North Atlantic and northern Europe, as well as with more distal regions, such as in the eastern Pacific, in western North America, and in the tropics (Figure S5c in Supporting Information S1). HISTALP records were also significantly associated with wind speeds over the North Atlantic and northern Europe (Figure S5d in Supporting Information S1).

5. Discussion

Results indicate that Southern and European Alps annual ELAs covary with atmospheric variables on regional to near-global extents. Annual ELAs in both localities reflected atmospheric temperature patterns over large spatial scales, especially in respective mid-latitude settings (Figures 3a and 3c; Figures S9a and S9c in Supporting

Table 1
Correlation Values Determined for European (E.) Annual ELA and Southern (S.) Alps Annual Snowline PC1 Values and Regional Climate Indices

	Correlation (*r*)	
Index	E Alps	S Alps
SAM (DJF)	–	0.516
SOI (DJF)	–	0.607
ONI (DJF)	–	−0.493
PDO (JJA and DJF)	−0.355	−0.498
IPO (JJA and DJF)	−0.382	−0.626
NAM (DJFM)	0.129	0.064
NAO (JJA)	−0.255	–
AO	−0.188	–
PNA (JJA)	0.482	–
AMO (JJA)	0.324	–
AMO (JJA) smoothed	0.392	–

Note. The European data set was assessed for the months of JJA (summer ablation season) and the Southern Alps data set for DJF. SAM = Southern Annular Mode (Marshall, 2003; Marshall & NCAR Staff, 2018). SOI = Southern Oscillation Index or El Niño Southern Oscillation (ENSO) (Trenberth & NCAR Staff, 2020). ONI = Oceanic Niño Index ("ONI," 2022). PDO = Pacific Decadal Oscillation (Mantua, 1999; "PDO," 2021). IPO = Interdecadal Pacific Oscillation (Henley et al., 2015). NAM = Northern Annular Mode (NCAR Staff, 2021). NAO = North Atlantic Oscillation (Chen & Van den Dool, 2003; Hurrell, 1995; "NAO," 2020; Van Den Dool et al., 2000). AO = Arctic Oscillation ("AO," 2020; Thompson & Wallace, 2000; Zhou et al., 2001). PNA = Pacific-North American Pattern (Barnston & Livezey, 1987; Chen & Van den Dool, 2003; "PNA," 2020; Van Den Dool et al., 2000). AMO = Atlantic Multidecadal Oscillation ("AMO," 2020; Enfield et al., 2001; Sutton & Hodson, 2005). "AMO smoothed" represents a running 121-month average of the AMO timeseries ("AMO," 2020; Enfield et al., 2001).

Information S1). Southern Alps glaciers show nearly circumpolar correlation with atmospheric mid-latitude temperatures while Europeans Alps glaciers correlated with the mid-latitudes temperatures in two regional bands: one over the North Atlantic and Western Europe, and one over the eastern Pacific. These correlations extend vertically from sea level to the top of the troposphere (i.e., at 100–200 mb, Figure S9 in Supporting Information S1). These observations reinforce the emerging view that both the Southern and European Alps glacier mass-balance is generally temperature controlled (Chinn et al., 2005; Huss et al., 2010; Lorrey et al., 2022). Our analysis expands on that work and indicates a broader spatial correspondence than has previously been reported. The vertical continuity of the spatial correlations patterns suggest that the relationship between glaciers and temperature relates to large scale atmospheric circulation. Furthermore, both regions show a strong relationship between mid-latitude glaciers and tropical climate. In the Southern Alps, the three-dimensional structure of the correlation resembles an arch that connects the lower atmosphere of the SH mid-latitudes to the tropical Indo-Pacific region (Figure S10 in Supporting Information S1), which we take to indicate an important atmospheric connection between Southern Alps glaciers and the Indo-Pacific Warm Pool region. Similarly, European annual ELAs are significantly correlated with temperatures throughout the tropics, extending throughout the tropospheric column (Figure 3a and Figure S9c in Supporting Information S1). However, annual ELA correlations with tropical temperatures tend to be reduced in detrended analyses, perhaps reflecting a low-frequency signal consistent with global temperature rise over the past century.

Significant correlations between Southern and European Alps annual ELAs and wind speeds indicate that annual ELAs are highly sensitive to the latitudinal position of respective westerly wind belts (i,e., the Southern Westerly Winds (SWW) and the Northern Westerly Winds (NWW), respectively; Figures 3b and 3d; Figures S9b and S9d in Supporting Information S1). By these observations, annual ELAs were high when the core of the westerlies was located in a poleward location, leading to climate conditions that favored negative glacier mass-balance and terminus recession. In contrast, annual ELAs were low when the westerlies were translocated to an equatorward position, leading to climate conditions favoring positive glacier mass-balance and terminus advance. We consider that the position of the Westerly Winds modulates the proportion of warm subtropical versus cold subpolar air masses over the glaciers (Fitzharris et al., 2007; Hooker & Fitzharris, 1999; Mackintosh et al., 2017; Salinger et al., 2019; Tyson et al., 1997), governing the covariation of mid-latitude temperatures and snowlines.

We suggest that the effects of local circulation changes on the Southern Alps glacier mass-balance (e.g., Fitzharris et al., 2007; Hooker & Fitzharris, 1999; Mackintosh et al., 2017) are connected to the pan-hemispheric behavior of the SWW. Not only is the pattern of correlation/anticorrelation with annual snowlines and the SWW nearly symmetric around the pole, despite regional variations in the behavior of the surface SWW (Goyal et al., 2021), it also extends vertically throughout the troposphere, corresponding with the height of the SWW circulation. Such a broad region of correspondence reinforces suggestions that the SWW connect Southern Alps mass-balance with climate variations elsewhere in the SH mid-latitudes (Clare et al., 2002; Fitzharris et al., 2007; Tyson et al., 1997). Based on these observations, we consider that the circum-hemispheric SWW belt plays a fundamental role in regulating atmospheric temperatures and glacier mass-balance in the SH mid-latitudes.

As with our Southern Alps snowline-wind speed analysis, we also observe a corresponding, albeit more regional, relationship between European Alps annual ELA and the position of the NWW. This pattern also extends throughout the tropospheric column in the North Atlantic region.

10.1029/2022GL099897

Our analysis shows that strong (and in the SH, circumpolar) correlations found in PC1 of the glacial records are most associated with decadal patterns of variability. The primary mode of variability (PC1) associated with the Southern Alps annual snowlines is with the SAM, which describes the decadal latitudinal position of the SWW (see correlation maps Figure 3b and Figure S9b in Supporting Information S1). Likewise, the primary mode of variability (PC1) in the European Alps annual ELA is with the PNA, which has been linked to the behavior of the NWW. These results further highlight the importance of the westerly windfields in modulating air masses influencing the melt of mid-latitude glaciers.

Quantifying how mid-latitude glaciers monitor zonal wind fields will aid in interpreting reconstructions of past glacier fluctuations based on mapped and dated glacial landforms. A number of studies have reconstructed changes in past glacial extent, and corresponding paleo-ELAs, in the European and Southern Alps during and since the Last Glaciation at the two sites examined in this study (e.g., Denton et al., 2021; Ivy-Ochs, 2015; Ivy-Ochs et al., 2009; Putnam et al., 2013). Based on the results on this study, past glacier behavior in the Southern Alps could be taken to broadly reflect temperatures across much of the SH mid-latitudes, as well as the past position of the SWW. Likewise, European Alps glacier reconstructions could be taken to reflect past regional temperature fluctuations and the position of the NWW. Such paleo-glacier reconstructions could therefore help to determine the role of the westerlies and tropics during past global climate changes. Our results are consistent with observations from other mid-latitude glaciated environments, such as in the western North America (Menounos et al., 2019) and in southern Patagonia (e.g., Dussaillant et al., 2019), that also stress the importance of atmospheric circulation in modulating glacier mass balance. Further inspection of glacier-climate connections in other parts of the world could help to further quantify knowledge of the spatial extent of glacier-climate relationships.

6. Conclusion

The results of this study show that mid-latitude mountain glaciers in New Zealand and Europe monitor climate on broad hemispheric and regional spatial scales, respectively. Significant correlation among recent annual snowline and annual ELA changes, temperature, and wind speed, suggest an important role for the westerly wind systems in modulating air temperatures on mid latitude glacier systems, and therefore acting as a fundamental control on glacier extent in both hemispheres. Glacier-climate relationships identified here can inform paleoclimatic interpretations of paleo-glacier reconstructions, with implications for understanding the past behavior of the westerlies. Finally, the westerly wind systems in both hemispheres are projected to contract poleward over coming decades as a consequence of the ongoing increase in atmospheric CO_2 (Goyal et al., 2021; Russell et al., 2006; Toggweiler & Russell, 2008). The tight links observed here between mid-latitude glacier systems and wind-modulated temperatures indicate that ongoing and future poleward contraction of the winds will likely provide a powerful, and as-yet underappreciated feedback on mid-latitude glacier melt in a warming world.

Data Availability Statement

Data analyzed for this research, as well as results data are available on Pangaea (Audet et al., 2022). European Location map in Figure 1 is © EuroGeographics for the administrative boundaries. The Southern Alps end-of-summer snowline data used for correlating glacier snowlines with global DJF ERA5 climate variables are available in the NIWA End of Summer Snowline Survey 2015 report (Willsman et al., 2015) via https://niwa.co.nz/climate/research-projects/climate-present-and-past/southern-alps-glaciers/end-of-summer-snowline-survey. The European Alps annual ELA data used for correlating glacier ELAs with global JJA ERA5 climate variables are available on the WGMS Fluctuations of Glaciers Browser via https://doi.org/10.5904/wgms-fog-2018-11, https://wgms.ch/data_exploration/ ("Data Exploration," 2020; WGMS, 2017). In the Fluctuations of Glaciers Browser, search for Mass Balance datasets in the Central Europe, Alps region. The ERA5 climate reanalyis data set used to determine the spatial extent of correlation between glaciers snowlines and atmospheric variables is available on the Copernicus Climate Change Service (C3S) Climate Data Store via https://doi.org/10.24381/cds.6860a573, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview with credentials (Hersbach et al., 2019, 2020). As per the Copernicus C3S License, this work contains modified Copernicus Climate Change Service Information 2020. Neither the European Commission nor ECMWF are responsible for any aspect of this work or the use of their data within it. The NZ7S temperature data used to calculate the correlation of New Zealand weather station temperature data with global DJF ERA5 climate variables in the study are available on NIWA via https://niwa.co.nz/seven-stations (Mullan et al., 2010). However, the monthly chronology for each station used in this study (instead of for the average of all 7 stations) was not available on the public site, and had to be requested by email from NIWA Climate Scientist Stephen Stuart (Stephen.Stuart@niwa.co.nz). The HISTALP temperature data used to calculate the correlation of European Alps weather station temperature data with global DJF ERA5 climate variables in the study are available on ZAMG via https://www.zamg.ac.at/histalp/dataset/station/csv.php (Auer et al., 2007; "HISTALP," 2012). When downloading the data via CSV, we selected "regions (XR)" under the location dropdown, and downloaded the Mean Temperature of each region for the relevant years (1979–2017). The NOA, AO, and PNA climate indices data used for determining correlations with glacier annual ELA are available at the NOAA National Weather Service Climate Predition Center via https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml ("AO," 2020; "NAO," 2020; "PNA," 2020). The SAM climate index data used for determining correlations with glacier annual ELAs are available via https://doi.org/10.1175/1520-0442%282003%29016<4134%3ATITSAM>2.0.CO%3B2, https://legacy.bas.ac.uk/met/gjma/sam.html (Marshall, 2003; Marshall & NCAR Staff, 2018). Monthly signal SOI based on monthly standardization data used for determining correlations with glacier annual ELAs are provided by the Climate Analysis Section, NCAR, Boulder, USA, Trenberth (1984) via https://climatedataguide.ucar.edu/sites/default/files/2022-10/SOI.signal.txt (Trenberth & NCAR Staff, 2020). Updated regularly. The ONI climate index data used for determining correlations with glacier annual ELAs are available at the NOAA National Weather Service Climate Predition Center via https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php ("ONI," 2022). The PDO climate index data used for determining correlations with glacier annual ELAs are available at the NOAA National Centers for Environmental Information via https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat (Mantua, 1999; "PDO," 2021). The IPO climate index data used for determining correlations with glacier annual ELAs are available at the NOAA Physical Sciences Laboratory via https://doi.org/10.1007/s00382-015-2525-1, https://psl.noaa.gov/data/timeseries/IPOTPI/ (Henley et al., 2015). NAM Index Data used for determining correlations with glacier annual ELAs are provided by the Climate Analysis Section, NCAR, Boulder, USA via https://climatedataguide.ucar.edu/climate-data/hurrell-wintertime-slp-based-northern-annular-mode-nam-index (NCAR Staff (Eds), 2021). Updated regularly. The AMO climate index data used for determining correlations with glaciers are available at the NOAA Physical Sciences Laboratory via https://psl.noaa.gov/data/timeseries/AMO/ ("AMO," 2020; Enfield et al., 2001; Sutton & Hodson, 2005). The author(s) wish to acknowledge use of version 7.6 of the PyFerret program for preparation of ERA5 data, correlation analyses of ERA5 with glaciers, and production of graphics in this paper. PyFerret is a product of NOAA's Pacific Marine Environmental Laboratory. Information about downloading and installing the latest version is available at ferret.pmel.noaa.gov/ferret/ where the software is distributed under the Open Source Definition and developed openly at Github (More information is available at http://ferret.pmel.noaa.gov/Ferret/). Version 3.2.0 of the VAPOR software used for visualization of vertical structure of correlations between atmospheric variables and glacier snowlines is preserved at https://doi.org/10.5065/d6j38qhc, available via Apache v2.0 license (Visualization & Analysis Systems Technologies, 2020). Climate Reanalyzer was used for calculation and visualization of 1997–2012—1979–1996 climate anomalies in Figure S14 in Supporting Information S1 and is preserved at https://climatereanalyzer.org/reanalysis/monthly_maps/, Climate Change Institute, University of Maine, USA.

Acknowledgments

A. Audet was supported by a University of Maine teaching assistantship and the Quesada Family Fund. Andrew Lorrey was supported by NIWA's Strategic Science Investment Fund project CAOA2201 "Climate Present and Past". Andrew Mackintosh was supported by Australian Research Council (ARC) SRIEAS Grant 2R200100005, Securing Antarctica's Environmental Future. Brian Anderson was supported by Marsden Grant 17VUW094. This work was supported by a grant from the National Science Foundation (EAR 1903220). The authors thank three anonymous reviewers for their constructive comments.

References

Anderson, B., & Mackintosh, A. (2006). Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand. *Geology*, *34*(2), 121–124. https://doi.org/10.1130/G22151.1

Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A., & Fitzsimons, S. (2010). Climate sensitivity of a high-precipitation glacier in New Zealand. *Journal of Glaciology*, *56*(195), 114–128. https://doi.org/10.3189/002214310791190929

Arctic Oscillation. (2020). Arctic oscillation [Dataset]. Climate Prediction Center. Retrieved from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml

Atlantic Multidecadal Oscillation. (2020). Atlantic multidecadal oscillation index (AMO) [Dataset]. NOAA Physical Sciences Laboratory. Retrieved from https://psl.noaa.gov/data/timeseries/AMO/

Audet, A., Putnam, A. E., Russell, J., Lorrey, A., & Denton, G. H. (2022). Correlation of glacier ELA/snowlines & temperature station data with ERA5 temperature and wind speed, 1979 to 2017 [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.948198

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., et al. (2007). HISTALP - historical instrumental climatological surface time series of the Greater Alpine Region. *International Journal of Climatology*, *27*(1), 17–46. https://doi.org/10.1002/joc.1377

Barnston, A. G., & Livezey, R. E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review*, *115*(6), 1083–1126. https://doi.org/10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2

Chen, W. Y., & Van den Dool, H. (2003). Sensitivity of teleconnection patterns to the sign of their primary action center. *Monthly Weather Review*, *131*(11), 2885–2899. https://doi.org/10.1175/1520-0493(2003)131<2885:SOTPTT>2.0.CO;2

Chinn, T., Fitzharris, B. B., Willsman, A., & Salinger, M. J. (2012). Annual ice volume changes 1976-2008 for the New Zealand Southern Alps. *Global and Planetary Change*, *92–93*, 105–118. https://doi.org/10.1016/j.gloplacha.2012.04.002

Chinn, T., Winkler, S., Salinger, M. J., & Haakensen, N. (2005). Srecent glacier advances in Norway and New Zealand: A comparison of their glaciological and meteorological causes. *Geografiska Annaler - Series A: Physical Geography*, *87*(1), 141–157. https://doi.org/10.1111/j.0435-3676.2005.00249.x

Chinn, T. J. H. (1995). Glacier fluctuations in the Southern Alps of New Zealand determined from snowline elevations. *Arctic & Alpine Research*, *27*(2), 187. https://doi.org/10.2307/1551901

Clare, G. R., Fitzharris, B. B., Chinn, T. J. H., & Salinger, M. J. (2002). Interannual variation in end-of-summer snowlines of the Southern Alps of New Zealand, and relationships with Southern Hemisphere atmospheric circulation and sea surface temperature patterns. *International Journal of Climatology*, *22*(1), 107–120. https://doi.org/10.1002/joc.722

Cullen, N. J., Anderson, B., Sirguey, P., Stumm, D., Mackintosh, A., Conway, J. P., et al. (2017). An 11-year record of mass balance of Brewster Glacier, New Zealand, determined using a geostatistical approach. *Journal of Glaciology*, *63*(238), 199–217. https://doi.org/10.1017/jog.2016.128

Data Exploration. (2020). Data exploration [Dataset]. WGMS. Retrieved from https://wgms.ch/data_exploration/

Denton, G. H., Putnam, A. E., Russell, J. L., Barrell, D. J. A., Schaefer, J. M., Kaplan, M. R., & Strand, P. D. (2021). The Zealandia Switch: Ice age climate shifts viewed from Southern Hemisphere moraines. *Quaternary Science Reviews*, *257*, 106771. https://doi.org/10.1016/j.quascirev.2020.106771

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., et al. (2019). Two decades of glacier mass loss along the Andes. *Nature Geoscience*, *12*(10), 802–808. https://doi.org/10.1038/s41561-019-0432-5

Enfield, D. B., Mestas-Nuñez, A. M., & Trimble, P. J. (2001). The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters*, *28*(10), 2077–2080. https://doi.org/10.1029/2000GL012745

Fitzharris, B. B., Chinn, T. J., & Lamont, G. N. (1997). Glacier balance fluctuations and atmospheric circulation patterns over the Southern Alps, New Zealand. *International Journal of Climatology*, *17*(7), 745–763. https://doi.org/10.1002/(SICI)1097-0088(19970615)17:7<745::AID-JOC160>3.0.CO;2-Y

Fitzharris, B. B., Clare, G. R., & Renwick, J. (2007). Teleconnections between Andean and New Zealand glaciers. *Global and Planetary Change*, *59*(1–4), 159–174. https://doi.org/10.1016/j.gloplacha.2006.11.022

Goyal, R., Gupta, A. S., Jucker, M., & England, M. H. (2021). Historical and projected changes in the Southern Hemisphere surface westerlies. *Geophysical Research Letters*, *48*(4), 1–13. https://doi.org/10.1029/2020gl090849

Henley, B. J., Gergis, J., Karoly, D. J., Power, S., Kennedy, J., & Folland, C. K. (2015). A tripole index for the interdecadal Pacific oscillation [Dataset]. Physical Sciences Laboratory, *45*(11–12), 3077–3090. https://doi.org/10.1007/s00382-015-2525-1

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2019). ERA5 monthly averaged data on pressure levels from 1979 to present [Dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.6860a573

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

HISTALP. (2012). HISTALP [Dataset]. ZAMG. Retrieved from https://www.zamg.ac.at/histalp/dataset/station/csv.php

Hooker, B. L., & Fitzharris, B. B. (1999). The correlation between climatic parameters and the retreat and advance of Franz Josef Glacier, New Zealand. *Global and Planetary Change*, *22*(1–4), 39–48. https://doi.org/10.1016/S0921-8181(99)00023-5

Hurrell, J. W. (1995). Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. *Science*, *269*(5224), 676–679. https://doi.org/10.1126/science.269.5224.676

Huss, M., Hock, R., Bauder, A., & Funk, M. (2010). 100-year mass changes in the Swiss Alps linked to the Atlantic multidecadal oscillation. *Geophysical Research Letters*, *37*(10), 1–5. https://doi.org/10.1029/2010GL042616

Ivy-Ochs, S. (2015). Variaciones glaciares en los Alphs europoes al final de la última glaciación. *Cuadernos de Investigacion Geografica*, *41*(2), 295–315. https://doi.org/10.18172/cig.2750

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W., & Schlüchter, C. (2009). Latest pleistocene and holocene glacier variations in the European Alps. *Quaternary Science Reviews*, *28*(21–22), 2137–2149. https://doi.org/10.1016/j.quascirev.2009.03.009

Lorrey, A., Vargo, L., Purdie, H., Anderson, B., Cullen, N., Sirguey, P., et al. (2022). Southern Alps equilibrium line altitudes: Four decades of observations show coherent glacier-climate responses and a rising snowline trend. *Journal of Glaciology*, 1–14. https://doi.org/10.1017/jog.2022.27

Mackintosh, A. N., Anderson, B. M., Lorrey, A. M., Renwick, J. A., Frei, P., & Dean, S. M. (2017). Regional cooling caused recent New Zealand glacier advances in a period of global warming. *Nature Communications*, *8*(1), 14202. https://doi.org/10.1038/ncomms14202

Mantua, N. J. (1999). The Pacific Decadal Oscillation. A brief overview for non-specialists. In *To appear in the encyclopedia of environmental change*.

Marshall, G., & Staff, NCAR. (2018). Marshall southern Annular mode (SAM) index (Station-based) [dataset]. NCARClimate. Retrieved from https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based

Marshall, G. J. (2003). Trends in the southern Annular mode from observations and reanalyses. *Journal of Climate*, *16*(24), 4134–4143. https://doi.org/10.1175/1520-0442(2003)016<4134:TITSAM>2.0.CO;2

Marzeion, B., Hofer, M., Jarosch, A. H., Kaser, G., & Mölg, T. (2012). A minimal model for reconstructing interannual mass balance variability of glaciers in the European Alps. *The Cryosphere*, *6*(1), 71–84. https://doi.org/10.5194/tc-6-71-2012

Meier, M. F. (1962). Proposed definitions for glacier mass budget terms. *Journal of Glaciology*, *4*(33), 252–263. https://doi.org/10.3189/S0022143000027544

Menounos, B., Hugonnet, R., Shean, D., Gardner, A., Howat, I., Berthier, E., et al. (2019). Heterogeneous changes in Western North American glaciers linked to decadal variability in zonal wind strength. *Geophysical Research Letters*, *46*(1), 200–209. https://doi.org/10.1029/2018GL080942

Mullan, A. B., Stuart, S. J., Hadfield, M., & Smith, M. J. (2010). *Report on the review of NIWA's "seven-station" temperature series*. NIWA Information Series.

NCAR Staff. (Eds.). (2021). Hurrell wintertime SLP-based northern Annular mode (NAM) index [Dataset]. NCAR - Climate Data Guide. Retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-wintertime-slp-based-northern-annular-mode-nam-index

Nogami, M. (1972). The snow line and climate during the last glacial period in the Andes mountains. *The Quaternary Research (Daiyonki-Kenkyu)*, *11*(2), 71–80. https://doi.org/10.4116/jaqua.11.71

North Atlantic Oscillation. (2020). North Atlantic oscillation [Dataset]. Climate Prediction Center. Retrieved from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml%23publication

Oceanic Niño Index. (2022). Oceanic Niño index (ONI) [Dataset]. Climate Prediction Center. Retrieved from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Oerlemans, J. (1997). Climate sensitivity of Franz Josef Glacier, New Zealand, as revealed by numerical modeling. *Arctic and Alpine Research*, *29*(2), 233. https://doi.org/10.2307/1552052

Oerlemans, J. (2005). Atmospheric science: Extracting a climate signal from 169 glacier records. *Science*, *308*(5722), 675–677. https://doi.org/10.1126/science.1107046

Oerlemans, J., & Fortuin, J. P. F. (1992). Sensitivity of glaciers and small ice caps to greenhouse warming. *Science*, *258*(5079), 115–117. https://doi.org/10.1126/science.258.5079.115

Pacific Decadal Oscillation. (2021). Pacific decadal oscillation (PDO) [Dataset]. National Centers for Environmental Information (NCEI). Retrieved from https://www.ncdc.noaa.gov/teleconnections/pdo/

Pacific North American Pattern. (2020). Pacific North American pattern [Dataset]. Climate Prediction Center. Retrieved from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna.shtml

Pelto, M. S. (2010). Forecasting temperate alpine glacier survival from accumulation zone observations. *The Cryosphere*, *4*(1), 67–75. https://doi.org/10.5194/tc-4-67-2010

Putnam, A. E., Schaefer, J. M., Denton, G. H., Barrell, D. J. A., Birkel, S. D., Andersen, B. G., et al. (2013). The last glacial maximum at 44°S documented by a 10Be moraine chronology at lake ohau, southern Alps of New Zealand. *Quaternary Science Reviews*, *62*, 114–141. https://doi.org/10.1016/j.quascirev.2012.10.034

Putnam, A. E., Schaefer, J. M., Denton, G. H., Barrell, D. J. A., Finkel, R. C., Andersen, B. G., et al. (2012). Regional climate control of glaciers in New Zealand and Europe during the pre-industrial Holocene. *Nature Geoscience*, *5*(9), 627–630. https://doi.org/10.1038/ngeo1548

Rabatel, A., Letréguilly, A., Dedieu, J.-P., & Eckert, N. (2013). Changes in glacier equilibrium-line altitude in the Western Alps from 1984 to 2010: Evaluation by remote sensing and modeling of the morpho-topographic and climate controls. *The Cryosphere*, *7*(5), 1455–1471. https://doi.org/10.5194/tc-7-1455-2013

Reynhout, S. A., Sagredo, E. A., Kaplan, M. R., Aravena, J. C., Martini, M. A., Moreno, P. I., et al. (2019). Holocene glacier fluctuations in Patagonia are modulated by summer insolation intensity and paced by Southern Annular Mode-like variability. *Quaternary Science Reviews*, *220*, 178–187. https://doi.org/10.1016/j.quascirev.2019.05.029

RGI Consortium. (2017). Randolph Glacier inventory – A dataset of global glacier outlines: Version 6.0: Technical report [Dataset]. Digital Media. https://doi.org/10.7265/N5-RGI-60

Russell, J. L., Dixon, K. W., Gnanadesikan, A., Stouffer, R. J., & Toggweiler, J. R. (2006). The Southern hemisphere westerlies in a warming world: Propping open the door to the deep ocean. *Journal of Climate*, *19*(24), 6382–6390. https://doi.org/10.1175/JCLI3984.1

Russell, J. L., & Wallace, J. M. (2004). Annual carbon dioxide drawdown and the Northern Annular mode. *Global Biogeochemical Cycles*, *18*(1), 1–8. https://doi.org/10.1029/2003gb002044

Salinger, M. J., Fitzharris, B. B., & Chinn, T. (2019). Atmospheric circulation and ice volume changes for the small and medium glaciers of New Zealand's Southern Alps mountain range 1977–2018. *International Journal of Climatology*, *39*(11), 4274–4287. https://doi.org/10.1002/joc.6072

Sutton, R. T., & Hodson, D. L. R. (2005). Ocean science: Atlantic Ocean forcing of North American and European summer climate. *Science*, *309*(5731), 115–118. https://doi.org/10.1126/science.1109496

Thompson, D. W. J., Wallace, J. M., & Hegerl, G. C. (2000). Annular modes in the extratropical circulation. Part II: Trends. *Journal of Climate*, *13*(5), 1018–1036. https://doi.org/10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2

Toggweiler, J. R., & Russell, J. (2008). Ocean circulation in a warming climate. *Nature*, *451*(7176), 286–288. https://doi.org/10.1038/nature06590

Trenberth, K. (1984). *SOI data provided by the climate analysis section*. NCAR. Retrieved from https://climatedataguide.ucar.edu/sites/default/files/2022-10/SOI.signal.txt

Trenberth, K., & National Center for Atmospheric Research Staff. (Eds.). (2020). Southern oscillation indices: Signal, noise and tahiti/Darwin SLP (SOI) [Dataset]. The Climate Data Guide.Retrieved from https://climatedataguide.ucar.edu/climate-data/southern-oscillation-indices-signal-noise-and-tahitidarwin-slp-soi

Tyson, P. D., Sturman, A. F., Fitzharris, B. B., Mason, S. J., & Owens, I. F. (1997). Circulation changes and teleconnectioxs between glacial advances on the west coast of New Zealand and extended spells of drought years in South Africa. *International Journal of Climatology*, *17*(14), 1499–1512. https://doi.org/10.1002/(SICI)1097-0088(19971130)17:14<1499::AID-JOC207>3.0.CO;2-O

Van Den Dool, H. M., Saha, S., & Johansson, Å. (2000). Empirical orthogonal teleconnections. *Journal of Climate*, *13*(8), 1421–1435. https://doi.org/10.1175/1520-0442(2000)013<1421:EOT>2.0.CO;2

Visualization & Analysis Systems Technologies. (2020). Visualization and analysis Platform for Ocean, atmosphere, and solar Researchers: (VAPOR version 3.2.0) [Software]. UCAR/NCAR - Computational and Information System Lab. https://doi.org/10.5065/d6j38qhc

WGMS. (2017). Global glacier change bulletin No. 2 (2014-2015). https://doi.org/10.5904/wgms-fog-2018-11

Willsman, A., Chinn, T., & Marcara, G. (2015). New Zealand Glacier Monitoring: End of summer snowline Survey 2015. Retrieved from https://niwa.co.nz/climate/research-projects/climate-present-and-past/southern-alps-glaciers/end-of-summer-snowline-survey

Willsman, A., & Macara, G. (2022). New Zealand Glacier Monitoring: End of summer snowline Survey 2020.

Zhou, S., Miller, A. J., Wang, J., & Angell, J. K. (2001). Trends of NAO and AO and their associations with stratospheric processes. *Geophysical Research Letters*, *28*(21), 4107–4110. https://doi.org/10.1029/2001GL013660

References From the Supporting Information

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., et al. (2011). Glossary of glacier mass balance and related terms. In *IHP-VII technical documents in hydrology No. 86, IACS contribution No. 2*. UNESCO-IHP.

Dowson, A. J., Sirguey, P., & Cullen, N. J. (2020). Variability in glacier albedo and links to annual mass balance for the gardens of Eden and Allah, Southern Alps, New Zealand. *The Cryosphere*, *14*(10), 3425–3448. https://doi.org/10.5194/tc-14-3425-2020