Thermal State of Permafrost in the Central Andes (27°S-34°S)

Cassandra E.M. Koenig[1,2], Christin Hilbich[1], Christian Hauck[1], Lukas U. Arenson[3] & Pablo Wainstein[4]

[1]Department of Geosciences, University of Fribourg, Fribourg, Switzerland
[2]BGC Engineering Inc., Toronto, ON, Canada
[3]BGC Engineering Inc., Vancouver, BC, Canada
[4]BGC Engineering Inc., Calgary, AB, Canada

Correspondence to: Cassandra Koenig (cassandra.koenig@unifr.ch)~~(cassandra.koenig@unifr.ch)~~

Abstract

Permafrost ~~The importance of monitoring the~~ thermal state is poorly understood~~of permafrost has been widely acknowledged due to the numerous hazards associated with permafrost degradation under climate change. International collaborative efforts are~~ in ~~place to collate standardized permafrost monitoring data, with the goal of establishing baselines and early warning systems for potential consequences of large-scale permafrost loss. Most of these data have been compiled from circumpolar regions and mountain environments in the Northern Hemisphere, with a scarcity of ground temperature monitoring data in~~ South America compared to other regions due to ~~. To date, this lack of data has~~ limited in-situ data.~~the understanding of the thermal state and possible degradation of mountain permafrost in Chile and Argentina.~~ This study represents the first coordinated regional compilation of borehole~~effort to compile and examine trends within ground~~ temperature data from high-altitude mountain permafrost sites in the Central Andes (~~(i.e.,~~ 3,500 m to 5,250 m, 27°S-34°S) to examine baseline ground thermal conditions. Measurements~~500 m) mountain permafrost regions of the Central Andes. Ground temperature measurements were available~~ from 53 boreholes ~~installed by the private sector~~ along a north-south transect at the Chilean-Argentine border reveal ground thermal~~(between 27°S and 34°S), within cold and warm permafrost, as well as in non-permafrost zones. The dataset reveals similarities in ground temperature~~ characteristics similar to~~with~~ other mountain permafrost regions, including high spatial and temporal variability, correlations with altitude and slope aspect, and distinct~~unique~~ thermal attributes of rock glaciers. Observations~~These observations~~ suggest that the ground thermal regime of the Central Andes is shaped by similar processes as~~similar to those of~~ other mountain environments~~permafrost regions~~, a perspective that was~~hypothesis~~ previously lacking data support. The~~proposed but not widely supported with data until now. With the longest record in the dataset spanning 9 years, it is currently not possible to determine whether ground temperatures are increasing in response to atmospheric warming. Instead, the~~ high temporal variability observed in the short records (<9 years)~~data likely~~ reflects short-term microclimatic ~~micro-climatic~~ fluctuations and topo-climatic attributes unique to the Andean cryosphere. This includes~~ — including~~ hyper-arid conditions, intense solar radiation, limited~~lack of~~ vegetative cover and organic matter, less massive ice (except for rock glaciers), and mountain topography in a southern hemisphere location. The susceptibility of the area to regional climatic phenomena (such as SAM, ENSO and PDO) suggests~~implies~~ that long-term trends may only be determined~~discernible~~ from extended datasets spanning several decades. This study highlights the need for

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~continuous and~~ ongoing ground temperature monitoring~~, of ground temperatures in the region. The study itself represents a unique~~ and the importance of ~~noteworthy~~ collaboration between ~~private~~ industry, governments, and scientists to advance ~~, towards the advancement of~~ understanding of a key climate change indicator in a data-scarce region ~~with a paucity of ground-based data~~.

1 Introduction

Permafrost is an Essential Climate Variable (ECV) that serves as~~within the Global Climate Observing System (GCOS) and~~ a cryospheric indicator of climate change (WMO, 2016; Streletskiy et al., 2017). Several studies have documented large-scale warming and thawing of permafrost in recent decades (e.g., Romanovsky et al., 2017; Derksen et al., 2019; Etzelmüller et al., 2020; Haberkorn et al., 2021; Nyland et al., 2021). Current research suggests that permafrost will continue to warm in many regions in the near term (i.e., 2031-2050) due to projected global increases in surface air temperatures, with acceleration expected~~which could accelerate~~ in the second half of the 21st century under extreme shared socioeconomic pathway ~~(SSP)~~ scenarios (Abram et al., 2019).

Baseline permafrost monitoring data is essential for risk-informed engineering design and environmental impact assessments of resource development projects. In mountain regions, near~~Near~~-surface (i.e., 0-10 m) thawing of permafrost ~~is known to~~ significantly affects~~impact~~ land stability, causing subsidence~~, and~~ slope failures, and ~~releasing~~ water release from ice-rich landforms ~~in mountainous environments~~ (Gruber and Haeberli, 2007; Krautblatter et al., 2010; Romanovsky et al., 2017; Kokelj et al., 2017). In Arctic and boreal regions, where permafrost soils store significant amounts of organic carbon (e.g. Schuur et al., 2009), permafrost thaw may amplify surface warming via~~through~~ the permafrost carbon-climate feedback (Schaefer et al., 2014; Koven et al., 2015; Schuur et al., 2015; Miner et al., 2022; Schuur et al., 2022). Understanding the present and potential future thermal conditions of permafrost is therefore essential for guiding ~~the development of~~ robust infrastructure development and mitigating environmental risks in the face of climate change.

Two important parameters for characterizing and monitoring permafrost~~the~~ thermal state ~~of permafrost~~ are 1) active layer thickness (ALT), or depth to permafrost; and 2) ground temperature measured at or below the depth of zero annual amplitude (DZAA). The active layer, classically defined as the layer above permafrost that freezes and thaws annually (van Everdingen, 1998), delineates the depth to the top of permafrost ~~table~~ when measured at the time of maximum annual thaw. This is ~~distinct from the thermally defined active layer in permafrost regions, which is the distance from the ground surface to the DZAA and~~ not necessarily the same as the depth to the permafrost table particularly where permafrost is degrading and a talik has formed.~~associated with annual phase change (Dobiński, 2020).~~ The DZAA represents the ~~minimum~~ depth at which seasonal temperature variations are fully attenuated by the ground~~, and are no longer observable. It is~~ often defined as the depth where ~~seasonal~~ amplitudes diminish to 0.1°C or less (van Everdingen, 1998). Ground temperature ~~measured~~ at or below the DZAA is therefore considered a good indicator of long-term permafrost thermal state because it represents the mean annual temperature of the ground over time (Lachenbruch and Marshall, 1986). Active layer thickness and temperature at the DZAA

Formatted: English (United Kingdom), Pattern: Clear

Formatted: English (United Kingdom), Pattern: Clear

Formatted: English (United Kingdom)

are both affected by climate change, particularlychanging climatic conditions, specifically rising air temperatures, and changes to precipitation patterns andthat impact temporal snow distribution, which influence heat in turn strongly influences the transfer of heat from above the ground surface to the subsurfacedepth (Isaksen et al., 2007; Christiansen et al., 2010; Biskaborn et al., 2019).

Most sites gatheringThe importance of monitoring permafrost thermal state on a global scale has been widely recognized (Biskaborn et al., 2015; Smith et al., 2022), and international efforts have been established to gather standardized permafrost temperature data are monitoring data of this kind. Most monitoring sites providing data to these programs are in polar and high mountain areas of North America, and Europe and Russia/Siberia, with fewer sites located in Russia, Central Asia, and Antarctica , and South America (e.g., Smith et al., 2022). Two examples of collaborative programs collecting permafrost temperature data are the Global Terrestrial Network for Permafrost (GTN-P) (Biskaborn et al., 2015) and the Swiss Permafrost Monitoring Network (PERMOS, 2019). In addition, ALT measurements have been collated as part of the Circumpolar Active Layer Monitoring (CALM) network since the 1990s in the Arctic, Antarctic, and at many high elevation and mountain permafrost regions (; Brown et al., 2000; PERMOS, 2019)). Regional syntheses of these ground temperature and ALT data have provided documentation of permafrost thermal state at. At some locations, permafrost thermal state has been documented continuously for up to 40 years (e.g., Romanovsky, et al., 2010b), showingwith many sites presenting evidence of increasing permafrost temperatures, particularly in the Arctic (Romanovsky et al., 2010a). However, Despite the progress towards a global synthesis of permafrost thermal state and trends with time, challenges remain in assessing linkages to long-term changes in response to climateclimatic change remains challenging at many locations due to sparse borehole distribution and short ora general paucity of ground temperature monitoring boreholes, which are often sparsely distributed within permafrost regions and can have discontinuous monitoring records. These challenges often arise from that are also limited in duration (Biskaborn et al., 2019; Smith et al., 2022). Common reasons for this include site access difficulties, and high installation and maintenance costs and the narrow focus. Unique objectives of monitoring programs, particularlyindividual instruments can also limit data collection coverage, especially in mountain permafrost regions (e.g.,(Biskaborn et al., 2019; Noetzli et al., 2021; Smith et al., 2022).).

The lack of ground temperature monitoring data in permafrost research, especially at depths beyondgreater than a few metres, is particularly evidentpronounced in South America, where. Here, permafrost isregions are largely understudied compared to other regions of the world (Arenson et al., 2022). Despite a long-standing , despite an established awareness of the existence of permafrost in the Andes for many decades (e.g. ,Catalano, 1926; Corte 1953). Ground, ground-based studies remain limitedin this region tend to be scarce due to the region's high elevations, harsh climate and, rugged terrain. Challenges such as limited funding and inadequate , and lack of infrastructure for accessingto access remote locations further complicate, which make data acquisitionextremely challenging to obtain (Arenson and Jakob, 2010; Hilbich et al., 2022; Mathys et al., 2022). While some ground temperature monitoring studies in the Andes have been published (e.g., Trombotto et al., 1997; Trombotto and Borzotta, 2009; DGA, 2010; Andrés et al., 2011; Monnier and Kinnard, 2013; Atacama Ambiente, 2017; DGA, 2019; Nagy et al., 2019; Yoshikawa et al., 2020; Mena et al., 2021; Vivero et al., 2021; Table 1), most instruments have not been

Formatted: Font color: Black

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

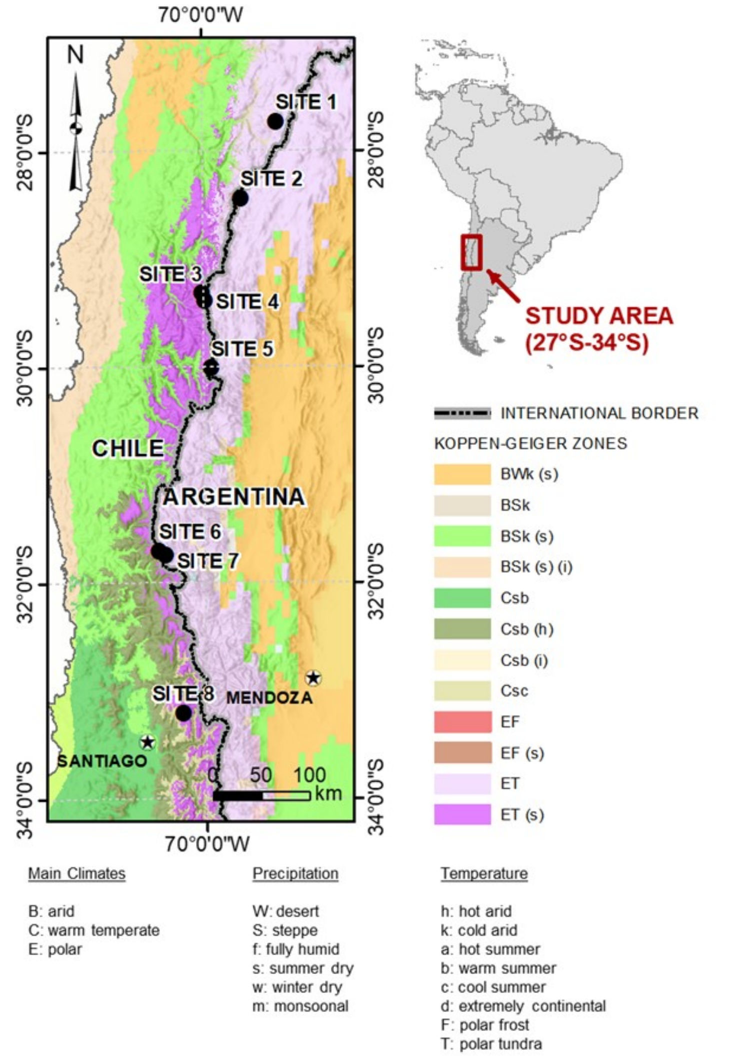
established for the explicit purpose of monitoring permafrost thermal change with time. Consequently, monitoring records oftenin the region tend to lack the necessary duration and depth required to discern average ground temperatures or trends in warming/cooling trends below the DZAA, limiting characterizationcomparisons of the ground thermal state in the Andes compared towith other regions where large-scale permafrost degradation has been extensively documented. Manyis evident. For example, many ground temperature monitoring studies in South America have focused on estimating the lower regional altitude of permafrost, collecting and thus only collected temperature measurements only up to depths of one metre deep and over periods shorterof less than five years (Andrés et al., 2011; Nagy et al., 2019; Yoshikawa et al., 2020; Mena et al., 2021; Vivero et al., 2021). This lack of deeper measurements monitoring data from deep boreholes has been acknowledged to a certain degree in a proposed permafrost national monitoring plan for Chile (DGA, 2019), which recommendsincludes recommendations for long-term monitoring of permafrost sites using boreholes extendingideally installed to the base of permafrost. However, no installations under this plan have not exceeded 2 m in depth to date (Table 1).

SomeOn the other hand, some permafrost studies in the Andes have utilized deeper boreholes to characterize permafrost thermal conditions and to monitordocument changes in temperature over time. For example, Trombotto and Borzotta (2009) documentedrevealed permafrost degradation inof a rock glacier in Argentina through a temperature monitoring record in a 5-m-deep borehole over a span of nearly 10 years, with an annual increases in ALT deepening of the active layer by up to 25 cm. Monnier and Kinnard (2013) reported findings from the installation of two boreholes with thermistor strings reaching 18-25 mintended for ground temperature monitoring in the upper Choapa valley of northern Chile. These boreholes are equipped with thermistor strings reaching depths of 18 m and 25 m. Monitoring of the 25-m-deep borehole between 2010 and 2013 showedhas consistently shown stable temperatures near 0°Cclose to the melting point of ground ice along the profile, (i.e., 0°C), with an active layer estimated to range between 5-7 m thickdeep (Monnier and Kinnard, 2013). Preliminary data from In a third study by Atacama Ambiente (2017), approximately nine months of ground temperature measurements from three boreholes (20-40 m deep) installed to depths ranging from 20-40 m at the Goldfields Salares Norte mining project in Chile, were reported. The preliminary data from these boreholes indicated favorable conditions for the presence of permafrost between approximately 5 m and 13 m depth at one boreholelocation, with the other two boreholes installed in unfrozen ground (Atacama Ambiente, 2017). AlthoughWhile these six boreholes (only four of which are in permafrost) reported from three studies provideoffer valuable insights into the thermal state and changes to permafrost, the fact that they represent the bulk of time-series measurements of ground temperatures in South America at depths greater than 2 m, emphasizes the absence of an Andes-wide data repository akin to what is available for the northern hemisphere. This lack of coordinated effort to compile continuous ground temperature monitoring data from sufficient depths hampers the development of a comparable understanding of permafrost dynamics across the region.

Given theseDespite the limitations highlighted in the preceding discussions, a unique opportunity currently exists to advance knowledge of permafrost thermal state in South America through collaboration between researchers and private industry. This is especially true in the border area of Chile and Argentina, which holds significant reserves of precious metals and other natural resources at different stages of exploration, extraction, and development. ScientificSite investigations, that often

Formatted: English (United Kingdom)

including the~~include~~ collection of ground temperature data in permafrost zones, are necessary to support environmental permitting and engineering designs. These investigations generate~~Such monitoring generates~~ valuable data that can help~~be used to~~ assess the ground thermal regime in regions that~~which~~ have not yet been characterized~~to be documented~~ and shared with the broader research community. In this study, subsurface thermal conditions along a North-South transect in the ~~semi-arid~~ Central Andes (27°S-34°S) were examined by summarizing ground temperature data from a suite of boreholes installed by the private sector at eight distinct industrial project sites (Figure 1). The data were provided~~Temperature measurements presented herein were made available~~ to the authors by BGC Engineering Inc., with ~~the~~ permission of the individual project owners. The dataset was~~data were~~ accompanied by confidential field notes and reports detailing~~containing relevant information regarding~~ instrumentation and ~~general~~ site conditions ~~during monitoring~~ to support the interpretations presented.~~ in this study.~~ All instruments were ~~monitoring instrumentation was~~ installed for environmental impact assessments ~~(EIAs)~~ or engineering design studies prior to the preparation of this paper.



70°0'0"W
N
SITE 1
SITE 2
SITE 3
SITE 4
SITE 5
SITE 6
SITE 7
SITE 8
CHILE
ARGENTINA
MENDOZA
SANTIAGO
28°0'0"S
30°0'0"S
32°0'0"S
34°0'0"S
0 50 100 km
70°0'0"W
STUDY AREA
(27°S-34°S)
INTERNATIONAL BORDER
KOPPEN-GEIGER ZONES
BWk (s)
BSk
BSk (s)
BSk (s) (i)
Csb
Csb (h)
Csb (i)
Csc
EF
EF (s)
ET
ET (s)
Main Climates
B: arid
C: warm temperate
E: polar
Precipitation
W: desert
S: steppe
f: fully humid
s: summer dry
w: winter dry
m: monsoonal
Temperature
h: hot arid
k: cold arid
a: hot summer
b: warm summer
c: cool summer
d: extremely continental
F: polar frost
T: polar tundra

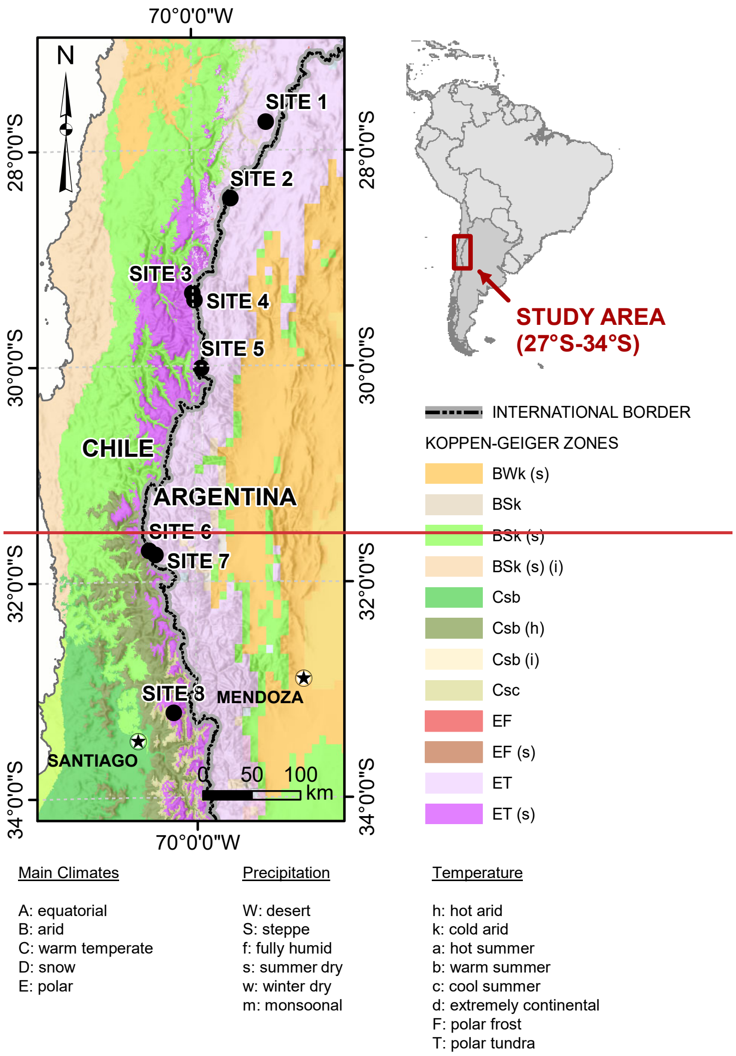


Figure 1: Ground temperature monitoring locations and regional climatic setting. Koppen-Geiger zones are based on Kottek et al., (2006) **for Argentina and** Sarricolea et al., (2017) **for Chile.**

Citation	Site Location	Approx. Lat / Long	No. Boreholes	Landform / Surface Substrate	Monitoring Location Name	Max. Measurement Depth (m)	Elevation (m)	Monitoring Period	Comments
Trombotto et al. (1997); Trombotto & Borzotta (2009)	Cordón del Plata range (Argentina)	32°54'S-33°01S / 69°27'W-69°15W	2	Morenas Coloradas Rock Glacier	Balcón I	5	3,560	1989-1992 + 5 manual measurements collected in summers of 2004-2008	Inactive thermokarst (average temperature ~0°C; seasonal variation correlates with measured discharge; estimated deepening ~25 cm per year)
					Balcón II	3	3,770	2001-2007	Morenas Coloradas rock glacier, active thermokarst (permafrost deepening ~15 cm per year between 2002-2004)
DGA (2010)	Elqui River Catchment, La Laguna basin, Coquimbo (Chile) - Cerro Tapado, Topado Complex	30°06'S-33°24S / 69°59'W	2	Llano de las Liebres Rock Glacier	Liebres 1	2.7	4,050	Apr-Dec 2010	Permafrost (if present) is below deepest sensor and estimated to be at least 3m deep
					Liebres 2	7.4	3,786	Apr-Dec 2010	Permafrost (if present) is below deepest sensor and estimated to be at least 8m deep
DGA (2010); Vivero et al. (2021)	Elqui River Catchment, La Laguna basin, Coquimbo (Chile) - Cerro Tapado, Topado Complex	30°06'S-33°24S / 69°59'W	2	del Topado Rock Glacier	BH1 (Tapado 1)	2	4,440	2011-2015	Permafrost (if present) is below deepest sensor and estimated to be at least 3m deep
					BH2 (Tapado 2)	2.4	4,405	2011-2015	Permafrost (if present) is below deepest sensor and estimated to be at least 2.6m deep
Andres et al. (2011)	Chachani volcanic complex (Peru)	16°11S / 71°31'W	3	Slope of Chachani Volcano	CHACHA-1	1.2	4,850	2007-2008	--
					CHACHA-2	1.2	4,976	2007-2008	--
					CHACHA-3	1.2	5,331	2007-2008	Possible permafrost location
Monnier & Kinnard (2013)	Andes Rock Glacier, upper Choapa valley (Chile)	31°48S / 70°30'W	2	Quebrads Noroeste Rock Glacier	DDH2010-1	25.0	3,767	2010-2011	5–7m thick active layer
Centro de Estudios Avanzados en Zonas Áridas					DDH2010-2	18.0	~3,800	2010-2011	Measurements only performed 3 times per year
Atacama Ambiente (2017)	Goldfields Salares Norte Project (Chile)	27°S / 68° W	3	--	SNDD034	22.0	4,705	Mar-Dec 2017	Manual monthly measurements, non-permafrost borehole
					SNGET008	21.5	4,472	Mar-Dec 2017	Manual monthly measurements, non-permafrost borehole
					SNGET027	40.0	4,580	Mar-Dec 2017	Manual monthly measurements, permafrost from ~5-13 m deep

Citation	Site Location	Approx. Lat / Long	No. Boreholes	Landform / Surface Substrate	Monitoring Location Name	Max. Measurement Depth (m)	Elevation (m)	Monitoring Record Length	Comments
Trombotto et al. (1997); Trombotto & Borzotta (2009)	Cordón del Plata range (Argentina)	32°54'S-33°01S / 69°27'W-69°15W	2	Morenas Coloradas Rock Glacier	Balcón I	5	3,560	1989-1992 + 5 manual measurements collected in summers of 2004-2008	Inactive thermokarst (average temperature ~0°C; seasonal variation correlates with measured discharge; estimated deepening ~25 cm per year)
					Balcón II	3	3,770	2001-2007	Morenas Coloradas rock glacier, active thermokarst (permafrost deepening ~15 cm per year between 2002-2004)
DGA (2010)	Elqui River Catchment, La Laguna basin, Coquimbo (Chile) - Cerro Tapado, Topado	30°06'S-33°24S / 69°59'W	2	Llano de las Liebres Rock Glacier	Liebres 1	2.7	4,050	Apr-Dec 2010	Permafrost (if present) is below deepest sensor and estimated to be at least 3m deep
					Liebres 2	7.4	3,786	Apr-Dec 2010	Permafrost (if present) is below deepest sensor and estimated to be at least 8m deep
DGA (2010); Vivero et al. (2021)	Elqui River Catchment, La Laguna basin, Coquimbo (Chile) - Cerro Tapado, Topado Complex	30°06'S-33°24S / 69°59'W	2	del Topado Rock Glacier	BH1 (Tapado 1)	2	4,440	2011-2015	Permafrost (if present) is below deepest sensor and estimated to be at least 3m deep
					BH2 (Tapado 2)	2.4	4,405	2011-2015	Permafrost (if present) is below deepest sensor and estimated to be at least 2.6m deep
Andres et al. (2011)	Chachani volcanic complex (Peru)	16°11S / 71°31'W	3	Slope of Chachani Volcano	CHACHA-1	1.2	4,850	2007-2008	--
					CHACHA-2	1.2	4,976	2007-2008	--
					CHACHA-3	1.2	5,331	2007-2008	Possible permafrost location
Monnier & Kinnard (2013) Centro de Estudios Avanzados en Zonas Áridas (CEAZA)	Andes Rock Glacier, upper Choapa valley (Chile)	31°48S / 70°30'W	2	Quebrads Noroeste Rock Glacier	DDH2010-1	25.0	3,767	2010-2011	5–7m thick active layer
					DDH2010-2	18.0	~3,800	2010-2011	Measurements only performed 3 times per year
Atacama Ambiente (2017)	Goldfields Salares Norte Project (Chile)	27°S / 68° W	3	--	SNDD034	22.0	4,705	Mar-Dec 2017	Manual monthly measurements, non-permafrost borehole
					SNGET008	21.5	4,472	Mar-Dec 2017	Manual monthly measurements, non-permafrost borehole
					SNGET027	40.0	4,580	Mar-Dec 2017	Manual monthly measurements, permafrost from ~5-13 m deep
DGA (2019)	Tupungatito Volcano (Chile)	33°S / 69° W	2	Rocky ridge, near Tupungatito glacier	Tupungatito A	2.0	5,575	23-Dec-19	--
				Rocky ridge, part of a lava flow from the Tupungatito volcano	Sitio B, Tupungatito	1.2	4,425	24-Dec-19	--
	Glaciar Bello (Chile)	33°S / 70°W	1	100 m NW of Bello Glacier	Bello	1.7	4,840	--	No measurements published in report
Nagy et al. (2019)	Mt. Ojos del Salado (Chile)	26°56'S-27°29'S / 68°32'W-69°15'W	6	Debris Covered Plateau	Laguna Negro Francisco	0.6	4,200	2014-2016	--
					Murray Lodge	0.35	4,550	2014-2016	--
					Atacama Camp	0.6	5,260	2012-2016	Possible permafrost borehole
					Tejos Camp	0.6	5,830	2012-2016	Possible permafrost borehole
					Crater Edge	0.2	6,750	2012-2016	Possible permafrost borehole
					Mt. Ojos del Salado summit	0.1	6,893	2012-2016	Possible permafrost borehole
Yoshikawa et al. (2020)	Coropuna volcanic complex (Peru)	15°32S / 72°32'W	15	Hydrothermally Altered Lava	Coropuna-N3	0.3	5,694	2012-2019	--
					Coropuna-N2	0.3	5,564	2012-2019	--
					Coropuna-S4	0.3	5,100	2012-2019	--
					Coropuna-S3	0.3	5,053	2012-2019	--
					Coropuna-N1	0.3	4,886	2012-2019	--
					Coropuna-S2	0.3	4,711	2012-2019	--
					Coropuna-S1	0.3	4,247	2012-2019	--
					Coropuna-Borehole	3	5,170	2012-2019	--
	Chachani volcanic complex (Peru)	16°13S / 71°29'W			CHACHANI-CH3	0.3	4,711	2012-2019	--
					CHACHANI-Borehole	4	5,331	2012-2019	Possible permafrost borehole
					CHACHANI-Borehole surface	0.02	5,331	2012-2019	Possible permafrost borehole
					CHACHANI-South facing	1	5,329	2012-2019	Possible permafrost borehole
					CHACHANI-Higher albedo	1	5,323	2012-2019	Possible permafrost borehole
					CHACHANI-CH2	0.3	4,700	2012-2019	--
					CHACHANI-CH1	0.3	4,200	2012-2019	--
Mena et al. (2021)	Chajnantor Volcano, Atacama (Chile)	22°59S / 67°43'W	1	Slope of Chajnantor Volcano	--	14	5,640	2019	Permafrost borehole, 5 m thick, gradient of 200°C/km; ALT ~ 14 cm

Table 1: Previously published ground temperature monitoring studies in permafrost regions of the Andes.

Formatted: English (United States)

Table 1 (cont.): Previously published ground temperature monitoring studies in permafrost regions of the Andes.

Citation	Site Location	Approx. Lat / Long	No. Boreholes	Landform / Surface Substrate	Monitoring Location Name	Max. Measurement Depth (m)	Elevation (m)	Monitoring Period	Comments
DGA (2019)	Tupungatito Volcano (Chile)	33°S / 69° W	2	Rocky ridge, near Tupungatito glacier	Tupungatito A	2.0	5,575	23-Dec-19	--
				Rocky ridge, part of a lava flow from the Tupungatito volcano	Sitio B, Tupungatito	1.2	4,425	24-Dec-19	--
	Glaciar Bello (Chile)	33°S / 70°W	1	100 m NW of Bello Glacier	Bello	1.7	4,840	--	No measurements published in report
Nagy et al. (2019)	Mt. Ojos del Salado (Chile)	26°56'S-27°29'S / 68°32'W-69°15'W	6	Debris Covered Plateau	Laguna Negro Francisco	0.6	4,200	2014-2016	--
					Murray Lodge	0.35	4,550	2014-2016	--
					Atacama Camp	0.6	5,260	2012-2016	Possible permafrost borehole
					Tejos Camp	0.6	5,830	2012-2016	Possible permafrost borehole
					Crater Edge	0.2	6,750	2012-2016	Possible permafrost borehole
					Mt. Ojos del Salado summit	0.1	6,893	2012-2016	Possible permafrost borehole
Yoshikawa et al. (2020)	Coropuna volcanic complex (Peru)	15°32S / 72°32'W	15	Hydrothermally Altered Lava	Coropuna-N3	0.3	5,694	2012-2019	--
					Coropuna-N2	0.3	5,564	2012-2019	--
					Coropuna-S4	0.3	5,100	2012-2019	--
					Coropuna-S3	0.3	5,053	2012-2019	--
					Coropuna-N1	0.3	4,886	2012-2019	--
					Coropuna-S2	0.3	4,711	2012-2019	--
					Coropuna-S1	0.3	4,247	2012-2019	--
					Coropuna-Borehole	3	5,170	2012-2019	--
	Chachani volcanic complex (Peru)	16°13S / 71°29'W			CHACHANI-CH3	0.3	4,711	2012-2019	--
					CHACHANI-Borehole	4	5,331	2012-2019	Possible permafrost borehole
					CHACHANI-Borehole surface	0.02	5,331	2012-2019	Possible permafrost borehole
					CHACHANI-South facing	1	5,329	2012-2019	Possible permafrost borehole
					CHACHANI-Higher albedo	1	5,323	2012-2019	Possible permafrost borehole
					CHACHANI-CH2	0.3	4,700	2012-2019	--
					CHACHANI-CH1	0.3	4,200	2012-2019	--
Mena et al. (2021)	Chajnantor Volcano, Atacama (Chile)	22°59S / 67°43'W	1	Slope of Chajnantor Volcano	--	14	5,640	2019	Permafrost borehole, 5 m thick, gradient of 200°C/km; ALT ~ 14 cm

2 Regional Setting

The study area is located in the Central Andes ~~region~~ (27°S-34°S, Figure 1), where the climate is strongly influenced by ~~interactions between~~ the southeast Pacific anticyclone (SEPA), ~~) and~~ the Humboldt Current, and~~as well as~~ barrier effects of the mountains.~~mountainous terrain.~~ Cold,~~ and~~ humid westerlies associated with the Humboldt Current are diverted northward by the SEPA, while the Andes deflect~~Andean Mountain range deflects~~ Pacific air masses upwards and limit~~limits the~~ westward flow~~advection~~ of moist air from the Amazon basin (Masiokas et al., 2020; Schulz et al., 2012). This creates~~results in~~ the region's characteristic hyper-arid climate ~~of the region~~ and orographic precipitation, which peaks~~ that reaches its peak~~ in the austral winter (June to August)~~),~~ falling predominantly as snow. Average annual precipitation ~~across the region~~ ranges between approximately 100 mm and 500~~2,000~~ mm, with greater amounts generally observed at lower latitudes (Garreaud et al., 2020; Viale and Garreaud, 2015)~~).~~. The region~~ also~~ experiences pronounced climatic fluctuations on interannual and interdecadal timescales due to interactions between the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002; Montecinos and Aceituno, 2003; Schulz et al., 2012; Vuille et al., 2015; Garreaud et al., 2020). The Southern Annular Mode (SAM) also impacts climatic conditions on weekly to decadal timescales through modulation of south-westerly winds (Saavedra et al., 2018; González-Reyes et al., 2020; King et al., 2023). These climatic oscillations play a crucial role in shaping weather patterns and hydrological cycles in the Dry Andes, affecting agriculture, water resources, and ecosystems. The PDO influences long-term climate variability, with positive (negative) phases bringing warmer (cooler) and wetter (drier) conditions. ENSO strongly affects interannual climate variability, with El Niño events bringing warmer, wetter conditions, increasing snowfall in the Andes, while La Niña events lead to cooler, drier conditions. SAM variation influences interannual seasonal precipitation and snow cover in the Andes; positive phases are linked to reduced precipitation, and negative phases are associated with increased precipitation (Vera and Silvestri, 2009).

The eight project sites ~~considered~~ in this study are ~~all~~ situated at high altitudes, ranging in elevation from 3,500 m to over 5,250~~500~~ m above sea level. Each site exhibits significant~~Significant~~ topographic variability~~ also exists at the individual project level~~, with total relief ranging from 250 m to 1,200 m. The project sites fall~~ at any given site. As a whole, the study area falls~~ within the 'Andean Arid Diagonal' (Bruniard, 1982), a contiguous zone of arid to semi-arid climate separating tropical and temperate climates of the northern and southern ~~portions of the~~ Andes (Figure 1). This includes parts~~portions~~ of the Cold Mountain Desert (BWk) and High Mountain Tundra (ET) climatic belts (Kottek et al., 2006), which are distinguished by ~~their~~ unique variations in altitude, precipitation, and temperature~~ trends~~. Climatic conditions of the BWk belt,~~ are~~ dominant ~~at elevations~~ below ~4,000 m ~~and~~ are characterized by low humidity and minimal precipitation. With seasonal~~Seasonal~~ average temperatures ranging~~range~~ from ~18°C in January to ~8°C in July, permafrost will not form and is~~making it highly~~ unlikely ~~for permafrost~~ to exist ~~or form~~ in this zone;~~. Instead,~~ where it~~permafrost~~ does exist, it is ~~expected to be~~ naturally degrading. Rock glaciers are the most common periglacial landform within the BWk belt and have ~~been shown to have~~ variable ground ice content~~contents~~ across the study area, reflecting different degrees of permafrost degradation (Hilbich et al., 2022). In contrast, the climate of the ET belt (elevations ~~generally~~ >4,000 m) is associated with low temperatures year-round and mean annual air temperatures (MAATs) below 0°C (Vuille et al., 2003; Garreaud, 2009), creating favourable conditions for permafrost formation. During the~~Daily temperatures within the ET belt can exceed 15°C in~~ summer months (December to February), ~~but average~~ temperatures ~~within the ET belt~~typically remain above 0°C, with daily highs exceeding 15°C and averages below 10°C. Surface geomorphic indicators of permafrost in this belt,~~have been~~ identified in ~~this belt both in~~ the field and through remotely~~remote~~ sensed imagery,~~imaging, and~~ include rock glaciers, gelifluction slopes, and ~~in some cases,~~ patterned ground (Arenson and Jakob, 2010). In both climatic belts, snow accumulates~~tends to accumulate~~ at high altitudes during winter and remains ~~frozen~~ until spring (~~approximately~~ October to November), followed by~~following which~~ a unimodal snowmelt-dominated regime ~~is~~ produced annually for all rivers originating from mountain peaks (Masiokas et al., 2016).

The distribution of permafrost across the Andes is complex, driven by high variability of mountain topography and climatic conditions at the catchment level. This~~ variability~~ leads to significant variations in ground thermal conditions ~~that can vary significantly~~ over ~~distances of~~ tens to hundreds of metres. Slight~~As with other mountain regions, slight~~ variations in altitude (usually spanning a few hundred metres) can generate marked differences in air temperature, precipitation, vegetation, snowpack, solar radiation, and glacial cover over short lateral distances ~~(e.g., Hock~~(Arenson et al., 2022)~~2019). However, the combination of hyper~~. Hyper-arid conditions,~~ and~~ intense solar radiation and the~~paired with a~~ southern hemisphere location creates nuanced variations in water and energy balances, shaping~~which uniquely shapes~~ the distribution of permafrost in the Andes and distinguishing~~distinguishes~~ them from other mountain regions. The resultant effects on infiltration, subsurface freezing and thawing, and the movement of air and water through the ground contribute to the highly heterogeneous occurrence of permafrost in the region noted in several ground-based studies, with an even more complex distribution of ground ice (e.g., Hilbich et al., 2022). This is~~tends to be~~ particularly evident in rock glaciers, where ~~which have been shown to have considerable variations in~~ ground ice content varies widely from case to case (Arenson and Jakob, 2010; Hauck et al., 2011; Mollaret et al., 2020; Halla et al., 2021; Hilbich et al., 2022) and~~as well as~~ within individual landforms~~a single landform~~ (Jones et al., 2019; Halla et al., 2021). In the southern Central Andes (32°S–36°S), the ~~present-day~~ lower altitudinal limit of permafrost is~~has been~~ estimated between 2,900 m and 3,200 m, with occasional occurrences up to ~~approximately~~ 3,700 m (Saito et al., 2016). This varies~~is known to vary~~ with slope aspect due to variations in intensity of solar radiation, favouring the persistence of isolated patches of permafrost at lower elevations on pole-facing slopes compared to slopes oriented towards the equator (Yoshikawa et al., 2020; Arenson et al., 2022).

Several studies ~~examining climate change~~ in the region have identified a progression from a cooler humid climate to warmer and drier conditions in recent decades (e.g., Carrasco et al., 2005; Falvey & Garreaud, 2009; Schulz et al., 2012; Jacques-Coper & Garreaud, 2015; Garreaud et al., 2020). A~~. A pronounced~~ rise in air temperatures in the mid-1970s interrupted a ~~an existing period that was previously characterized by a~~ slightly negative trend in maximum daily temperatures (Jacques-Coper and Garreaud, 2015)~~(Schulz et al., 2012).~~. This ~~air temperature~~ rise was followed by a ~~distinct~~ downward trend in maximum and minimum air temperatures ~~that continued~~ into the early 2000s, coinciding~~ and coincided~~ with a cold-to-warm sea surface temperature (SST) shift of the PDO to its cool phase, possibly increasing ~~(Schulz et al., 2012), which may have resulted in an~~

Formatted: English (United States)

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: Font color: Black

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: English (Canada)

~~increased frequency of~~ El Niño events (Jacques-Coper and Garreaud, 2015; Schulz et al., 2012)~~).~~. Between 1979 and 2006, Falvey and Garreaud (2009) observed a cooling of ~~air temperatures on the order of~~ 0.225°C/decade along the coast of Central and Northern Chile ~~(from 17°S to 37°S). According to the authors, this was~~ due to the ~~emergence of cold water from the~~ Humboldt Current, while ~~promoted by southerly winds. For the same period, the authors report that~~ inland meteorological stations (Lagunitas and El Yeso) showed a ~~steady~~ warming of ~~approximately~~ 0.2528°C/decade. ~~Interactions of~~ ENSO and IPO oscillations~~phenomena~~ may have ~~also~~ contributed to a decline in precipitation in coastal Chile in~~during~~ the late~~last quarter of the~~ 20th century (Schulz et al., 2012), and the ongoing ~~as well as to the drought that currently persists in Central Chile (Garreaud et al., 2020). This sustained dry period (termed the "~~Central Chile Megadrought, which has been marked by a 25-45% ~~") is the most extreme on record, with mean~~ precipitation deficit from ~~deficits up to 45% between~~ 2010 to~~and~~ 2020 (Garreaud et al., 2020). ~~Additionally,~~ Carrasco et al., (2005) documented a ~~regional elevation~~ rise in~~of~~ the zero-degree mean annual air temperature (MAAT) isotherm in Central Chile from 1975-2001, with elevations rising by 122 m in winter and 200 m in summer. This~~The increased energy availability associated with this~~ shift facilitates snowmelt and a transition from solid to liquid precipitation, ~~both of which could~~ potentially triggering~~trigger~~ permafrost degradation ~~in the area; as the presence of snow cover modulates atmosphere-to-ground heat transfer (e.g.,~~ (Zhang, 2005)~~) and infiltration can enhance the absorption of latent heat, both factors impact the thermal regime of the ground~~.

3 Methodology

3.1 Ground Temperature~~Monitoring~~ Data and Permafrost Presence

Between ~~Starting at various points in time between~~ 2006 and 2017, ground temperature monitoring was systematically initiated~~monitored~~ at eight industrial project sites located between 27°S and 34°S and within approximately 25 km of the Chile-Argentine border (Figure 1). The compiled dataset presented in this study includes measurements collected from 53 boreholes distributed across the region, with 27 located in Chile and 26 in Argentina. The boreholes were installed to depths varying from 10 to 100 m at surface elevations ranging from 3,625 m to 5,251 m, in areas with and without permafrost. Of the total, 30 boreholes intercepted permafrost, while the remaining 23 were installed within unfrozen, or non-cryotic ground (Figure 2). Due to data interruptions and short monitoring duration, some boreholes in cryotic ground did not meet the two-year criterion of continuous ground temperature monitoring to confirm the presence of permafrost (van Everdingen, 1998). However, given that measurements were available from below the DZAA (i.e., from depths ≥ 10 m), it is reasonable to infer the presence of permafrost in boreholes where the temperature is at or below 0°C, even without a complete two-year record. Surface morphologies mapped at the borehole locations during thermistor installation include bedrock, colluvium, rock glaciers (containing ground ice), and landslide deposits (Table S1). Except for those in rock glaciers, the boreholes typically intercept bedrock within ~10-20 m of the ground surface.

~~.~~ Ground temperatures were monitored along the profile of each borehole using Negative Temperature Coefficient (NTC) thermistor strings (models YSI 4400-, RST TH00-, or Geoprecision TNode-series). Thermistors were accurate within a range

Formatted ... [1]
Formatted ... [2]
Formatted ... [3]
Formatted ... [4]
Formatted ... [5]
Formatted ... [6]
Formatted ... [7]
Formatted ... [8]
Formatted ... [9]
Formatted ... [10]
Formatted ... [11]
Formatted ... [12]
Formatted ... [13]
Formatted ... [14]
Formatted ... [15]
Formatted ... [16]
Formatted ... [17]
Formatted ... [18]
Formatted ... [19]
Formatted ... [20]
Formatted ... [21]
Formatted ... [22]
Formatted ... [23]
Formatted ... [24]
Formatted ... [25]
Formatted ... [26]
Formatted ... [27]
Formatted ... [28]
Formatted ... [29]
Formatted ... [30]
Formatted ... [31]
Formatted ... [32]
Formatted ... [33]
Formatted ... [34]
Formatted ... [35]
Formatted ... [36]
Formatted ... [37]
Formatted ... [38]
Formatted ... [39]
Formatted ... [40]
Formatted ... [41]
Formatted ... [42]
Formatted ... [43]

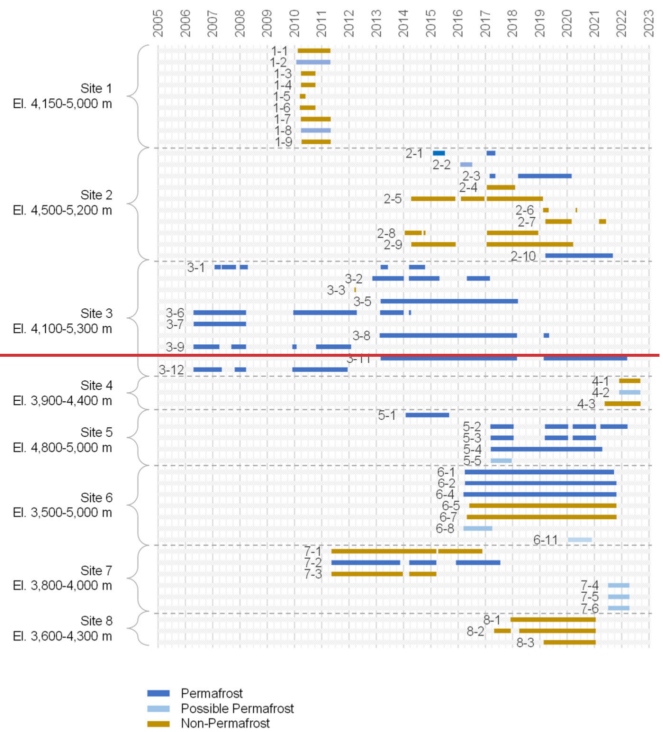
of ±0.1 to ±0.5°C from base temperature, with precision ranging between 0.1°C and 0.25°C. Sensors were positioned at varying depths reflective of the objectives of each borehole, starting from the ground surface (0 m) and spaced at increasing spacings ranging from 0.5 to 15 m (depending on the objectives and maximum depth of the borehole). Loggers were used for data collection at most locations although manual readings were made on occasion. The frequency of data collection varied with location, rangingacross locations is also variable, and ranges from hourly to daily measurements. Surface morphologies mapped at the boreholes at the time of thermistor installation can be broadly classified as bedrock, colluvium, rock glaciers (containing ground ice), and landslide deposits (Table A1). Except for instances where they are installed in rock glaciers, the boreholes typically intercept bedrock within ~10-20 m of the ground surface. Thus, measurements at most locations reflect thermal conditions of the deeper underlying bedrock.

The duration of monitoring varied by boreholevaries across boreholes, ranging from less than one month to nine years (Figure 2). Several, with several locations experiencedexperiencing interruptions to data collection due(Figure 2). These data gaps were attributed to numerous factors such as, including physical interferences (e.g., electrical storms,), instrument malfunctions, and inaccessibility for downloaddata downloads or maintenance due to remoteness, adverse weather conditions, slope instability and/or changing regulatory requirements. In some cases, interruptions occurred simply because a borehole was temporarily not being monitored as part of the project's objectives. A comprehensive discussion of data collection challenges, leading to monitoring gaps, along with known data artifacts and rationale for filtering rationale is included in Section 3.2.

A continuous ground temperature monitoring record is required for a duration of at least two years to demonstrate the existence of permafrost (van Everdingen, 1998). Given the aforementioned data discontinuities and (in some cases) short monitoring duration, not all boreholes could be unambiguously designated as permafrost locations. For the purposes of this study, the criteria used for designating a borehole as a permafrost location required that monthly average temperatures remained at or below 0°C within the borehole for (1) at least two consecutive years with no measurement gaps, or (2) a longer period of time for instruments with data gaps, provided that at least one measurement was collected in each calendar month over the course of the entire record. Boreholes with temperatures below 0°C that did not meet these criteria were considered "possible permafrost" locations, and boreholes with temperatures above 0°C along the full profile were considered "non-permafrost" locations (Figure 2). Permafrost and possible permafrost locations are referred to collectively in this paper as cryotic boreholes, and non-permafrost locations as non-cryotic boreholes. Gaps in individual monitoring records were filled asaccording to the procedure outlined in Section 3.3 prior to interpretation of the data. Rawfurther interpretations. The raw data for each borehole are presented within a series of plots compiled in the supplementary information package accompanying this paper (Figures S1-S53A1-A53).

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)


2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Site 1
El. 4,150-5,000 m
Site 2
El. 4,500-5,200 m
Site 3
El. 4,100-5,300 m
Site 4
El. 3,900-4,400 m
Site 5
El. 4,800-5,000 m
Site 6
El. 3,500-5,000 m
Site 7
El. 3,800-4,000 m
Site 8
El. 3,600-4,300 m
Permafrost
Possible Permafrost
Non-Permafrost

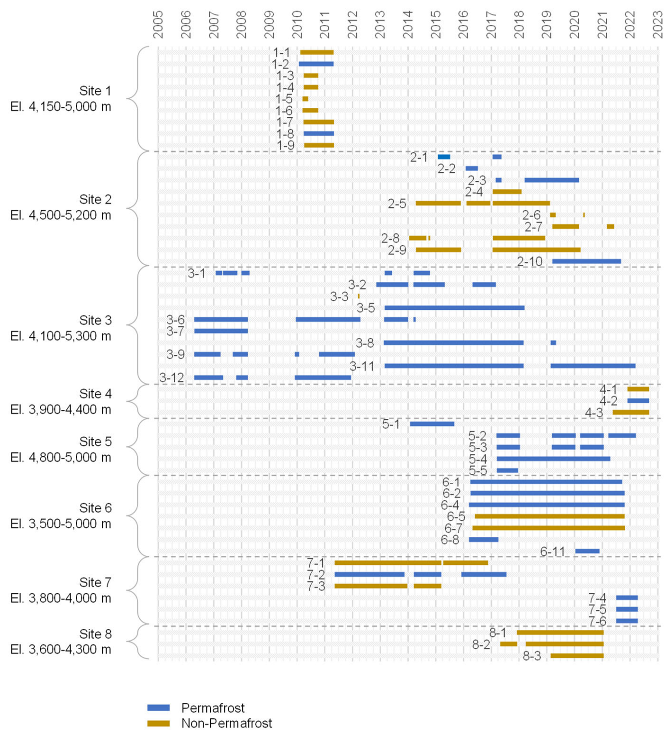


Figure 2: Summary of available borehole temperature time series over time.

3.2 Data Quality, Gaps and Filtering

~~The challenges with monitoring ground temperatures in high mountain regions are well documented in permafrost research (e.g., Noetzli et al., 2021).~~ Long-term operation of borehole infrastructure in high mountain regions ~~such environments~~ can be hindered by natural factors including erosion, mass movements or meteorological effects, all of which may lead to instrument malfunction that can reduce data quality or create gaps in monitoring records. Challenging ~~logistics in blocky heterogeneous~~ terrain, remoteness, and~~as well as a~~ lack of financial support can limit site access, leading to poor ~~resulting in insufficient~~ instrument maintenance and ~~loss of~~ data loss. Other factors affecting ~~impacts to~~ ground temperature monitoring unrelated~~not~~

necessarily limited to mountainous regions may includeresult from instrument damage bydue to wildlife, vandalism, nearby construction, activities or damage during instrument drilling and installation of the instruments themselves.

Many of these challenges were encountered across the monitoring sites in the current study area, with most, and documented instances of instrument interferences or malfunctions identifiedwere used to identify and omit artifacts from the dataset prior to interpretation. In some cases, artifacts or recorded data errors were previously filtered by field staff before analysis. Theand not stored in the dataset provided to the authors. From the available information, the most common causes ofreason for data interruptions werestemmed from battery power loss, faulty connections, or sensor failures occurring between instrument maintenance visits. IrregularSince funding for ground temperature monitoring basedwas not allocated to any of the projects on specifica regular basis (but instead depended on irregular work scopes and budgets that were driven by individual project needs, led to inconsistent and unpredictableobjectives and regulatory requirements as they arose), predictability of field work and was often lacking. Consequently, the instrument maintenance schedules were inconsistent and unpredictable, making it challenging to perform routine upkeep (e.g., battery replacement of sensorsuch as replacing batteries or complete repairs on damaged sensors) proactively or in a timely manner over the various monitoring periods.

Drilling activities were also frequently identified as a source of interference to monitoring. While several thermistors were installed in pre-existing exploration boreholes, more thanover half of the locations were drilled explicitly for ground temperature monitoring. This purposes. As such, early temperature measurements in these boreholes were potentially overestimated due to thermal disturbances from drilling. Locations affected included all boreholes at Sites 1, 4, 6 and 8, as well as boreholes 3-8, 3-11, 7-4, 7-5, 7-6 and 8-3. Dry sonic methods were used to drill all boreholes except atAt Site 1, which were advanced by diamond coring using water or polymer fluid. Early temperature measurements in these boreholes may have been overestimated due to thermal disturbances from the drilling process, especially where fluid circulation was involved. Elevatedelevated temperatures at Site 1 are evident at the onset of monitoring, particularly from depths of 10 m and below (Figures S1-S9A1-A9). Although temperatures gradually decrease as drilling related disturbances dissipateddissipate, it remains uncertain whether ground temperatures at Site 1 had fully stabilized within the roughly one-yearrelatively short monitoring period. Early of approximately one year. As they are unlikely to represent average ground temperature conditions, early measurements from Site 1 and other locations with approximately one yearyear's worth of data (i.e., boreholes 6-8 and 6-11, 7-4, 7-5 and 7-6) were treated with cautiongiven less weight in the analyses conducted in this study, particularly those collected during the initial two to three months, as they are unlikely to represent average ground temperature conditions. of monitoring. Drilling interferences were less of a concern for boreholes 3-8, 3-11, 8-3 and most boreholes at Site 6, which have longer monitoredmonitoring records.

At several monitoring locations, changesChanges in ground conditions may were also understood to have potentially compromised measurementthe quality. of measurements at several monitoring locations. For example, construction activities that altered local runoff patterns caused a large gully to form nearduring a field visit in 2017, a sizeable gully was noted adjacent to borehole 5-1 that did not exist in previous years (Figure 3). Field staff first noted the gully in 2017, but anomaliesAnomalies in the data and multiple sensor failures suggested that erosional activity associated with gully formation

Formatted: English (United Kingdom)

had affected borehole temperatures at this location since late 2015. Consequently, measurements beyond September 2015 were excluded from analysis. Another instance of natural ground disturbance influencing monitoring was noted during a 2017 field visit to borehole 2-2, where a previously unseen debris flow was observed near the borehole 2-2 (Figure 4). As withSimilar to the situation at borehole 5-1, erroneous data were identified and excluded from analyses.

ProjectIn some cases, project-driven optimization of monitoring sometimesalso led to data interruptions (or shortened record lengths) and informed additional filtering. For example, data collection ceasedwas discontinued at selectseveral boreholes at Site 2 once permafrost was determined to be absent, and thermistor strings were relocated to areas with a higher elevations wherelikelihood of encountering permafrost was more likely. Two. This involved moving two thermistors were moved (from (at boreholes 2-4 and 2-5) to higher elevations (boreholes 2-6 and 2-7) resulting in the), and thus termination of monitoring at the original locations. During the relocation of the thermistor from originally deployed at borehole 2-4 to 2-6, it also became evident that the sensor at ~24 mmeters depth was damaged. Initially, anomalously high measurements recorded by this sensor at its original location were considered plausible, possibly due to warm groundwater or exothermic reactions at depth. However, similar anomalies persisted at the new location (borehole 2-6), suggesting measurements were artifacts and should be excluded from further analysis.

The supplementary information package accompanying this paper displays all raw data except for cases where artifacts were confidently identified and removed (e.g., related to erosion events or known instrument failures). Thermal disturbances from drilling and occasional unexplained artifacts are visible in the figures but were omitted from analyses. TheseUnexplained anomalies could be the result of water or air flow through blocky materials, or common electrical storms which are common in central Chile (e.g., -Montana et al., 2021). As there was no clear indication that they were erroneous, these anomalies were retained on the plots for transparency and dataset completeness of the dataset.

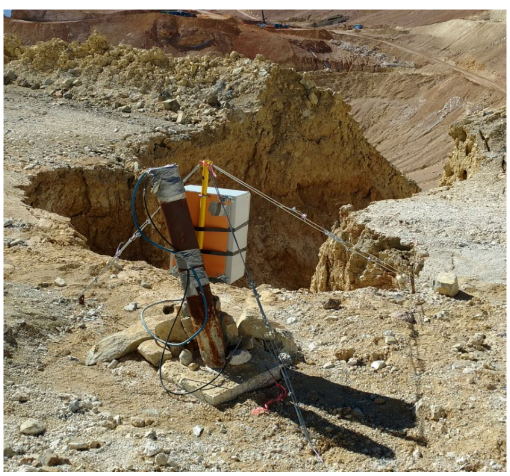


Figure 3: Photograph of borehole 5-1 showing erosional gully that formed during the 2015 calendar year.

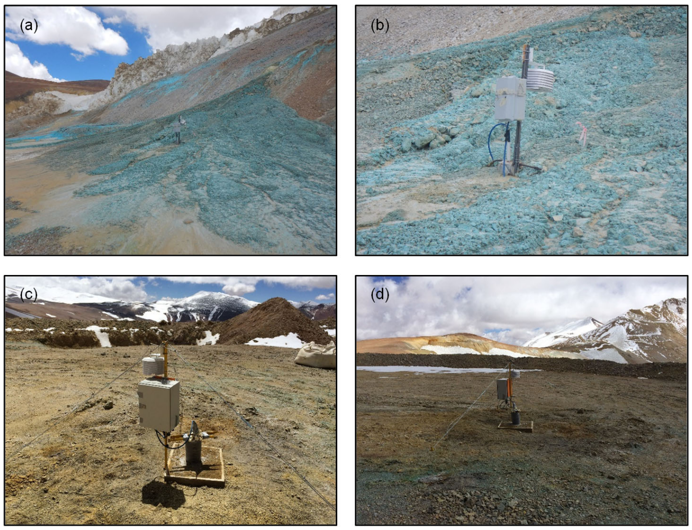


Figure 4: (a) and (b) Original location of thermistor string at borehole 2-2 and the adjacent surface debris flows. The thermistor string was moved to boreholes 2-3 (illustrated in (c) and (d)) which is approximately 50 m higher in altitude.

3.3 Filling of Data Gaps

Gaps in ground temperature time-series were interpolated using ~~a~~ non-linear least squares regression to enhance data visualization and remove seasonal bias from analysis.~~subsequent analyses.~~ At thermistors that showed seasonal variation, a sinusoidal function with a superimposed linear trend was fit to filtered data to approximate seasonal and ~~potential~~ longer-term temperature variations~~trends~~. For sensors located below the ~~interpreted~~ DZAA, ~~a simple~~ linear interpolation was used. Initial conditions for each sensor were specified by setting function parameters (i.e., period, amplitude, phase shift, offset, slope) that produced a reasonable visual match to observed data. Parameters were then optimized using the generalized reduced gradient (GRG) non-linear solver in Microsoft Excel to minimize the sum of squared residuals, targeting a~~ between observed and estimated values, with a target~~ normalized root mean square (NRMS) below ~~value of less than~~ 10%. The quality~~goodness~~ of fit ~~for each instrument~~ was first assessed visually, with~~and~~ manual adjustments made~~were~~ occasionally ~~made~~ to improve the overall match of the solution to the data.~~ (NRMS values remained below 15%).~~ Missing values ~~in each thermistor record~~ were then filled on a daily timestep using the fitted equation and are plotted alongside~~together with~~ raw data in the supplementary information package (Figures S1~~A1~~ through S53~~A53~~).

It is noted that this approach has limitations in estimating temperatures within the active layer or in boreholes containing ground ice, as it cannot due to its inability to represent latent heat effects during phase changes. Additionally, it is not suitable for long records with complex warming or cooling trends, which maycould also vary over the course of the monitoring period., cannot be represented using this approach. Despite these limitations, the method provided a useful way to estimate missing values and visualize seasonal patterns and short-term variationsgeneral trends in the data, making it appropriate and was considered reasonable for this study, where as the longest data recordsrecord at eacha given instrument areis less than 20 years.

4 Ground Thermal State

4.1 Seasonal and Interannual Ground Temperature Variations

A total of 22 cryotic (permafrost and 12 non-/or possible permafrost) and 12 non-cryotic (non-permafrost) boreholes have continuous records spanning at least one year, making them suitable for examining seasonal temperature variations effects on ground temperatures (Figure 5). Most sensorsinstruments situated at depths near 10 m depth (Figure 5a) showexhibit clear seasonal temperature fluctuations, with greater seasonal amplitudes variation detected by sensors in unfrozen ground (~(amplitudes ranging from approximately 0.5°C to 1°C) compared to frozenthose within ground (<that remained below 0°C (amplitudes generally lower than 0.5°C). AtSensors positioned at depths nearclose to 20 m (Figure 5b), sensors areon the other hand, appear to be mostly below the DZAA, with somea few exceptions in boreholes within non-cryotic ground. SeasonalWithin both the 10 and 20 m-depth suites of measurements, seasonal variations at both depth horizons are less pronounced where ground temperatures hover around 0°C, reflecting latent heat effects fromassociated with annual freezing and thawing of ground ice. Similarly, attenuated temperatureShallow ground temperatures (<2m) at a minimum of 14 monitoring locations exhibit dampened daily fluctuations at shallow depths (<2m) were noted during the winter at 14 locations , suggesting an influence of snow cover (Table S1, A1). This is illustrated in the raw data time-series plots (Figures S1A1, through S53) and are likely attributable to snow cover. A53).

Unlike permafrost regions in the northern hemisphere, identification of anya consistent trend of rising ground temperatures within over time is not discernable from the Andean dataset. Instead, individual monitoring locations appear to date is not possible due to its short duration. It instead reflects baseline local topo-climatic conditions and short-term climate fluctuations associated with the mountainous terrain. Both short-termexhibit warming andor cooling are noted in the datasetduring their respective periods of record, with no correlation to location, altitude or surface substrate (Figure 5). Figure 6 illustrates theA wide variation in short-term rates of temperature change from range in warming and cooling trends was noted for locations with at least two years of data (19 permafrostcryotic and 9 non-permafrost boreholes; Figure 6). Warming (trends (ranging from 0 to 0.05°C /yr) was noted were detected in approximately half of the boreholes examined (15), with the restremaining locations showing short-term cooling. Non-permafrostAdditionally non-cryotic boreholes exhibitedappeared to exhibit greater variability in temperature change over the period of recordtime.

Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: Font: (Default) Times New Roman
Formatted: English (United States)
Formatted: English (United Kingdom)
Formatted: Font: +Headings (Times New Roman)

For comparison with other permafrost regions, Figure 6 includes representative long-term warming trends from other permafrost regions as documented in Smith et al. (2022) for . This includes continuous or “cold” Arctic permafrost (temperatures below -2°C, warming rates fromrange: ~0.04 to 0.11 -°C/yr, and monitored since the 1980s), discontinuous or “warm” Arctic permafrost (temperatures between -2° and 0°C, warming rates fromrange: ~0.01 to 0.05°C /yr, and monitored since the late 1970s to early 1980s) and mountain permafrost within the Swiss Alps (average: ~0.02 °C/yr, and monitored since in the late 1980s to early 1990s). These trends are presented for reference only; but it is notable thatInterestingly, the short-term estimated range in warming rates in the Andes align with trendsthose estimated for the Swiss Alps and the warm Arctic regions. However, when making Caution in this reference we strongly caution comparison is warranted however, as the reader, as northern hemisphere studies relyrelied on significantly longer (decadal or multi-decadal) datasets than the limitedmonitoring records in this study. The; the longest record considered in the Andean analysis was approximately nine years (borehole 3-11), with most records spanning between 2 and 7 years, making reliable comparisons with northern hemisphere studies premature.. In this context, the variability in the Andean dataset more likely reflects local topo-climatic conditions and short-term climate fluctuations in mountainous terrain. To establish causal relationships between ground temperatures and longlonger-term climate variability in the Andesto a similar level of confidence as has been accomplished for other permafrost regions, ongoing monitoring of ground temperatures alongside local climate variables is needed. Given the constraints of the current monitoring dataset, a comprehensive analysis of this scale is beyond the scope of this study and presents an opportunity for climate researchers.

Formatted: Font: +Headings (Times New Roman)

Figure 5: Monthly ground temperatures at depths of 10 m (a) and 20 m (b) at boreholes with at least a full year of measurements. Measurements in bedrock and in rock glaciers are plotted every two months for clarity in the figure.

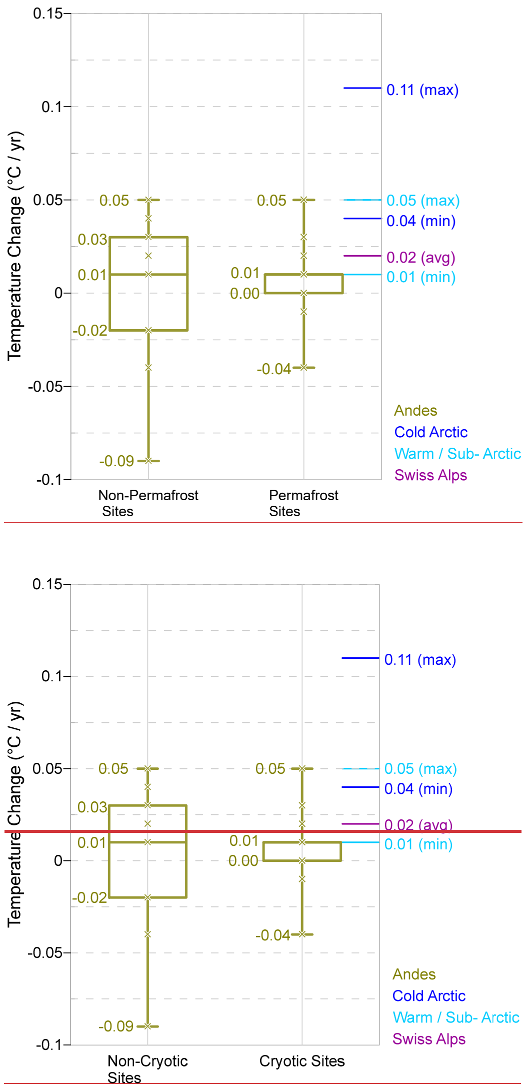


Figure 6: Short-termVariation in ground temperature changes with timetrends at 20 m depth in the Andes (this study), shown alongside long-term ground temperature trends compiled by Smith et al., (2022), and comparison with trends in permafrost regions

ofin the northern hemisphere (i.e., Cold Arctic, Warm / Sub-Arctic and Swiss Alps). The Andean estimates (n permafrost sites = 19; n non-permafrost sites = 9) are based on 2-9 years' worth of measurement and reflect short-term fluctuations in climate. Warmingas reported by Smith et al., (2022). Note that rates for othernorthern hemisphere studies (n Cold Arctic Sites = 9; n Warm / Sub-Arctic Sites = 11; n Swiss Alps sites = 5) were derived from decadal / multi-decadal datasets and represent. Trends in the effects of climate change. The terms "Cold Arctic permafrost" and "Warm/Sub-Arctic permafrost," from Smith et al. (2022), distinguish cold permafrost as below -2°C and warm permafrost as closer to 0°C. Estimates for the Andes sitesAndean dataset were estimated through interpolation of continuous measurements at locations where at least two years' worth of data was available. Trends are summarized in Table S1A1 with corresponding r^2 values.

4.2 Depth to Permafrost

The thickness of the active layer (or ALT) in permafrosteryotic boreholes was estimated by linearly interpolating measurements between thermistors positioned above and below the zero-degree isotherm at the time of maximum annual thaw. While Two permafrost locations (boreholes 3-7 and 3-12) were excluded from this exercise because the depth of thaw penetration remained above the shallowest sensors (i.approach may slightly overestimate ALT (e.g., Riseborough, 2008), a lack of shallow temperature measurements at the Andes sites prevents reliable extrapolation of the zero-degree isotherm from above. Additionally, snow cover varies considerably across boreholes; in areas with little snow, atmospheric gradients strongly influence temperatures in the active layer, whereas snow-covered areas insulate the ground (e.g., BTS method by Haeberli (1978)). Given these complexities, and that the goal was to track potential changes in permafrost depth and compare boreholes, linear interpolation was considered a reasonable approach, allowing for relative comparisons rather than estimating absolute ALT values.

Of the 30 permafrost boreholes, 20 were considered in this analysis. Two ., < 1 m deep). Within two rock glaciers (boreholes 6-1 and 6-4) were assessed as , and 6-4), the depth to permafrost exceeded the maximum depth of annual freeze/thaw. Therefore, the measurement of interest at these locations is more appropriately termed depth to permafrost table, as the depth to permafrost in these boreholes exceeded the maximum annual freeze/thaw depth. For boreholes 1-2 and 1-8, which lacked two consecutive years of data as opposed to ALT. At locations where permafrost was possible but not confirmed due to insufficient length of monitoring, the maximum annual thaw depth was estimated in a similar manner to ALT (or permafrost table), as) for cases where the recordsdata record encompassed a complete freeze-thaw cycle with subsequent refreezing. Permafrost This included two locations at Site 1 (boreholes 1-2 and 1-8). Possible permafrost locations with shorter monitoring records were not considered. Two permafrost locations (boreholes 3-7 and 3-12) were also excluded because the depth of thaw penetration remained above the shallowest sensors (< 1 m deep).This process was thus completed for a total of 20 boreholes using the filtered and gap-filled data (Sections 3.2 and 3.3).

Figure 7 shows that thawThaw depth and ALT typically range from ~0.5 to less than 4 m, although ALT at boreholes 3-5 and 6-2 reached depths ≥ 6 m. Consistent with field observations (Figures 7 and 8). Notably, depth to permafrost within rock glaciers is the highest within the dataset, ranging between 7.3 to 17.4 m below the ground surface during the 2021 calendar year. This is consistent with surficial evidence of advanced degradation innoted by the field staff for these specific landforms (though, although is not necessarily representative of the region), depth to permafrost within conditions in rock glaciers is across the region in general. Similar to the highest in the dataset, ranging from 7.3ground temperature time series, there does

Formatted: Font color: Black

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~not appear~~ to 17.4 m in 2021. There is no consistent increase~~be an overall trend~~ in ALT~~deepening of the active layer~~ over time across the dataset, and in ~~as might be anticipated with progressive atmospheric warming. In~~ some locations, the active layer may be ~~even show signs of~~ shallowing (e.g., boreholes 3-6 and 3-9, and possibly 2-10). In contrast, the top~~Deepening~~ of permafrost is deepening~~over time appears to be restricted to boreholes installed~~ in rock glaciers~~, which are estimated to be lowering~~ at rates of approximately 0.4 m/yr at borehole 6-1, 0.8 m/yr at borehole 6-2 and 1.5 m/yr at borehole 6-4. These results reflect short-term fluctuations in climate.

Contour diagrams of borehole temperature evolution with time (Figure 8) reveal~~illustrate the presence of~~ supra-permafrost taliks at boreholes 6-1 and 6-4. At borehole 6-4, the ~~diagram shows that the~~ top of permafrost was fully decoupled from the active layer throughout monitoring. In contrast, the formation of the talik at borehole 6-1 began forming~~appeared to begin~~ in mid-2019. ~~Estimates of the maximum annual depth to permafrost across the site are included in Table A1 alongside the date for which the estimates were made.~~

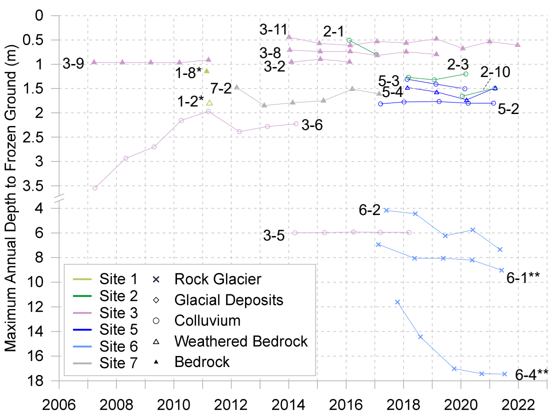


Figure 7: Maximum annual depth to frozen ground within permafrost ~~and possible permafrost~~ boreholes. Note scale break between 3.5 and 4m. * indicates thaw depth (boreholes 1-2 and 1-8); ** indicates depth to permafrost table (boreholes 6-1 and 6-4). Active layer thickness (ALT) is plotted for all other boreholes. See text for additional detail.

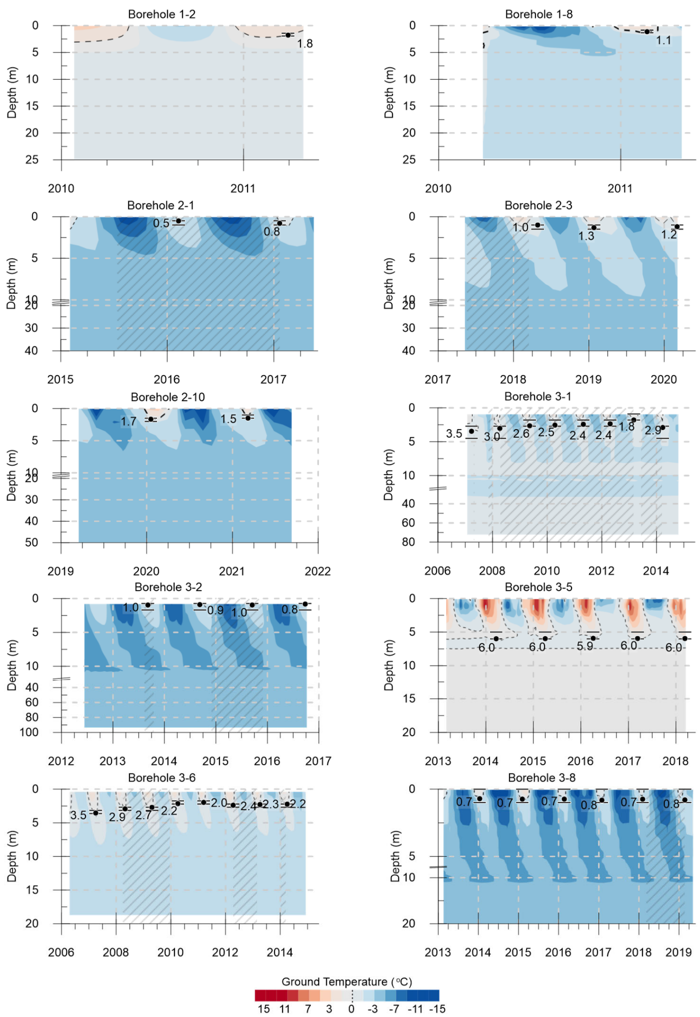
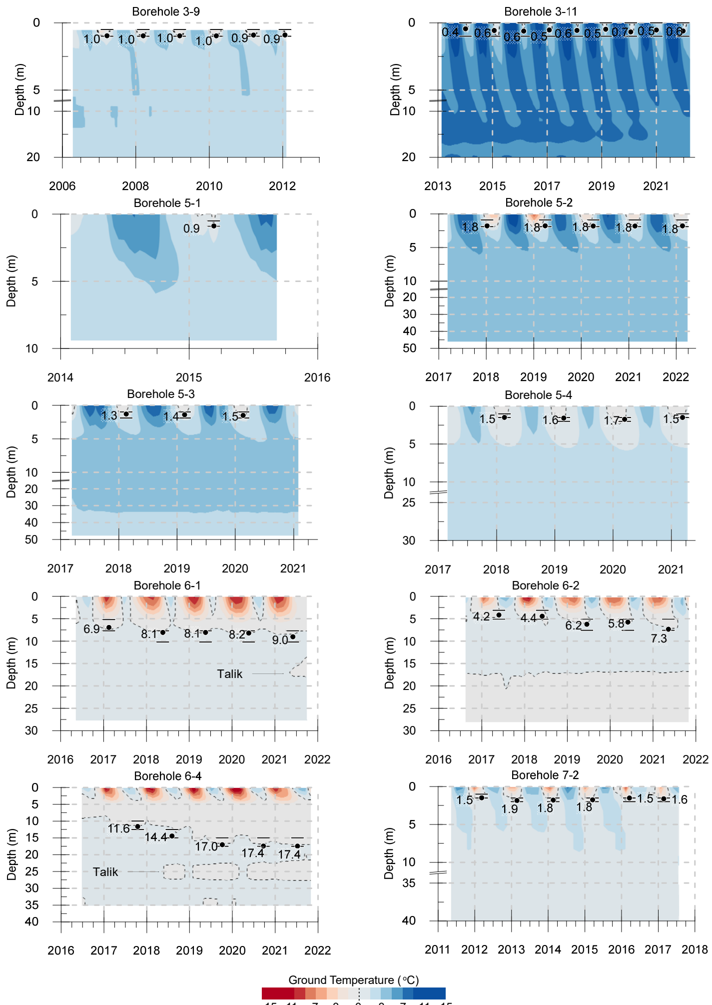


Figure 8: Interpreted borehole temperature evolution with time. Ground temperature contours estimated from raw data and gap-filled values; data gaps filled by interpolation are indicated by grey hatched areas. Depth to permafrost is indicated by black dots; horizontal lines indicate the depth of thermistors used to estimate permafrost depth. Note breaks in y-axes at selected boreholes for improve contour visualization.


Borehole 3-9
Borehole 3-11
Borehole 5-1
Borehole 5-2
Borehole 5-3
Borehole 5-4
Borehole 6-1
Borehole 6-2
Borehole 6-4
Borehole 7-2
Depth (m)
Talik
Ground Temperature (°C)
15 11 7 3 0 -3 -7 -11 -15

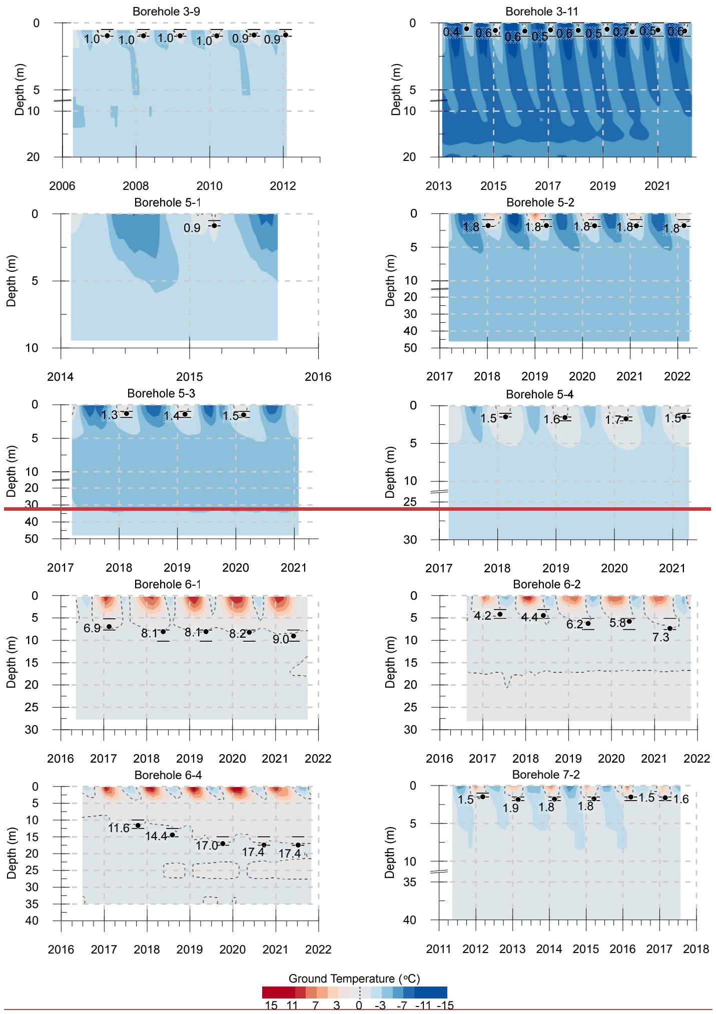


Figure 8 (cont.): Interpreted borehole temperature evolution with time. Ground temperature contours estimated from raw data and gap-filled values; data gaps filled by interpolation are indicated by grey hatched areas. Depth to permafrost is indicated by black dots; horizontal lines indicate the depth of thermistors used to estimate permafrost depth. Note breaks in y-axes at selected boreholes for improve contour visualization.

4.3 Ground Temperature Profiles

The temperature profile within a borehole is shapedmay be affected by four primary factors such as: regional geothermal heat flux, depth-related lithology variations, local ground surface topo-climatic variations, (which shapes the upper thermal boundary), and historical fluctuations in ground surface temperatures. These factors result in contribute to a widevariety of distinct profile shapes and broad range in ground temperatures across the dataset (from approximately -7 to 7°C) and varied profile curvatures (, Figure -9), reflectingwhich reflect the complex thermal landscape of the Andes. Variations in The variability of profile curvatureshape within individual boreholes suggest suggests that ground temperatures are generally not in equilibrium with modern climate conditions. Instead, they represent the present balance between surface and geothermal heat fluxes controlled by thermal properties of the ground, which vary with location across locations and depth. Borehole temperature gradients withinuniquely along each borehole. Within the upper 30 m areof measurements, thermal gradients were observed to be both positive (warming with depth) and negative (cooling with depth), withwhile some locations showing nearlyexhibit roughly isothermal conditions. Several boreholes in warm permafrost (3-5, 6-2, 6-5, 6-8, 6-11, 8-3) exhibit a composite temperature profile within the upper 30 m,this depth range. These boreholes are characterized by a nearly isothermal region where temperatures are close to 0°C, below which temperatures increase with depth due to the heat flux from the natural geothermal heat fluxgradient. The temperature profiles shown in Figures S1A1 through S53A53 reveal the presence of relatively thin layers of permafrost layers in several boreholes within rock glaciers, rangingwhich vary in thickness from approximately 2 to 40 m thick. Permafrost thickness in. Within cryotic boreholes that did not intercept the base of permafrost (but exhibited warming with depth) was), permafrost thickness is estimated to range from 40 -to > 500 m, based on the from projection of thermal gradients to the zero-degree depth intercept. Estimates of permafrost thickness are summarized in Table A1.

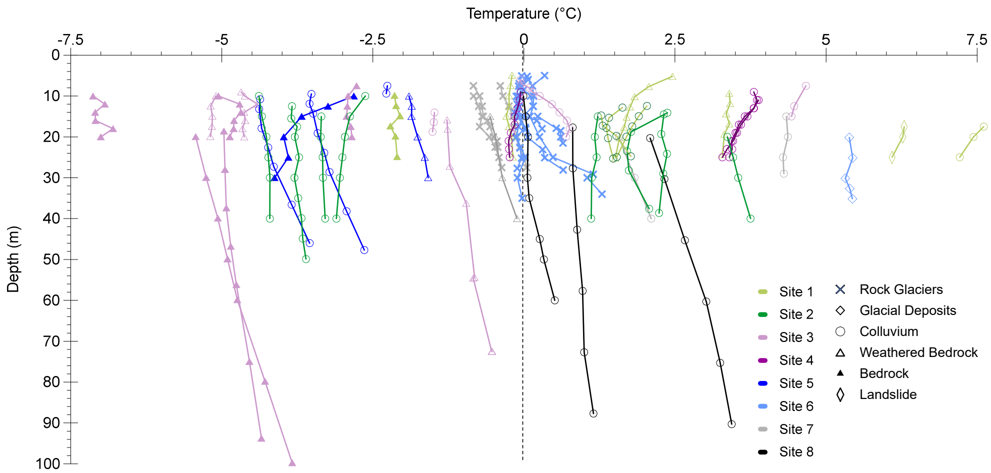
There is no clearIn general, there does not appear to be a relationship between profile shapegradient or curvature, or estimated permafrost thickness andwith latitude (i.e., site number), likely due to) or surface morphology (Figure 9). This is not surprising given the wide variationrange in ground surface elevations and surface slope orientations that occur within a few tens of metres at eachany given project site (Table S1A1 and Section 3.3). Such topographicTopographic heterogeneity results in significantat this scale can lead to strong variations in surface solar radiation and microclimatic conditions, which have that are likely to exhibit a greater influence on ground temperatures than variations in latitude. There also does not appear to be a relationship between would. While some variability in profile curvature or permafrost thickness withmay reflect contrasts in thermal properties of surface morphology, likely becausesubstrates, most boreholes interceptare known to have intercepted bedrock at depths ofbelow 10-20 m (BGC Engineering Inc, Pers. Comm. October 2023). As such, temperature profiles generally Hence, it is reasonable to assume that most thermal gradients below the DZAA primarily reflect thermal properties of shallow bedrock, with minimal surface substrates exerting little to no influence from surface substrateon measurements.

Potential exceptionsExceptions to this are noted, however, arise in boreholes installed in rock glaciers at Site 6 (i.e., boreholes 6-2, 6-5, 6-8 and 6-11), which, as noted above, are characterized by shallow isothermal conditions near ~ 0°C then increasing

Formatted: English (Canada)

Formatted: English (Canada)

temperatures with depth., which contain varying amounts of ground ice and reach thicknesses up to approximately 40 m in this dataset. The coexistence of air and ice in the pore space near the ground surface and within the active layer of these coarse blocky landforms results in a significantly lower thermal conductivity of the medium compared to bedrock. In addition, the relatively large pore space promotes air convection, which can significantly cool the active layer, leading to temperatures ~1°C colder than without convection (e.g. Wicky and Hauck, 2020). Below the active layer, the ice-rock mixture is likely to be less sensitive to variations in the near-surface thermal regime (although still distinct from bedrock), leading to a unique profile shape despite possibly similar thermal histories at the ground surface. As these particular landforms are known to contain Additionally, the evolution of ground temperatures over time would be notably influenced if there is appreciable ice content within rock glaciers, particularly if ice-rich permafrost is near theits phase change temperature, vertical segments of the profiles may reflect the . In conjunction with profile shape, these characteristics may allow unique inferences to be made about the anticipated evolution of ground temperatures in response to varying surface temperatures. For example, permafrost in rock glaciers at Site 6 is generally isothermal with depth at ~ 0°C, possibly because ground ice is melting of ground ice, slowed. In contrast, the colder permafrost in rock glaciers at Site 7 (at approximately -1°C at 10 metres depth) exhibits a positive thermal gradient (warming with depth). Ground temperatures (and therefore profile shapes) within rock glaciers at Site 7 are likely to be more sensitive indicators of surface temperature change compared to Site 6, where potential temperature trends are obscured due to latent heat effects.



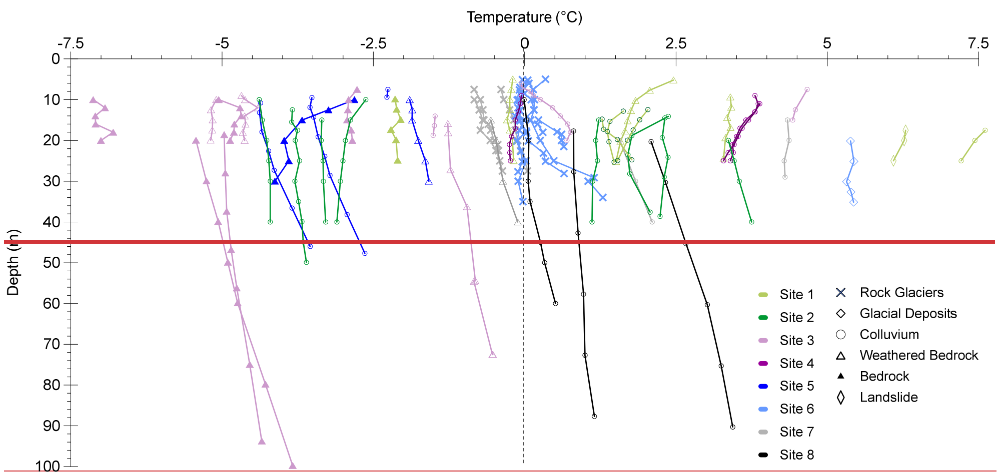


Figure 9: Ground temperature profiles at all boreholes. Average and most recent values shown for locations with ≥1 year and <1 year of data, respectively. Excludes shallow measurements (between ~5-20 m) influenced by seasonal temperature variations.

4.4 Thermal Gradients

Thermal While the assessment of warming or cooling trends presented in Section 4.1 is hindered by record length, the thermal gradients of individual boreholes may provide some insight into the recent thermal evolution of the ground in response to changing surface temperatures. The attenuation of historical surface ~~Since~~ temperature anomalies ~~at the ground surface are attenuated by the subsurface, historical shifts in surface temperatures~~ may be indicated by warm (~~or~~ cool) ~~side~~ deviations of~~observed in~~ shallow borehole temperatures from the linear trajectory of the deep gradient~~, within a borehole~~. This temperature deviation (or offset) was estimated as the difference between projected surface temperatures from shallow (< 30 m) and deep (30-100 m) gradients. Offsets estimated ~~from data collected~~ in this depth range reflect recent decade-scale shifts in surface temperatures, assuming equilibrium conditions and uniform thermal properties ~~of the borehole~~ with depth (e.g., Lachenbruch and Marshall, 1986). Since ~~the time lag of~~ thermal responses to ~~warming of the ground~~ surface ~~warming~~ at depths greater than ~100 m ~~is~~ likely lag~~to be~~ several decades, the offset provides a first approximation of secular temperature changes with time~~trends~~.

Nineteen~~A total of 19~~ boreholes (10 permafrost~~eryotic~~ and 9 non-permafrost~~eryotic~~ boreholes) in the Andean dataset extend to depths beyond~~greater than~~ 30 m and were considered in this analysis. Rock glaciers were excluded due to their unique thermal profiles (Section 4.3)~~,~~, as were ~~measurements from~~ boreholes 2-4 and 2-6 due to erroneous measurements at ~24 m (Section 3.2). Thermal gradients were estimated ~~using measurements~~ from the linear segments of profiles at intermediate depths (~~i.e.,~~ below the DZAA ~~and up~~ to ~~approximately~~ 30 m ~~below the ground surface~~) and from 30 m to the final depth of each borehole, except~~with one exception~~ at borehole 8-1. The shallower gradient at borehole 8-1 was estimated from the DZAA to 60 m, and the deep gradient from 60 m onward due to a slight decline observed in the thermal gradient at approximately this depth (Figure 9).

Results of the gradient analysis (Figure 10) are presented in a similar manner as the temperature changes~~trends~~ derived from the interpolation of time-series data (Figure 6) for conceptual comparison of the two analyses. As with the time-series analysis~~interpolation~~, the gradient analysis indicates both warming and cooling in recent history, with greater variability in the non-permafrost~~eryotic~~ boreholes. Warm-side deviations from deep thermal gradients are evident for 14 of the boreholes (7 permafrost~~eryotic~~ and 7 non-permafrost~~eryotic~~), and range from 0.05 to 0.9°C. The remaining boreholes (2 permafrost~~eryotic~~ and 3 non-permafrost~~eryotic~~) indicate cooling in recent decades, with offsets ranging from approximately -0.05 to -1.08°C. It is~~must be~~ emphasized ~~however~~ that these estimates are derived from many simplifying assumptions, and that three-dimensional analysis ~~of the geothermal fields,~~ accounting for ground thermal properties are~~, would be~~ necessary for a more accurate~~precise~~ understanding of near-surface ground temperature changes in recent history.

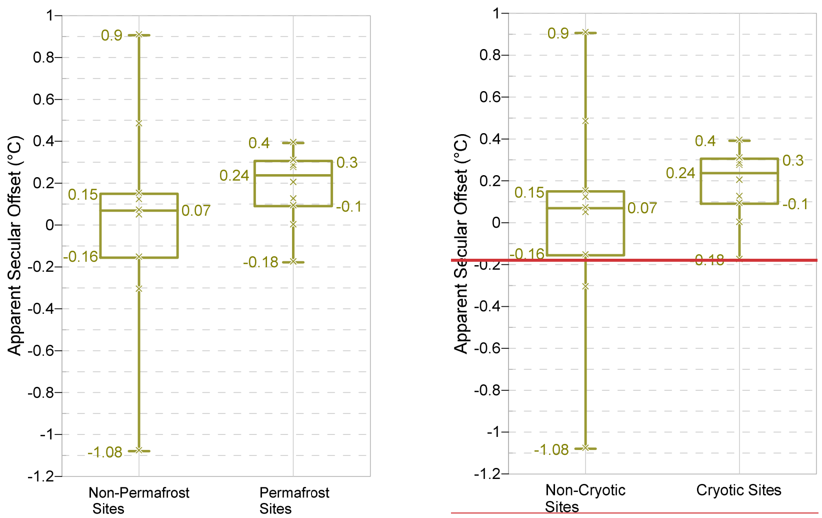


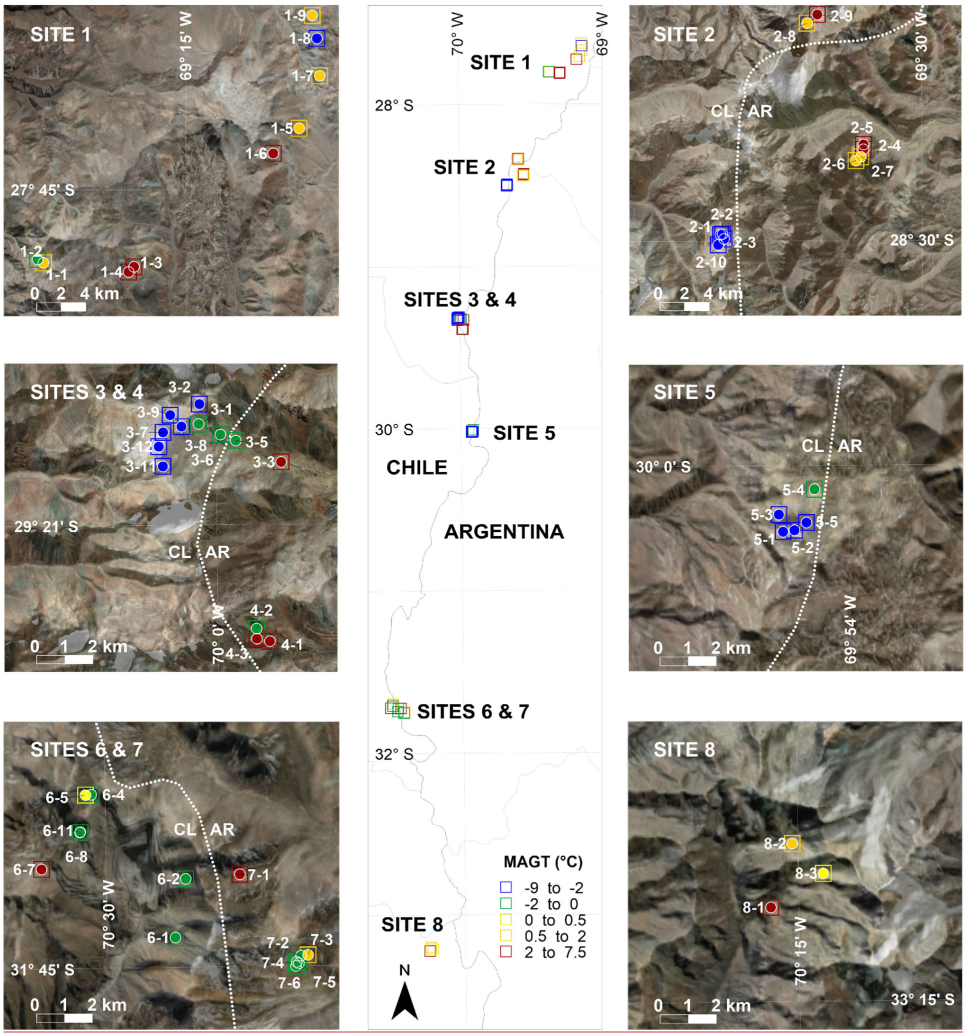
Figure 10: Variation in apparent secular offset in ground surface temperatures, estimated from gradient analysis (n permafrost sites = 19; n non-permafrost sites = 9). .

4.5 Aggregate Trends

RepresentativeAn examination of representative ground temperatures across the entire study region showreveals no correlation with between ground temperature and latitude, but; however, significant variation occurs over short lateral distances is evident at the site level (Figure 11). TransitionsThis includes transitions from cold to warm permafrost (< -2°C to 0°C) and/or to non-cryotic ground occurs with over horizontal distances as small as 1 km, highlighting the in some cases, reflecting a greater influence of catchment-scale topo-climatic variability overcompared to regional climate. Ground temperatures variations. An overall lowering of ground temperatures across the dataset is observed as altitude increases, with generally decrease with increasing altitude, showing no clear relationship withto mapped surface morphology, as since most measurements represent thermal conditions of shallow bedrock (Figure 12a). Rock glaciers, however, are again exceptions, with consistently show lower average temperatures than boreholes at similar elevations (< 0 °C in (i.e., temperatures within rock glaciers vs. 2-6°C inare typically ≤ 0 °C, whereas other boreholes). They also at similar elevations vary from approximately 2-6°C). Boreholes within rock glaciers also appear to mark the lowest altitudinal occurrence of permafrost within the dataset (slightly below 3,600 m) due to likely reflecting a sustained presence of ground ice due to latent heat combined with cooling effects of air convection within the blocky active layer compared to the broader dataset. Excludingother surface substrates. With rock glaciers, excluded, there is a slightly tighter correlation between ground temperatures correlates more strongly with and altitude at permafrosteryotic boreholes ($r^2 = 0.65$) than for the complete dataset ($r^2 = 0.53$), with lapse rates of approximately -4.3°C/km and -5.7°C/km, respectively.

Consistent with an overall tendency towards cooler temperatures at higher altitudes, both depthestimated depths to permafrost and permafrost thickness both decrease aswith increasing ground elevation increases (Figure 12b and c). Again, no correlation with surface morphology is evident in the dataset except infor rock glaciers, which show thediverge from the general trend observed in the remainder of the boreholes (i.e., most variable depth to permafrost and lowest estimated thickness within the dataset, reflecting). This departure reflects the unique constitution of the active layer in rock glaciers (elevated porosity and ground ice) compared to the broader dataset, as well as the advanced state of degradation ofin these landforms (e.g., supra-permafrost talik formation at boreholes 6-1 and 6-4, Figure 8). Excluding rock glaciers, the depth to top ofrelationship between permafrost decreases bydepth and altitude is approximately -1.9 m/km elevation gain ($r^2 = 0.30$), while permafrost). Permafrost thickness increasesappears to increase with increasing altitude at approximately 300 m/km ($r^2 = 0.45$).

Incorporating slope aspect into the analysis reveals that the zero-degree isotherm for ground temperature occurs at higher elevations on northeast-the north-east facing slopes, ranging from below 3,700 m (within rock glaciers) to approximately 5,000 m (Figure 13a). This asymmetry is partly duemay be attributed in part to variations in average incident solar radiation with aspect (Figure 13b), and more broadly to the geographical position of the study area within the southern hemisphere. Coincidentally, all monitoring locations within rock glaciers are on south-facing slopes, where and in areas that experience lower solar radiation may help sustain. In addition to their unique morphological characteristics, porosity and ground ice content, this lower average solar radiation may contribute to the persistence of permafrost in these particular landforms.



SITE 1
SITE 2
SITES 3 & 4
SITE 5
SITES 6 & 7
SITE 8
CHILE
ARGENTINA
28° S
30° S
32° S
70° W
69° W
MAGT (°C)
-9 to -2
-2 to 0
0 to 0.5
0.5 to 2
2 to 7.5
N
CL AR

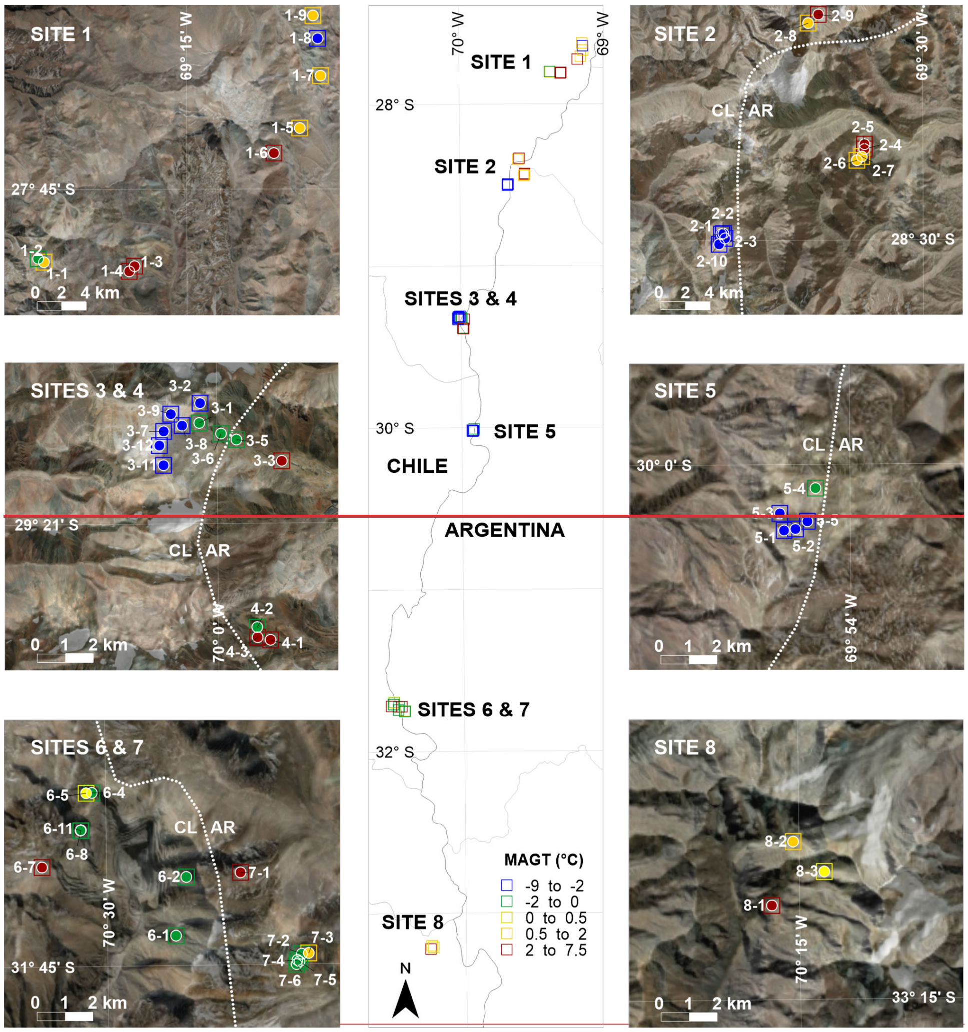


Figure 11: Representative ground temperatures across the study area. Measurements are shown for depths of 20 m and/or within permafrost~~cryotic~~ zones of the boreholes (boreholes 3-5, 6-2, 6-4, 6-8 and 6-11), or from the deepest sensor if the thermistor string was shorter than 20 m (boreholes 3-3 and 5-1). Temperature values and measurement depths are summarized in Table S1~~A1~~.

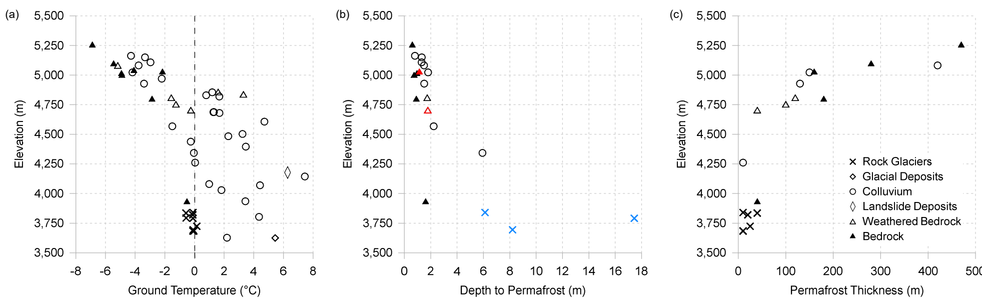
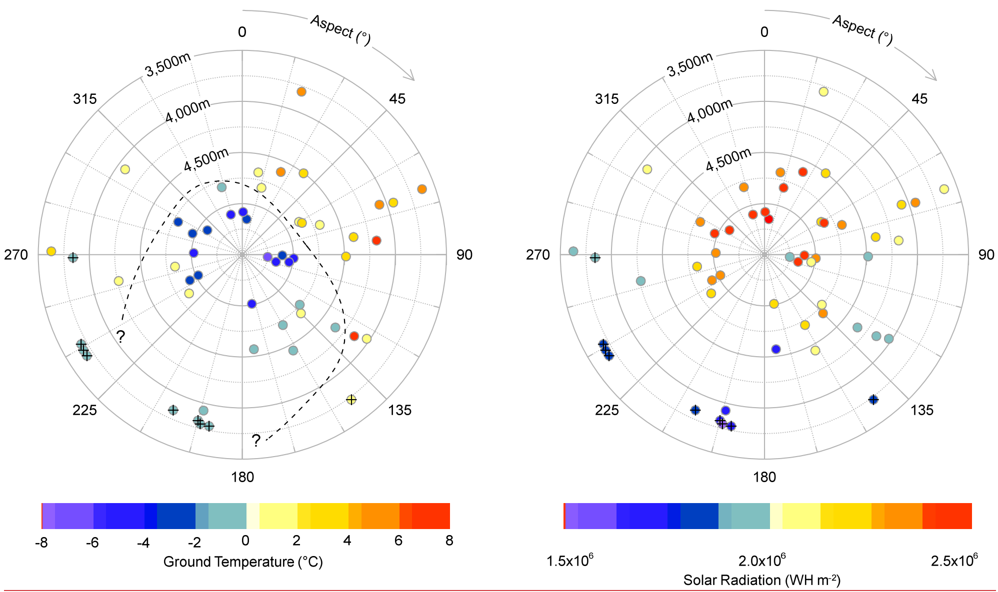


Figure 12: Relationship of (a) ground temperatures and (b) depth to permafrost and (c) permafrost thickness with altitude. Thaw depth and depth to permafrost table coloured red and blue on diagram (b). The remaining points on diagram (b) represent the thickness of the active layer (ALT).


Aspect (°)
0
45
90
135
180
225
270
315
3,500m
4,000m
4,500m
?
?
-8
-6
-4
-2
0
2
4
6
8
Ground Temperature (°C)
Aspect (°)
0
45
90
135
180
225
270
315
3,500m
4,000m
4,500m
1.5x10^6
2.0x10^6
2.5x10^6
Solar Radiation (WH m-2)

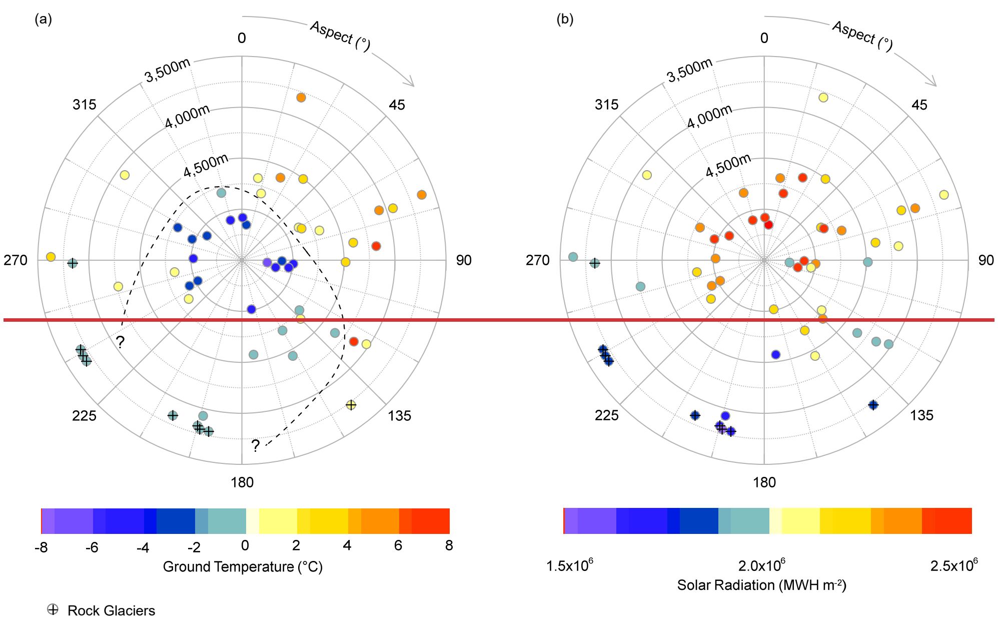


Figure 13: Aspect-elevation diagrams showing variations in (a) ground temperature and (b) average incident solar radiation. Aspect was estimated from ASTER GDEM v3 Worldwide Elevation Data (1 arc-second Resolution). Solar radiation estimated using ESRIesri Area Solar Radiation toolset. (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/area-solar-radiation.htm).

5 Discussion

5.1 Significance of the Dataset

Permafrost extent, thermal state, and the nuanced thermal characteristics of rock glaciers have been well characterized through extensive research conducted in circumpolar regions and mountain environments of the northern hemisphere. Many studies have been able to unequivocally demonstrate permafrost degradation in response to atmospheric warming, as they are based on multi-decadal ground temperature datasets, some with measurement records spanning up to 40 years in length (e.g., Smith et al., 2022; PERMOS, 2023). Despite the growing interest and important strides towards building an understanding of permafrost in the Andes (e.g., Trombotto et al., 1997; Trombotto and Borzotta, 2009; DGA, 2010; Andrés et al., 2011; Monnier and Kinnard, 2013; Nagy et al., 2019; Yoshikawa et al., 2020; Mena et al., 2021; Vivero et al., 2021), the volume of research in the region remains comparatively limited. As a result, the understanding of permafrost in the Andes is less comprehensive than the well-established knowledge of permafrost elsewhere, highlighting the need to verify hypotheses using in-situ measurements. This study provideshas revealed new insights into permafrost dynamics in the Central Andes, some which were previously hypothesized based on studies from other permafrost regions but lacked sufficient data to confirm their broader relevance to South America. It represents The present study constitutes the largest and most regionally extensive compilation of ground temperature data from high altitude (>3,500 m) sites with permafrost in South America to date, filling a critical knowledge gap in permafrost research.. Using data from 53 boreholes (varying from 10 m to 100 m deep)in depth and within both permafrost and non-permafrost zones, the compilation provides a unique snapshot of ground thermal state within the Andean Cordillera of Chile and Argentina. Adequate depth of monitoring throughout the dataset enables characterizationallows for a depiction of average temperatures below the DZAAdepth of seasonal influences, visualization of borehole thermal gradients, and first-order estimates of the permafrost thickness of, and depth to, permafrost. This level of insight surpasses that of the few key existing monitoring studies in the Andes, which generallytypically are limited to boreholes justthat reach only a few metres deepmeters in depth (Trombotto et al., 1997; Trombotto and Borzotta, 2009; DGA, 2010; Andrés et al., 2011; DGA, 2019; Nagy et al., 2019; Yoshikawa et al., 2020; Mena et al., 2021; Vivero et al., 2021).

AnPerhaps the most important implication of this work is that the data can be used to validatesubstantiate existing characterizations of permafrost distribution models in the region, which were previously developed from field observations and statistical methods, but without any borehole temperature data (e.g., Arenson and Jakob, 2010; Ruiz and Trombotto, 2012). Additionally, havingthe availability of ground temperature data within permafrost and non-permafrost zones helps reducein this study reduces the risk of site-selection bias towards permafrost presence, which can complicate evaluations of spatially distributed models predicting permafrost. Beyond validating existing permafrost distribution models in the region, data from this study may also be utilized to support upscaling endeavors like those of Mathys et al. (2022), which aim to quantify ice content in Andean permafrost regions and informprovide crucial insights for future water resource planning and decision-making amidst the challenges posed by climate change.

SeveralOn its own, several important insights can be derived from the presented dataset that broaden the understanding of permafrost thermal state in both the Andes and the global permafrost context. Some of these findingsinsights are consistent with observations in other permafrost regions, while others maycould be uniquely representrepresentative of the Central Andes, or more precisely, the region within the altitudinal and latitudinal constraints of the dataset (i.e., 3,625 m to 5,251 m and 27°S-34°S). These are discussed further in the sections that follow.

5.2 Temporal Variations in Ground Temperature Evolution and Response to Climatic Influences

The A distinguishing characteristic of the presented dataset from other permafrost studies is that the Andean data compilation shows no consistent trend do not show a clear indication of warming in recent history. Instead, ; rather, they indicate both warming and cooling of the ground are inferred from over time series, seemingly without correlation to location, elevation, or surface substrate. This is observed in the time series data (Section 4.1) and deduced from analyses of thermal gradient analysis

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

gradients (Section 4.4). Limited by the short monitoring period), with the lack of correlation between temperature change with topography for both methods illustrated (Figure 14a and Figure 14b). Both analysis methods present limitations to data interpretation, notably the short record length in time series (<10 years), the time series analysis captures) hindering the assessment of long-term trends, and the analyses of thermal gradients (despite potentially being more reliable indicators of decadal-scale temperature change) relying on numerous simplifying assumptions about the medium. Some variability in temperature evolution with time may, however, reflect local topographic conditions and short-term climate fluctuations driven by seasonal and inter-annual climate variability and the study area's mountainous topography. While thermal gradient analysis may offer more reliable decadal-scale estimates of ground temperature change, its failure to show a consistent trend could stem from oversimplified assumptions about borehole geology and varying climatic conditions across locations.

Due the short record length, geologic complexity and topo-climatic variability between sites, it is not possible to determine whether the ground thermal regime in the study area follows long-term warming trends observed in other permafrost regions. However, it is worth noting that similar deviationsthat obscure longer-term global trends. Similar short-term permafrost temperature fluctuations, which deviate from long-term trends have been observed in global datasets,air temperature rises and are linked to short-term local meteorological conditions, are known to exist within global datasets despite overarching trends of subsurface warming (influences (e.g., Biskaborn et al., 2019; Etzelmüller et al., 2020; Haberkorn et al., 2021). Additionally, localized. Localized changes in snow cover, vegetation, and soil moisture content, especially in mountain environments, are known to significantly impact the thermal state of the ground, as evidenced by. For example, periods of permafrost cooling in the Alps in were observed during 2016 and 2023, and attributed to anomalously low snow conditions during those years (PERMOS, 2023). Also in the Alps, summer heat waves during 2016 and 2019 were shown to correlate with short-term increases in active layer thickness (PERMOS, 2023), and water percolation has been linkedshown to acceleratedaccelerate permafrost degradation (Luethi et al., 2017). Interannual variability At several of our monitoring locations in the Andes, snow cover isvariability may be inferred fromby the occurrence of near-surface isothermal conditions within the active layer at several of our Andean boreholesfrom year to year (Figures S1A1 through S53). The resultingA53). This would contribute to both the temporal and spatial variability in ground temperatures observed in the presented dataset due to irregular insulation of the ground during winters, along with inconsistent and possible infiltration of meltwater in the spring, likely contributes to both temporal and spatial variability of ground temperatures in the dataset, although latent heat released from thein association with annual freezing and thawing of porewater may also play a role. The significant dryness of the Central Andes compared to other mountain environments, which has been exacerbated in recent years by the megadrought (Garreaud et al., 2020), also leads to comparatively less water available from snowmeltsnow melt to infiltrate the ground and promote permafrost degradation. Long-termAnother possibility for lack of a clear warming trends may alsotrend in ground temperatures could be obscured bythat temporary, localized surface temperature inversions, which can cause are occurring, or have occurred in recent years, causing air temperatures at lower elevations in the dataset to be cooler than might otherwise be expected, and vice versa. Such inversions have been shown to createlead to unique permafrost conditions in near-proximity dissimilar valleys in Yukon,

Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)
Formatted: English (United Kingdom)

Canada, where groundwith air temperatures at some high-altitude sites arefound to be significantly warmer than those attheir adjacent valley bottoms ((Lewkowicz et al., 2012; Noad and Bonnaventure, 2023).

At a more regional scale, the combined influence of SAM, the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on South American climate patterns (e.g., Mantua and Hare, 2002; Montecinos and Aceituno, 2003; Vuille et al., 2015; Saavedra et al., 2018; Garreaud et al., 2020; Yoshikawa et al., 2020; González-Reyes et al., 2020; King et al., 2023)) can temporarilyexhibit temporary influence on the ground thermal regime across the study area. This would occur primarily through changes to spatial and temporal snowpack distribution, and snow-albedo feedback, andas well as through variations in water infiltration that impact latent heat absorption. Although temperature can impact absorption of latent heat. Interactions of ENSO and IPO may have contributed to a decline in precipitation in the late 20th century (Schulz et al., 2012), potentially influencing historical ground temperatures. However, oceanic phenomena are presumed to have had little influence on the rainfall deficit associated with the megadrought that has persisted in Central Chile for the past two decades (Garreaud et al., 2020). Temperature and precipitation patterns directly related to SAM,the ENSO and PDO, and their potential impacts to the ground thermal regime, were not examined in this paper. However, some patterns are apparent for the Central Andes and may be applicable to the study area. This includes temporary cooling trends observed in shallow (2 m deep) ground temperatures simultaneously with deceleration of several rock glaciers at a site with permafrost in Central Chile (and located within the range of sites in this study) aligningthat coincided with lower MAATs during the same period (2010-2015). These cooling trends were postulated to be linked to the predominance of La Niña (cold and dry phase of the ENSO) and neutral ENSO conditions since 2009 (Vivero et al., 2021).

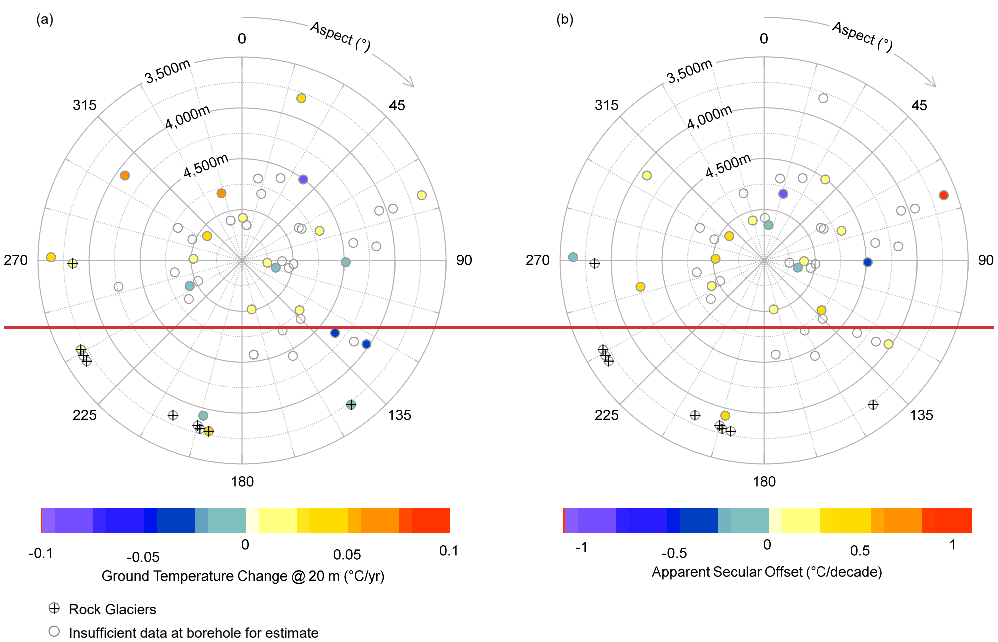
With a monitoring record that currently falls short of the ideal length to assess impacts of atmospheric warming on ground temperatures (i.e., 20 years or more), air temperature data collected in the study region may offer complimentary insights to the observations presented in this work. A summary of MAATs in mountainous regions in South America by (Hock et al., 2019), which is based on very limited monitoring data, indicatesillustrates lower warming rates or even slight cooling trends when compared to global studies. One meteorological station located at Site 3 (~5,000 m, ~29°S) demonstrates relatively stable air temperatures over 20 years of monitoring (1999-2021, Figure 1415). This apparent stability and/or slight lowering of MAATs in South America suggests that the trajectory of ground temperatures in the Andes is also likely to be unique from other regions that show clear signs of warming. TheIt is also worth noting that the unique topo-climatic attributes of the Andean cryosphere – characterized by specifically the combination of arid conditions, high solar radiation, minimallack of vegetative cover and organic matter, and less massive ice (except for rock glaciers) together with mountain topography – may expedite energy transfer processes and reduce latency of temperature change compared to other permafrost regions, both in mountains and the Arctic. Regardless of the specific mechanisms drivinginfluencing ground temperature evolution in the Andes, the preceding discussions emphasize the importance of continued monitoring to establish robust connections with climate change. This effort must also consider local climate and geographic conditions, as well as relationships with oceanic phenomena.

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)



~~**Figure 14: Aspect-elevation diagrams showing variations in (a) ground temperature change and (b) apparent secular offset. Some estimates shown in (a) are from depths other than at 20m (i.e., at the maximum sensor depth for thermistor strings shorter than 20m, or depth adjusted to illustrate trends within cryotic zones).**~~

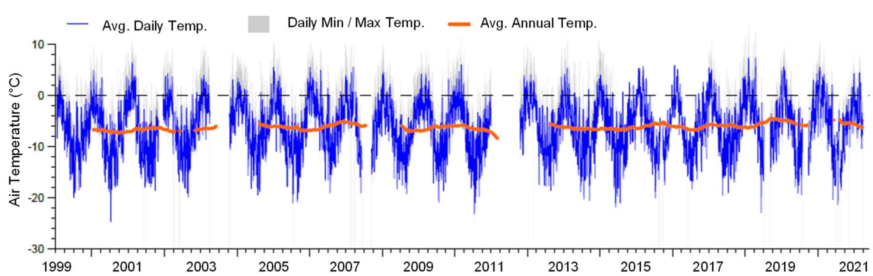


Figure 14: Air temperature time series collected at Site 3 (El 4,927 m). Shows stability of temperature data over 20 years. Source: BGC Engineering Inc. (2021).

5.3 Shared Characteristics with other Mountain Permafrost Regions

Although the topo-climatic conditions of the Andes are unique among permafrost zones, ~~the ground temperature data compiled in this study illustrate~~ some common characteristics with other mountain ~~permafrost~~ environments can be discerned from the data compiled in this study. High~~. Attributes of the dataset such as high~~ spatial heterogeneity in ground temperatures, correlations with altitude and slope aspect, and~~as well as~~ distinct thermal characteristics of rock glaciers compared to other landforms, suggest~~imply~~ that similar~~analogous~~ processes are shaping the current and changing ground thermal regime in the Central Andes.

Significant variations in ground temperature over short horizontal distances - ~~—~~shifting from cold to warm permafrost (< -2°C ~~-~~to 0°C) and/or non-permafrost~~cryotic~~ ground within less than 5 km - ~~horizontally —~~emphasizes the strong microclimatic influence on the distribution of permafrost at catchment level over regional climate stressors. The~~Together with nearby geophysical surveying efforts by Hilbich et al. (2022), this highlights the challenge of upscaling point information, such as boreholes and geophysical results, to larger catchments in the Andes (Mathys et al., 2022). The overall~~ pattern of decreasing ground temperatures, greater ~~and~~ depth to permafrost, and increasing permafrost thicknesses with increasing altitude, reflects the~~an~~ orographic influence of air temperatures, a ~~across the dataset, which is an attribute~~ common feature of~~to~~ mountainous regions.

The spatial pattern of ground temperatures with respect to slope aspect reflects~~may reflect~~ the asymmetry of incident solar radiation of the geographic region, resulting in a higher elevation of the zero-degree ground temperature isotherm on northeast facing slopes. These characteristics were previously inferred~~assumed to exist~~ for the Central Andes based on regional climate and mapping studies ~~in the region~~ (e.g., Saito et al., 2016) ~~, ground temperature characterizations in mountain permafrost elsewhere~~ and general knowledge of mountain permafrost environments (e.g., Haeberli, 1973). However, until now, these assumptions ~~they~~ were not extensively validated~~illustrated~~ with ground temperature data specific to the Andes~~, and as discussed above, the findings of this study have created a new opportunity for permafrost researchers to validate their analyses of permafrost distribution in the region~~.

Rock glaciers emerge as thermally unique permafrost landforms in the Andean dataset, a characteristic that has been~~Also~~ widely observed in~~demonstrated for~~ other mountain permafrost regions (e.g. Barsch, 1977).~~, rock glaciers emerge as thermally unique permafrost features in the Andean dataset.~~ This uniqueness~~distinction of rock glaciers from other boreholes~~ arises from~~due to~~ their ~~characteristic~~ coarse blocky morphology and high~~resultant elevated~~ porosity,~~; attributes~~ which enable substantial variations in air, water, and ground ice content - factors~~. This variability is~~ known significantly~~to exert a significant~~ influence ~~on~~ ground temperatures, both spatially and temporally. This effect is particularly pronounced~~, especially~~ when rock glaciers contain substantial ground~~amounts of~~ ice ~~and~~ near the phase change temperature (e.g., Haeberli et al., 2006). Ground temperatures within rock glaciers in the Andean dataset do not follow general altitudinal relationships~~trends~~ of other boreholes—instead, they consistently show lower temperatures than other boreholes at similar elevations, likely due to ~~the combination of~~ reduced thermal conductivity, ~~and~~ convective cooling in the ~~blocky~~ active layer and the sustained presence of ground ice fromdue to latent heat. Depth Estimated depth to permafrost and permafrost thickness inwithin rock glaciers also deviate from the broader altitudinal relationshipselevation trends observed in the dataset, exhibitingwith a greater depth to permafrost consistent with rock glaciers marking the lower limit of permafrost in the dataset. Rock glaciers also exhibit the greatest and most variable depths to permafrost, and lowest estimated permafrost thickness within the dataset. Within rock glaciers, permafrost depth was estimated to be (i.e., > 7 m and permafrost thicknesses ranged betweendeep and approximately 2 m to 40 m (10 m thick in rock glaciers, compared to depths < 4 m and thicknesses typically < 4 m deep and > 40 m thick in other permafrost boreholes). The formation of a supra-permafrost talik at two locations (boreholes 6-1 and 6-4) reflects an advanced state of degradation observed in these landforms.

Finally, rock glaciers appear to mark the lowest altitudinal limit of permafrost in the Andean dataset, with the lowest measurements —slightly below 3,700 m at Site 6. The remaining, with the remainder of measurements withinin rock glaciers clusterclustering near 0°C between elevations of 3,700 m and 3,800 m, and other permafrostthe majority of cryotic boreholes are located at altitudes >in the dataset not in rock glaciers occurring above 4,250 m. Although this estimate is roughly alignsconsistent with previously reported limits in the region (i.e., ranging between 2,900 m and 3,200 m, and occasionally reaching elevations of 3,700 m (Saito et al., 2016).), caution is warrantedemphasized regarding the representativeness of the presented estimates due to sample coverage bias associated withresulting from industry- driven data collection, needs rather than specific permafrost delineation objectives. The same caution applies toin consideration of the asymmetry of the interpreted zero-degree ground temperature isotherm with respect to aspect for the full dataset.; while. While rock glaciers occur on south-facing slopes and in areas that experience lower solar radiation, their absence on north facing slopes may partially be a consequence of sampling bias rather than influence of solar radiation effects.

6 Conclusion

This study presentsrepresents the first regional compilation of in-situ ground temperature data collected from mountain permafrost regions of the Central Andes (27°S-34°S) at depths below seasonal influences. Compiled from 53 boreholes along a 650 km- long north-south transect near the Chilean-Argentine border, the dataset offerscontributes new insights into regional baseline thermal conditions andthat broaden the understanding of permafrost temperature dynamics in South America. The presented analyses highlight similaritiesdemonstrate parallels with ground temperature characteristics of other mountain permafrost regions of the world, while also revealing unique aspects of the ground thermal regime inunique to the Central Andes. Pronounced spatial variability in ground temperatures, correlations with altitude and slope aspect, and distinctdistinctive thermal characteristicsattributes of rock glaciers relative to other landforms suggest that processes influencing the ground thermal regime in the Central Andes are analogous to other mountain permafrost environments. HoweverAt the same time, the unique combination of topo-climatic and geomorphic attributes of the Andean cryosphere (including high aridity, solar radiation, lack of vegetation and organic matter, lower overall massive ice content andcombined with mountainous terrain) may enhance energy transfer with the ground compared to other permafrost regions. The length of monitoring in the dataset—less than ten years of consecutive measurements—currently does not allow for assessment of long-term trends in response to climate change. In addition, the region's susceptibility to regional climate~~oceanic~~ phenomena such as SAM, ENSO and PDO, which occur on decadal timescales, implies that~~, in contrast to the northern hemisphere, it is likely that~~ long-term ground temperature trends for the Central Andes may only be derived from very long time-series spanning several of these cycles. The observed temporal variability in the dataset thus reflects local topographic factors and short-term microclimatic~~micro-climatic~~ fluctuations unique to the catchment(s) monitored.

This compilation fills a critical knowledge gap in permafrost research, providing~~In addition to the insights gained from the analyses presented, this study creates~~ an opportunity to ~~validate and~~ refine existing permafrost distribution models in the Andean region, which ~~that~~ were developed from indirect evidence of permafrost occurrence. Integrating insights from~~results of~~ this study can enhance~~improve~~ the accuracy and reliability of these models, aligning them more closely with ~~the~~ well-calibrated models established for Europe and North America, which are based on ~~that benefit from~~ extensive in-situ data. This study~~The presented dataset~~ may also support data upscaling efforts towards~~, which play a pivotal role in~~ quantifying ground ice content in permafrost regions across broader spatial scales in the region – efforts that~~. Such endeavors~~ are essential for informing predictive models, especially in the context of climate change, where accurate assessments of permafrost dynamics are crucial for effective water resource planning and decision-making. By integrating~~The integration of~~ results from this compilation~~, into such upscaling efforts thus holds promise for~~ researchers can further~~to~~ advance the~~a more comprehensive~~ understanding of interactions between permafrost and hydrology in the Andean region under ongoing global atmospheric warming.

Many of the data collection challenges outlined in this paper are common to mountain permafrost studies elsewhere.~~outside of the Andes.~~ These include natural, logistical, and financial limitations, which occasionally led to interruptions or shortened monitoring records, or introduced artifacts into the ~~collected~~ data. In addition to these challenges, this study faced constraints related to~~stemming from~~ industry requirements~~needs~~ and regulatory mandates~~requirements~~, which dictated thermistor placement and influenced data collection and instrument maintenance schedules. Since monitoring efforts had~~objectives were required~~ to align with objectives~~needs~~ of environmental impact assessments~~, (EIAs),~~ boreholes were established primarily to meet these needs~~,~~ rather than for research purposes. Consequently, instrument positioning and data collection schedules were not optimized for permafrost characterization or long-term monitoring, as would be the case in a dedicated scientific research project.

The~~It is possible that the current~~ scarcity of in-situ data in the Central Andes may reflect ~~is a reflection of~~ compounding challenges posed by~~of~~ difficult terrain and significant sectorial constraints. In this context~~sense~~, the present study represents a unique and exemplary collaboration between industry, academia, and bi-national regulators, advancing ~~for~~ the ~~advancement of~~ understanding of a key indicator of climate change in a region that is underrepresented in the Global Climate Observing System ~~(GCOS)~~ and permafrost literature. This~~Through this~~ collaboration has provided~~,~~ new insights into ground thermal characteristics of the Central Andes ~~have been revealed~~, which were not previously demonstrated with ground-based data. It alsoThis highlights the importance ofvalue and imperative for multi-stakeholder partnerships in advancing knowledge of permafrost thermal state of permafrost alongside other critical issues related to climate change.

Competing interests

At least one of the (co-)authors is a member of the editorial board of The Cryosphere. This work was partially funded by BGC Engineering Inc and University of Fribourg as a graduate research project.The authors declare that they have no conflicts of interest.

Acknowledgements

The authors would like to acknowledge the team of engineers and scientists at BGC Ingenieria Ltda. in Chile and Argentina for the collection and processing of data presented in this paper. The support from BGC Engineering Inc. and their clients in providing the opportunity to compile and analyse this dataset is further acknowledged and appreciated.

Supplementary Information

Supplementary information related to this article is available online at XX URL XX

References

Abram, N., Gattuso, J.-P., Prakash, A., Cheng, L., Chidichimo, M. P., Crate, S. , Enomoto, H., Garschagen, M., Gruber, N., Harper, S., Holland, E., Kudela, R. M., Rice, J., Steffen, K., and von Schuckmann, K.: Framing and Context of the Report, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M. , Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 78–129, 2019.

Andrés, N., Palacios, D., Úbeda, J., and Alcalá, J.: Ground Thermal Condition at Chachani Volcano, Southern Peru, Geografiska Annaler: Series A, Physical Geography, 93, 151–162, https://doi.org/https://doi.org/10.1111/j.1468-0459.2011.00424.x, 2011.

Arenson, L. U. and Jakob, M.: A New GIS based Mountain Permafrost Distribution Model, Proceedings, 63rd Canadian Geotechnical Conference & 6th Canadian Permafrost Conference, 2010.

Arenson, L. U., Harrington, J. S., Koenig, C. E. M., and Wainstein, P. A.: Mountain Permafrost Hydrology—A Practical Review Following Studies from the Andes, Geosciences (Basel), 12, https://doi.org/10.3390/geosciences12020048, 2022.

Formatted: Font: 12 pt

Atacama Ambiente: Estudio de caracterización de temperaturas subsuperficiales mediante cintas termistoras, proyecto minero Salares Norte. Santiago: En: Estudio de impacto ambiental Salares Norte. Goldfields. Anexo 3.2.11-11. Soluciones de Gestión Ambiental, SGA., 2017.

Barsch, D.: Nature and importance of mass-wasting by rock glaciers in alpine permafrost environments, Earth Surface Processes, 2, 231–245, https://doi.org/https://doi.org/10.1002/esp.3290020213, 1977.

Biskaborn, B. K., Lanckman, J.-P., Lantuit, H., Elger, K., Streletskiy, D. A., Cable, W. L., and Romanovsky, V. E.: The new database of the Global Terrestrial Network for Permafrost (GTN-P), Earth Syst Sci Data, 7, 245–259, https://doi.org/10.5194/essd-7-245-2015, 2015.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., and Lantuit, H.: Permafrost is warming at a global scale, Nat Commun, 10, 264, https://doi.org/10.1038/s41467-018-08240-4, 2019.

Brown, J., Hinkel, K., and Nelson, F.: The Circumpolar Active Layer Monitoring (CALM) program, Polar Geography, 24, 166–258, https://doi.org/10.1080/10889370009377698, 2000.

Bruniard, E. D.: La Diagonal Árida Argentina: un Límite Climático Real, Revista Geográfica, 5–20, 1982.

Carrasco, J., Casassa, G., and Quintana, J.: Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century / Changements de l'isotherme 0°C et de la ligne d'équilibre des neiges dans le Chili central durant le dernier quart du 20ème siècle, Hydrological Sciences Journal/Journal des Sciences Hydrologiques, 50, 948, https://doi.org/10.1623/hysj.2005.50.6.933, 2005.

Catalano, L. R.: Contribución al Conocimiento de los Fenómenos Geofícos Atmosféricos (en base a observaciones efectuadas en la Puna de Atacama, territorio nacional de Los Andes), Ministerio de Agricultura. Dirección General de Minas, Geología e Hidrología, Buenos Aires, 1926.

Christiansen, H. H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J., Holmlund, P., Sannel, A. B. K., Sigsgaard, C., Åkerman, H. J., Foged, N., Blikra, L. H., Pernosky, M. A., and Ødegård, R. S.: The thermal state of permafrost in the nordic area during the international polar year 2007–2009, Permafr Periglac Process, 21, 156–181, https://doi.org/https://doi.org/10.1002/ppp.687, 2010.

Corte A: Contribución a Ia Morfología Periglacial de Ia Alta Cordillera con Especial Mención deI Aspecto Criopedológico, 54 pp., 1953.

Derksen, C., Burgess, D., Duguay, C., Howell, S., Mudryk, L., Smith, S., Thackeray, C., and Kirchmeier-Young, M.: Changes in snow, ice, and permafrost across Canada, in: Canada's Changing Climate Report, edited by: Bush, E. and Lemmen, D. S., Government of Canada, Ottawa, Ontario, 194–260, 2019.

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

Dirección General de Aguas (DGA): Dinámica de glaciares rocosos en el Chile semiárido. Technical report, Santiago de Chile, 2010.

Formatted: Spanish (Spain)

Dirección General de Aguas (DGA): Plan de Monitoreo Nacional de Permafrost, Santiago de Chile, 2019.

Dobiński, W.: Permafrost active layer, Earth Sci Rev, 208, 103301, https://doi.org/https://doi.org/10.1016/j.earscirev.2020.103301, 2020.

Etzelmüller, B., Guglielmin, M., Hauck, C., Hilbich, C., Hoelzle, M., Isaksen, K., Noetzli, J., Oliva, M., and Ramos, M.: Twenty years of European mountain permafrost dynamics—the PACE legacy, Environmental Research Letters, 15, 104070, https://doi.org/10.1088/1748-9326/abae9d, 2020.

van Everdingen, R. O.: Multi-Language Glossary of Permafrost and Related Ground ice Terms (Revised 2005); International Permafrost Association: Ottawa, ON, Canada, 1998.

Falvey, M. and Garreaud, R. D.: Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006), Journal of Geophysical Research: Atmospheres, 114, https://doi.org/https://doi.org/10.1029/2008JD010519, 2009.

Garreaud, R.: The Andes Climate and Weather, Adv. Geosci, 22, 3–11, https://doi.org/10.5194/adgeo-22-3-2009, 2009.

Formatted: Spanish (Spain)

Garreaud, R., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H., and Veloso, D.: The Central Chile Mega Drought (2010-2018): A Climate dynamics perspective, International Journal of Climatology, 40, https://doi.org/10.1002/joc.6219, 2020.

González-Reyes, Á., Jacques-Coper, M., Muñoz, A. A., González-Reyes, Á., Jacques-Coper, M., and Muñoz, A. A.: Seasonal precipitation in South Central Chile: trends in extreme events since 1900, Atmósfera, 34, 371–384, https://doi.org/10.20937/ATM.52871, 2020.

Gruber, S. and Haeberli, W.: Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change, J Geophys Res Earth Surf, 112, https://doi.org/https://doi.org/10.1029/2006JF000547, 2007.

Haberkorn, A., Kenner, R., Noetzli, J., and Phillips, M.: Changes in Ground Temperature and Dynamics in Mountain Permafrost in the Swiss Alps, Front Earth Sci (Lausanne), 9, 626686, https://doi.org/10.3389/feart.2021.626686, 2021.

Haeberli, W.: Die Basis-Temperatur der winterlichen Schneedecke als moglicher indikator fur die Verbreitung von permafrost in den Alpen, Zeitschrift für Gletscherkunde Und Glazialgeologie, 9, 221–227, 1973.

Haeberli, W.: Special aspects of high mountain permafrost methodology and zonation in the Alps, Proceedings of the Third International Permafrost Conference, 379–383, 1978.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., and Mühll, D. V.: Permafrost creep and rock glacier dynamics, Permafr Periglac Process, 17, 189–214, https://doi.org/https://doi.org/10.1002/ppp.561, 2006.

Halla, C., Blöthe, J. H., Tapia Baldis, C., Trombotto Liaudat, D., Hilbich, C., Hauck, C., and Schrott, L.: Ice content and interannual water storage changes of an active rock glacier in the dry Andes of Argentina, Cryosphere, 15, 1187–1213, https://doi.org/10.5194/tc-15-1187-2021, 2021.

Hauck, C., Böttcher, M., and Maurer, H.: A new model for estimating subsurface ice content based on combined electrical and seismic data sets, Cryosphere, 5, https://doi.org/10.5194/tc-5-453-2011, 2011.

Hilbich, C., Hauck, C., Mollaret, C., Wainstein, P., and Arenson, L. U.: Towards accurate quantification of ice content in permafrost of the Central Andes – Part 1: Geophysics-based estimates from three different regions, Cryosphere, 16, 1845–1872, https://doi.org/10.5194/tc-16-1845-2022, 2022.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, Al., Molau, U., Morin, S., Orlove, B., and and H. Steltzer: High Mountain Areas, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., M., T., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., Cambridge University Press, 131–202, https://doi.org/10.1017/9781009157964.003, 2019.

Isaksen, K., Sollid, J. L., Holmlund, P., and Harris, C.: Recent warming of mountain permafrost in Svalbard and Scandinavia, J Geophys Res Earth Surf, 112, https://doi.org/https://doi.org/10.1029/2006JF000522, 2007.

Jacques-Coper, M. and Garreaud, R. D.: Characterization of the 1970s climate shift in South America, International Journal of Climatology, 35, 2164–2179, https://doi.org/https://doi.org/10.1002/joc.4120, 2015.

Jones, D. B., Harrison, S., Anderson, K., and Whalley, W. B.: Rock glaciers and mountain hydrology: A review, Earth Sci Rev, 193, 66–90, https://doi.org/https://doi.org/10.1016/j.earscirev.2019.04.001, 2019.

King, J., Anchukaitis, K. J., Allen, K., Vance, T., and Hessl, A.: Trends and variability in the Southern Annular Mode over the Common Era, Nat Commun, 14, 2324, https://doi.org/10.1038/s41467-023-37643-1, 2023.

Kokelj, S. V, Lantz, T. C., Tunnicliffe, J., Segal, R., and Lacelle, D.: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada, Geology, 45, 371–374, https://doi.org/10.1130/G38626.1, 2017.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F.: World Map of the Köppen-Geiger Climate Classification Updated, Meteorologische Zeitschrift, 15, 259–263, https://doi.org/10.1127/0941-2948/2006/0130, 2006.

Koven, C. D., Lawrence, D. M., and Riley, W. J.: Permafrost carbon−climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics, Proceedings of the National Academy of Sciences, 112, 3752–3757, https://doi.org/10.1073/pnas.1415123112, 2015.

Krautblatter, M., Verleysdonk, S., Flores Orozco, A., and Kemna, A.: Temperature-calibrated imaging of seasonal changes in permafrost rock walls by quantitative electrical resistivity tomography (Zugspitze, German/Austrian Alps), J Geophys Res, 115, https://doi.org/10.1029/2008JF001209, 2010.

Lachenbruch, A. H. and Marshall, B. V.: Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic, Science (1979), 234, 689–696, 1986.

Lewkowicz, A. G., Bonnaventure, P. P., Smith, S. L., and Kuntz, Z.: Spatial and thermal characteristics of mountain permafrost, northwest Canada, Geografiska Annaler: Series A, Physical Geography, 94, 195–213, https://doi.org/https://doi.org/10.1111/j.1468-0459.2012.00462.x, 2012.

Luethi, R., Phillips, M., and Lehning, M.: Estimating Non-Conductive Heat Flow Leading to Intra-Permafrost Talik Formation at the Ritigraben Rock Glacier (Western Swiss Alps), Permafr Periglac Process, 28, 183–194, https://doi.org/https://doi.org/10.1002/ppp.1911, 2017.

Mantua, N. and Hare, S.: The Pacific Decadal Oscillation, J Oceanogr, 58, 35–44, https://doi.org/10.1023/A:1015820616384, 2002.

Masiokas, M., Christie, D., Quesne, C., Pitte, P., Ruiz, L., Villalba, R., Luckman, B., Berthier, E., Nussbaumer, S., Gonzalez Reyes, A., Mcphee, J., and Barcaza, G.: Reconstructing the annual mass balance of the Echaurren Norte glacier (Central Andes, 33.5° S) using local and regional hydroclimatic data, Cryosphere, 10, 927–940, https://doi.org/10.5194/tc-10-927-2016, 2016.

Masiokas, M. H., Rabatel, A., Rivera, A., Ruiz, L., Pitte, P., Ceballos, J. L., Barcaza, G., Soruco, A., Bown, F., Berthier, E., Dussaillant, I., and MacDonell, S.: A Review of the Current State and Recent Changes of the Andean Cryosphere, Front Earth Sci (Lausanne), 8, https://doi.org/10.3389/feart.2020.00099, 2020.

Mathys, T., Hilbich, C., Arenson, L. U., Wainstein, P. A., and Hauck, C.: Towards accurate quantification of ice content in permafrost of the Central Andes – Part 2: An upscaling strategy of geophysical measurements to the catchment scale at two study sites, Cryosphere, 16, 2595–2615, https://doi.org/10.5194/tc-16-2595-2022, 2022.

Mena, G., Yoshikawa, K., Schorghofer, N., Pasten, C., Ochoa-Cornejo, F., Yoshii, Y., Doi, M., Miyata, T., Takahashi, H., Casassa, G., and Sone, T.: Freeze–thaw cycles and snow impact at arid permafrost region in Chajnantor Volcano, Atacama, northern Chile, Arct Antarct Alp Res, 53, 60–66, https://doi.org/10.1080/15230430.2021.1878739, 2021.

Miner, K. R., Malina, E., and Bartsch, A.: Permafrost carbon emissions in a changing Arctic, Nat Rev Earth Environ, 55–67, https://doi.org/10.1038/s43017-021-00230-3, 2022.

Mollaret, C., Wagner, F., Hilbich, C., Scapozza, C., and Hauck, C.: Petrophysical Joint Inversion Applied to Alpine Permafrost Field Sites to Image Subsurface Ice, Water, Air, and Rock Contents, Front Earth Sci (Lausanne), 8, 85, https://doi.org/10.3389/feart.2020.00085, 2020.

Monnier, S. and Kinnard, C.: Internal structure and composition of a rock glacier in the Andes (upper Choapa valley, Chile) using borehole information and ground-penetrating radar, Ann Glaciol, 54, 61–72, https://doi.org/10.3189/2013AoG64A107, 2013.

Montana, J., Morales, C., Nicora, M. G., Ardila, J., Schurch, R., and Aranguren, D.: Lightning Activity Over Chilean Territory, Journal of Geophysical Research: Atmospheres, 126, e2021JD034580, https://doi.org/https://doi.org/10.1029/2021JD034580, 2021.

Montecinos, A. and Aceituno, P.: Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies, Journal of Climate - J CLIMATE, 16, 281–296, https://doi.org/10.1175/1520-0442(2003)016<0281:SOTERR>2.0.CO;2, 2003.

Nagy, B., Ignéczi, Á., Kovács, J., Szalai, Z., and Mari, L.: Shallow ground temperature measurements on the highest volcano on Earth, Mt. Ojos del Salado, Arid Andes, Chile, Permafr Periglac Process, 30, 3–18, https://doi.org/https://doi.org/10.1002/ppp.1989, 2019.

Noad, N. C. and Bonnaventure, P. P.: Examining the influence of microclimate conditions on the breakup of surface-based temperature inversions in two proximal but dissimilar Yukon valleys, Canadian Geographies / Géographies canadiennes, n/a, https://doi.org/https://doi.org/10.1111/cag.12886, 2023.

Noetzli, J., Arenson, L. U., Bast, A., Beutel, J., Delaloye, R., Farinotti, D., Gruber, S., Gubler, H., Haeberli, W., Hasler, A., Hauck, C., Hiller, M., Hoelzle, M., Lambiel, C., Pellet, C., Springman, S. M., Vonder Muehll, D., and Phillips, M.: Best Practice for Measuring Permafrost Temperature in Boreholes Based on the Experience in the Swiss Alps, Front Earth Sci (Lausanne), 9, https://doi.org/10.3389/feart.2021.607875, 2021.

Nyland, K. E., Shiklomanov, N. I., Streletskiy, D. A., Nelson, F. E., Klene, A. E., and Kholodov, A. L.: Long-term Circumpolar Active Layer Monitoring (CALM) program observations in Northern Alaskan tundra, Polar Geography, 44, 167–185, https://doi.org/10.1080/1088937X.2021.1988000, 2021.

PERMOS: Permafrost in Switzerland 2014/2015 to 2017/2018, in: Glaciological Report Permafrost No. 16–19 of the Cryospheric Commission of the Swiss Academy of Sciences, vol. 16–19, edited by: Noetzli, J. , Pellet, C., and and Staub, B., 104, 2019.

PERMOS: Swiss Permafrost Bulletin 2022, edited by: Noetzli, J. and Pellet, C., 23 pp., 2023.

Riseborough, D. W.: Estimating active layer and talik thickness from temperature data: implications from modeling result, in: Ninth International Conference on Permafrost, Vol. 2, 1487–1492, 2008.

Romanovsky, V., Smith, S., and Christiansen, H.: Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007–2009: a Synthesis, Permafr Periglac Process, 21, 106–116, https://doi.org/10.1002/ppp.689, 2010a.

Romanovsky, V., Drozdov, D., Oberman, N., Malkova, G., Kholodov, A., Marchenko, S., Moskalenko, N., Sergeev, D., Ukraintseva, N., Abramov, A., Gilichinsky, D., and Alexander, V.: Thermal State of Permafrost in Russia, Permafr Periglac Process, 21, 136–155, https://doi.org/10.1002/ppp.683, 2010b.

Romanovsky, V., Isaksen, K., D, D., Anisimov, O., A, I., Leibman, M., AD, M., Shiklomanov, N., S, S., and D, W.: Changing permafrost and its impacts. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, 65–102, 2017.

Ruiz, L. and Trombotto, D.: Mountain permafrost distribution in the Andes of Chubut (Argentina) based on a statistical model, Proceedings, Tenth International Conference on Permafrost (TICOP) Salekhard, Russia, 365–370, 2012.

Saavedra, F. A., Kampf, S. K., Fassnacht, S. R., and Sibold, J. S.: Changes in Andes snow cover from MODIS data, 2000–2016, Cryosphere, 12, 1027–1046, https://doi.org/10.5194/tc-12-1027-2018, 2018.

Saito, K., Trombotto Liaudat, D., Yoshikawa, K., Mori, J., Sone, T., Marchenko, S., Romanovsky, V., Walsh, J., Hendricks, A., and Bottegal, E.: Late Quaternary Permafrost Distributions Downscaled for South America: Examinations of GCM-based Maps with Observations, Permafr Periglac Process, 27, 43–55, https://doi.org/https://doi.org/10.1002/ppp.1863, 2016.

Sarricolea, P., Herrera Ossandón, M., and Meseguer-Ruiz, O.: Climatic regionalisation of continental Chile, J Maps, 13, 66–73, https://doi.org/10.1080/17445647.2016.1259592, 2017.

Schaefer, K., Lantuit, H., Romanovsky, V., Schuur, E., and Witt, R.: The impact of the permafrost carbon feedback on global climate, Environmental Research Letters, 9, 85003, https://doi.org/10.1088/1748-9326/9/8/085003, 2014.

Schulz, N., Boisier, J. P., and Aceituno, P.: Climate change along the arid coast of northern Chile, International Journal of Climatology, 32, 1803–1814, https://doi.org/https://doi.org/10.1002/joc.2395, 2012.

Schuur, E., McGuire, A. D., Schädel, C., Grosse, G., Harden, J., Hayes, D. J., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., Natali, S., Olefeldt, D., Romanovsky, V., Schaefer, K., Turetsky, M., Treat, C., and Vonk, J.: Climate change and the permafrost carbon feedback, Nature, 2015, 171–179, https://doi.org/10.1038/nature14338, 2015.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, J. O., and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556–559, https://doi.org/10.1038/nature08031, 2009.

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., Grosse, G., Jones, M., Koven, C., Leshyk, V., Lawrence, D., Loranty, M. M., Mauritz, M., Olefeldt, D., Natali, S., Rodenhizer, H., Salmon, V., Schädel, C., Strauss, J., Treat, C., and Turetsky, M.: Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic, Annu Rev Environ Resour, 47, 343–371, https://doi.org/10.1146/annurev-environ-012220-011847, 2022.

Smith, S., O'Neill, H. B., Isaksen, K., Noetzli, J., and Romanovsky, V.: The changing thermal state of permafrost, Nat Rev Earth Environ, 3, 10–23, https://doi.org/10.1038/s43017-021-00240-1, 2022.

Streletskiy, D., Biskaborn, B., Smith, S., Noetzli, J., Vieira, G., and Schoeneich, P.: Strategy and Implementation Plan 2016-2020 for the Global Terrestrial Network for Permafrost (GTN-P)., April 2017.

Trombotto, D. and Borzotta, E.: Indicators of present global warming through changes in active layer-thickness, estimation of thermal diffusivity and geomorphological observations in the Morenas Coloradas rockglacier, Central Andes of Mendoza, Argentina, Cold Reg Sci Technol, 55, 321–330, https://doi.org/https://doi.org/10.1016/j.coldregions.2008.08.009, 2009.

Trombotto, D., Buk, E., and Hernández, J.: Monitoring of Mountain Permafrost in the Central Andes, Argentina, Permafr Periglac Process, 8, 123–129, 1997.

Vera, C. and Silvestri, G.: Precipitation interannual variability in South America from the WCRP-CMIP3 Multi-model dataset, Clim Dyn, 32, 1003–1014, https://doi.org/10.1007/s00382-009-0534-7, 2009.

Viale, M. and Garreaud, R.: Orographic effects of the subtropical and extratropical Andes on upwind precipitating clouds, Journal of Geophysical Research: Atmospheres, 120, 4962–4974, https://doi.org/https://doi.org/10.1002/2014JD023014, 2015.

Vivero, S., Bodin, X., Farías-Barahona, D., MacDonell, S., Schaffer, N., Robson, B. A., and Lambiel, C.: Combination of Aerial, Satellite, and UAV Photogrammetry for Quantifying Rock Glacier Kinematics in the Dry Andes of Chile (30°S) Since the 1950s, Frontiers in Remote Sensing, 2, https://doi.org/10.3389/frsen.2021.784015, 2021.

Vuille, M., Bradley, R., Werner, M., and Keimig, F.: 20th Century Climate Change in the Tropical Andes: Observations and Model Results, Climatic Change, v.59, 75-99 (2003), 59, https://doi.org/10.1023/A:1024406427519, 2003.

Vuille, M., Franquist, E., Garreaud, R., Lavado, W., and Cáceres, B.: Impact of the global warming hiatus on Andean temperature: Global warming hiatus in the Andes, Journal of Geophysical Research: Atmospheres, 120, https://doi.org/10.1002/2015JD023126, 2015.

Wicky, J. and Hauck, C.: Air Convection in the Active Layer of Rock Glaciers, Front Earth Sci (Lausanne), 8, https://doi.org/10.3389/feart.2020.00335, 2020.

World Meteorological Organization (WMO): The Global Observing System for Climate: Implementation Needs. WMO Publication No. GCOS – 200. https://library.wmo.int/doc_num.php?explnum_id=3417, 2016.

Yoshikawa, K., Úbeda, J., Masías, P., Pari, W., Apaza, F., Vasquez, P., Ccallata, B., Concha, R., Luna, G., Iparraguirre, J., Ramos, I., la Cruz, G., Cruz, R., Pellitero, R., and Bonshoms, M.: Current thermal state of permafrost in the southern Peruvian Andes and potential impact from El Niño–Southern Oscillation (ENSO), Permafr Periglac Process, 31, 598–609, https://doi.org/https://doi.org/10.1002/ppp.2064, 2020.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Reviews of Geophysics, 43, https://doi.org/https://doi.org/10.1029/2004RG000157, 2005.

Page 13: [1] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [2] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [3] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

Font color: Auto, English (Canada)

Page 13: [4] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (United Kingdom)

Page 13: [5] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

Font color: Black, English (Canada)

Page 13: [6] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [7] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [8] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [9] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [10] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [11] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [12] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [13] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [14] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [15] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [16] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [17] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [18] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [19] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [20] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [21] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada), Not Superscript/ Subscript

Page 13: [22] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [23] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [24] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

Font color: Black, English (Canada)

Page 13: [25] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [26] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [27] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [28] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [29] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [30] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [31] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [32] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [33] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

Font color: Auto, English (Canada)

Page 13: [34] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [35] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [36] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [37] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [38] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [39] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [40] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [41] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

Font: Font color: Black, English (Canada)

Page 13: [42] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)

Page 13: [43] Formatted	Cassandra Koenig	2025-02-14 3:37:00 PM

English (Canada)