Dear Dr. Rovere,

Please find our revised manuscript of "Recent climate variations in Chile: constraints from borehole temperature profiles" (cp-2017-97). We thank the anonymous reviewers for their reviews. In response to their suggestions and questions, we have made several changes to the manuscript and added some information to clarify some points about data collection and processing. A detailed list and explanation of the changes follows. The changes have been highlighted on the attached copy of the revised manuscript.

Response to Comments

In response to Anonymous Reviewer 1

1) The introduction section is rather long. The text could be tightened at a number of places, highlighting the shortcomings of previous work and how this paper addresses those shortcomings. Key references to similar studies from other regions (Europe, North America, Canada, India, etc.) may be cited.

We agree with the reviewer and have tightened up the introduction and eliminated all information not directly relevant to study. We eliminated P2L12-19, P2L25-34, P3L4-10, P3L14-21, P3L33-P4L8. We also replaced P3L25-26 by P3L27-32 and P3L33-P4L8 by P4L8-L14 to emphasize how shortcomings of previous studies are addressed.

2) Other aspects that could be elaborated and/or investigated include, for example, (i) the choice of the lowermost 100 m for the linear regression

The lowermost 100 m is chosen for the linear regression since it is assumed to be sufficiently deep to be free of short period surface temperature perturbations and represent the geothermal steady state. Tests were run on the lowermost 300 m and showed that the steady state temperature and heat flux were stable and did not vary with the depth interval selected. Furthermore, we made tests using the technique of solving simultaneous for the $K+2$ unknown parameters and no notable differences were noted. This has been clarified in the manuscript (P5L3-4, P5L7-8).

3) ...(ii) thermal conductivity contrasts in a borehole column

For measurements made in 1994, Springer and Förster (1998) measured a thermal conductivity of 2.04 W/mK for the boreholes in northern coastal Chile (Michilla) and found no thermal conductivity variations in the region.

For measurements taken in 2012 and 2015, rock samples were not available to determine thermal conductivity. Lithological logs were only provided for borehole RC370. Sandstone makes up the majority of the lithology of the borehole and no significant lithological changes, which could result in thermal conductivity variations, were noted. Persistent changes in temperature gradient can be a sign of thermal conductivity variations. An example of such a break can be seen in Figure 1. In the appendix, we also point out how one rejected profile shows a change of slope due to thermal conductivity change (P14L22-24).
The temperature gradient with depth of the retained boreholes measured in 2012 and 2015 were calculated (Figure 2). They show no clear significant variations that could be associated with variations in thermal conductivity.

This has been noted in the revised manuscript (PL35,P8L22-26).

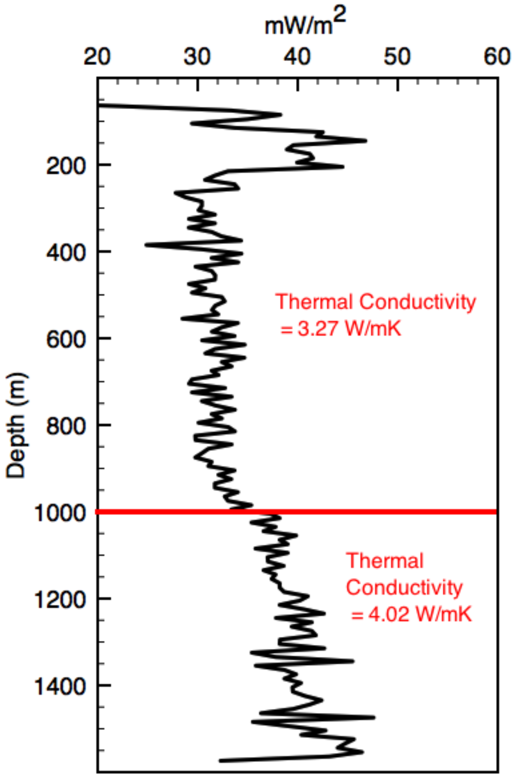

Figure 1: Variation in temperature gradient at Matagami, Québec, Canada

4) ...(iii) the choice of small time interval of 20 years for parameterization of the time before present

Test were run with time intervals of varying size and intervals varying with time (ex. longer time steps in the past and shorter ones closer to present). No significant differences were noted. This has been clarified in the revised manuscript (P8L8-9).

5) The rock formations met with in the boreholes are not provided in the manuscript.

The rock formations for the temperature-depth profiles measured in 1994 are outlined in Springer (1997) and Springer and Förster (1998). The rock formations at the three Michilla boreholes, the only site retained from this sampling period, are

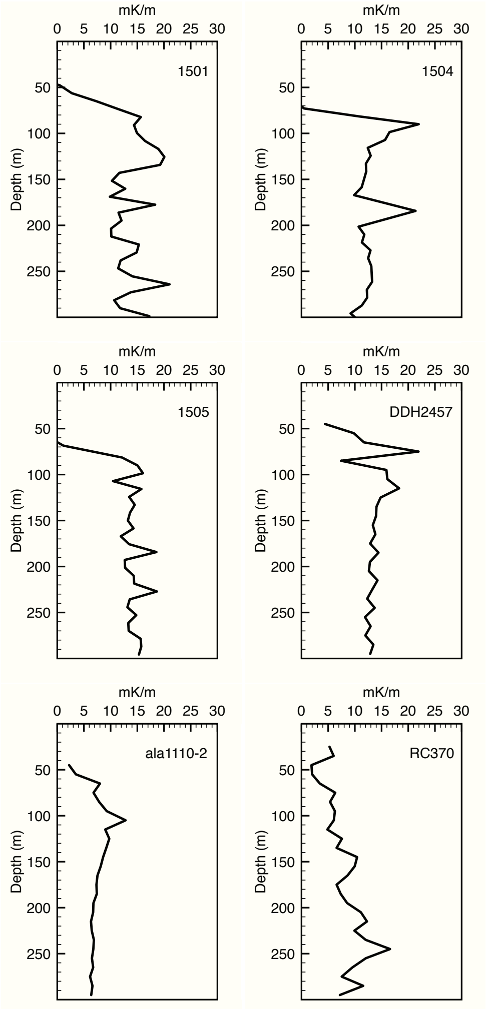

Figure 2: Temperature gradient of retained boreholes measured in 2012 and 2015.

andesite and diorite. For the non retained sites, granodiorite and rhyolite are the rock types at El Loa, granodiorite and sediments are at Mansa Mina and sediments are at Sierra Limon Verde. For the 2012 and 2015 measurement campaigns, the lithological log for RC370 was the only one provided. Sandstone makes up the majority of the lithology of the borehole with no significant lithological changes which could result in thermal conductivity variations. This has been added to the revised manuscript (P8L8-9, P8L13-16, P14L11, P14L171, P13L15).

6) The authors may want to explore other meteorological station records in the region.

We wish we could but there are no freely available meteorological records for the region. The majority of available records span only 10-20 years and are not useful for our study. For this reason, we turned to the CRUTEM4 data and the Copiapó station. The CRUTEM4 grid centered at 22.5S 72.5W covers northern coastal Chile and includes meteorological stations at Iquique (260 N of Michilla), Mejillones (55 km S of Michilla) and Antofagasta Cerro (80 km S of Michilla). Unfortunately, the record for all the stations is very short (less than 100 years). From these data (Figure 3), a warming of $\sim$1 K is occurs is observed at 1980 and possible cooling from 1930 to 1960 but an absence of data makes it difficult to draw any conclusions. While a climate signal is present, it could have not been persistent/strong enough to be inverted from borehole temperature profiles.

The grid centered at 27.5S 72.5W covers north central Chile and includes stations at La Serena, Vallenar, Copiapó, Caldera but the data span only the years 1940 to 2016. The stations do not show a marked temperature increase over the period, but it does show large amplitude variations including a marked cooling period from 1960 to 1970 similar to that at the Copiapó weather station. After 1970, there is modest warming consistent with the recent warming in the GST history for the north-central Chile, but its amplitude is $\sim$4 times less than that of the GST history (Figure 4). This will be explained in the revised manuscript (P11L8-22).

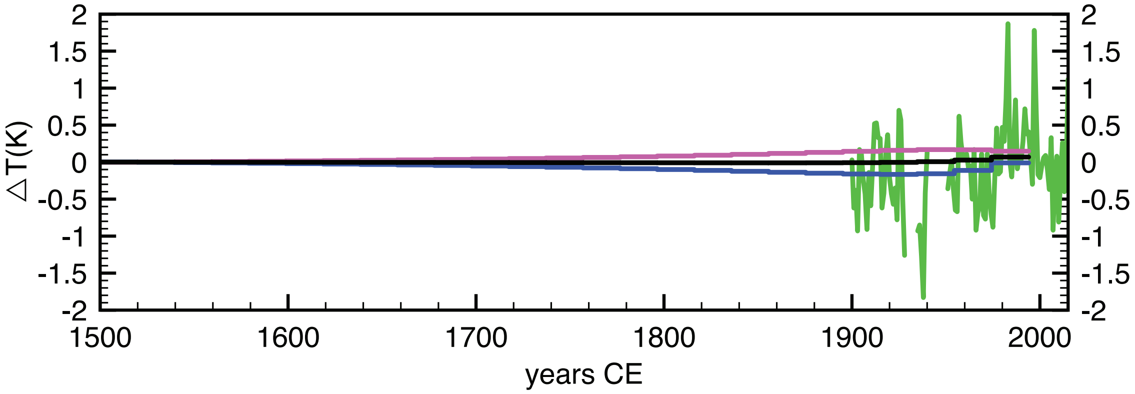

Figure 3: GST history and meteorological data from the CRUTEM4 for northern coastal Chile (Michilla), presented with respect to the 1961-1990 mean.

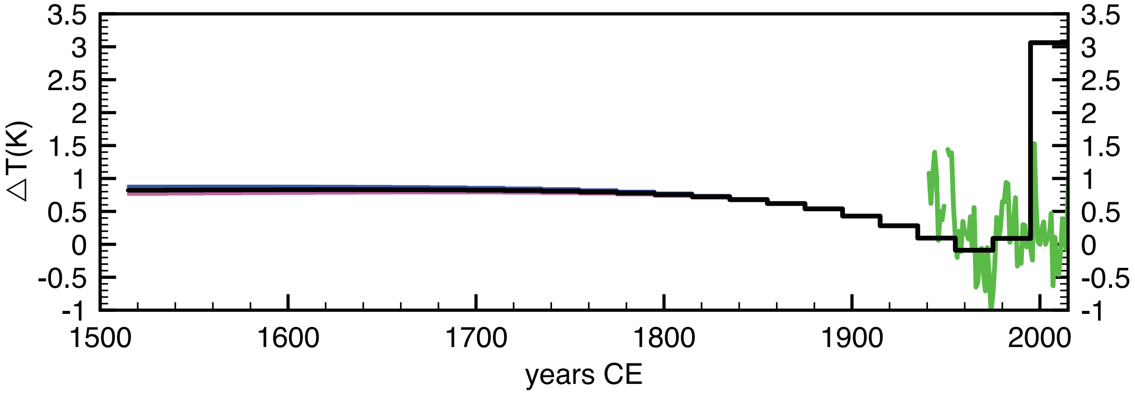

Figure 4: GST history and meteorological data from the CRUTEM4 for north-central Chile (Inca de Oro), presented with respect to the 1961-1990 mean.

7) Also, the recent warming could be discussed along with the information on land use changes in the region during the past few decades.

The sites are located in the Atacama Desert, a region with little to no vegetation. Land use change has probably not played a significant role in the recent warming.

This will be clarified in the revised manuscript (P10L13-15).

8) Minor comments: Tables 1, 2 and 3 could be combined into one table. If space is limited, this table could go as electronic supplement. Table 1: Qualify the last column header. Figure 1: Add a few place names for reference. Table 5: To values may be shown up to one decimal place. Fig. 14 may be deleted or included as electronic supplement.

Table 1, 2, and 3 have been combined into one table and the last column was qualified (P20). Place names are given on Figure 2. Because of the scale, we prefer not to add place names on Figure 1. The values in previous Table 5 were adjusted to show up to one decimal place (P22). Figure 14 was incorrectly located and has now been place in the appendix and is now Figure A1.

In response to Anonymous Reviewer 2

1) Introduction describes very clearly lack of paleoclimate records in Southern Hemisphere compared to the Northern Hemisphere and highlighting requirements of more paleoclimate records from Southern Hemisphere as well as in South America. However, it would be worth to cite some recent works related to borehole studies from Australia i.e. Suman et al. 2017 and Suman and White, 2017 that addresses some of the drivers of paleotemperature variations in Tasmania, Australia and may have similar influence in other place of Southern Hemisphere.

We thank the reviewer for pointing out these references and have been added to the revised manuscript (P2L13,P20L29-32).

2) Page 7 Line 4, "boreholes near significant topography were also rejected" is not clear. What does mean by significant topography? Specific topographic parameter i.e. slope, aspect or relief and their influence on borehole temperature data and/or temperature reconstruction should be used. Please make it clear.

Topography distorts the temperature isotherms (Jeffreys, 1938): a positive topography leads to a reduced temperature gradient and an increased apparent warming signal (ex. Blackwell et al. (1980), Guillou-Frottier et al. (1998)). Profiles were assumed to be affected by topography and rejected rejected if they were near a slope of 5% or more at distance comparable to borehole depth. This has been explained in the revised manuscript (P7L28-29).

3) Temperature reconstruction from northern coastal Chile (Michilla) did not show any temperature change in last 500 years. Is this supported by any other proxy results from surrounding area. If not, could you please double check 20th Century warming signal minimised by any other external driver or systematic thermal conductivity variations?

There is an absence of proxy data for northern coastal Chile (Michilla). From the CRUTEM4 grid over the region (22.5S 72.5W), a climate signal is observed (Figure 3), which does not agree with our GST reconstruction. The absence of signal in the reconstruction cannot be explained by thermal conductivity variations (Springer and Förster, 1998). Furthermore, land used changes/deforestation is unlikely to mask the signal as the boreholes are located in the Atacama desert which has not been affected by environmental changes. The selection criteria applied has also ensured boreholes influenced by topography or water flow were excluded from the study. This leads to the hypothesis that the signal could have not been persistent/strong enough to be inverted using borehole temperature profiles. This has been clarified in the revised manuscript (P7L32, P8L1,P9L12-13, P10L7-16).

4) There should be more meteorological records in that region. It would be worth to compare borehole reconstruction with an average of set of surrounding meteorological records not just one station record.

There are few meteorological data that extends back more than 20 years in the region. This lead us to compare with the CRUTEM4 and the Copiapó meteorological station. We have expanded our analysis of the CRUTEM4 data, as outlined in the point 6 in the response to Anonymous Reviewer 1, in the revised manuscript (P11L13-24).

5) Conclusion states spatial variation of paleoclimate in northern Chile but there is no discussion regarding this in Discussion section. It would be worth to discuss spatial variations with available data in Discussion section.

The recent warming observed in the north-central Chile GST inversion (1.9 K) agrees in magnitude with that from simultaneous inversion of two boreholes in the semi-arid region of Peru (1.6 K). However, it starts much earlier in the Peruvian GST inversion and no cooling between ∼1800 and 1980 (such as observed in north-central Chile) is observed. The inversion of the temperature-depth profile closest to the border with Chile (LM18) and at the northern edge of the Atacama desert shows a cooling of ∼0.5 K is present from ∼1800 to 1950, similar to that observed in north-central Chile. This is consistent with a hypothesis that this cooling signal is spatially variable. This is outlined in the manuscript (P11L2-5). Figure 10 has been modified to show the inversion of LM18.

Comparison of the north-central Chile GST reconstruction with paleoclimate reconstructions from sedimentary pigments in central Chile (von Gunten et al., 2009) and the southern South America austral summer surface air temperatures inferred from 22 annually resolved predictors from natural and anthropogenic archives (Neukom et al., 2011) show that the three regions experience an absence of warming or cooling from 1500 to 1700, indicating this could be a regional trend for southern South America. But, the cooling of 0.6 K inferred between ∼1800 and 1980 is only observed in north-central Chile. All three regions show a recent warming. In southern South America and central Chile, a recent warming of ∼0.5 K starting ∼150 years BP. On the other hand, the warming in north-central Chile begins significantly later, ∼20-40 years BP, and reaches a maximum of 1.9 K with respect to the long-term GST. These difference suggest the cooling and stronger warming are a north-central Chile trend and that there are spatial and temporal differing climate trends in Chile and southern South America. This has been clarified in the manuscript (P12L23-24).

The north-central Chile GST history was also compared with multi-model mean surface temperature anomaly from the last millennium of the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3) of the Coupled Model Intercomparison Project Phase 5 (CMIP5). No cooling is observed in the PMIP3/CMIP5 surface temperature simulation for the north-central Chile gridpoint and the warming is half and starts earlier than that reconstructed by the GST history. This further suggests that this cooling trend and greater amplitude recent warming are local trends for north-central Chile and cannot be resolved on the PMIP3/CMIP5 gridpoint scale.

We trust that we have addressed all the comments and that our revisions have resulted in improving significantly the manuscript.

Sincerely yours,

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Recent climate variations in Chile: constraints from borehole temperature profiles

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Abstract.

We have compiled, collected, and analyzed 31 temperature depth profiles from boreholes in the Atacama desert in central and northern Chile. After screening these profiles, we found that only 9 profiles at 4 different sites were suitable to invert for ground temperature history. For all the sites, no surface temperature variations could be resolved for the period 1500-1800. In the northern coastal region of Chile, there is no perceptible temperature variation at all from 1500 to present. In the northern central Chile region, between 26°S and 28°S, the data suggest a cooling from ≈1850 to ≈1980 followed by a 1.9 K warming starting ≈20-40 years BP. This result is consistent with the ground surface temperature histories for Peru and the semiarid regions of South America. The duration of the cooling trend is poorly resolved and it may coincide with a marked short cooling interval in the 1960s that is found in meteorological records. The total warming is greater than that inferred from proxy climate reconstructions for central Chile and southern South America, and by the PMIP3/CMIP5 surface temperature simulations for the north-central Chile grid points. The differences between different climate reconstructions, meteorological records, and models are likely due to differences in spatial and temporal resolution between the various data sets and the models.

1 Introduction

To assess and predict the long-term effects of the modern climate warming, it is crucial to simulate and understand Earth's complex climate and its variability. Most of the inferences on the future evolution of the climate system come from large scale general circulation models (GCMs) simulations. Experiments with GCMs allow for the study of future climate under different scenarios. Due to the limited resolution of GCMs, climatically relevant processes that operate at less than the GCM grid size scale are not parameterized in the same way by different models. These different parameterizations lead to a wide variability of results between simulations by different GCMs. Hence, there is a need to test models against paleoclimate reconstructions and to assess the robustness of their climate projections.

As the meteorological record only extends back as far as 150 years or less, proxy data based climate reconstructions are required to evaluate the performance of GCMs and provide insight to the long-term trends of climate variables. In contrast to the Northern Hemisphere where a lot of paleoclimatic reconstructions are available (e.g., Mann et al., 1999; Moberg et al., 2005; Rutherford et al., 2005), fewer climate reconstructions have been done for the Southern Hemisphere and those rely on a small number of data sets (Huang et al., 2000; Mann and Jones, 2003; IPCC , 2013). In absence of paleoclimatic data, the forcing of the Southern Hemisphere's climate system is poorly known. Several studies have been initiated to fill in this gap but they continue to underscore the need for more paleoclimate records from the Southern Hemisphere (e.g., Villalba et al., 2009; Neukom and Gergis, 2012)(Suman et al., 2017; Suman and White, 2017). ~~As of 2012, 174 monthly to annually resolved climate proxy records covering the last 2000 years have been collected (Neukom and Gergis, 2012). Using this expanded data set of terrestrial and oceanic paleoclimate records, Neukom et al. (2014) obtained a millennial ensemble reconstruction of annually resolved temperature variations for the Southern Hemisphere which they compared with an independent Northern Hemisphere temperature reconstruction ensemble. They found that the post-1974 warming period was the only period of the last millennium when both hemispheres experienced warm extremes. Their results imply that the global climate system cannot be solely represented by external forcing and Northern Hemisphere variations and underscore the need for more paleoclimate records from the Southern Hemisphere.~~

South America is a key continent for understanding the climate system of the Southern Hemisphere as it is the largest landmass in the Southern Hemisphere extending from 10°N to 55°S. Flanked by the Andes to the west, the continent separates the Atlantic and Pacific Oceans, influencing oceanic and atmospheric circulations, and global climate. There are few paleoclimatic data in South America and those are restricted to the southern portion of the continent, which may bias our understanding of the region. ~~This is an important region that lies in the center of the modern westerly wind field and therefore allows for the examination of past westerly wind variability (Boninsegna et al., 2009; Villalba et al., 2009; PAGES-2K Network, 2013; Flantua et al., 2016). Moy et al. (2009) analyzed multiple paleoclimate records, including meteorological, palynological, and dendrochronological data, and deduced a temperature decrease and an increase in westerly wind intensity during the Little Ice Age, following arid conditions during the Medieval Climate Anomaly. Neukom et al. (2010) examined the hydroclimate of southern South America for the past 500 years using a multiproxy approach and inferred a multi-centennial increase in summer precipitation and a decrease in winter precipitation into the 20th century. Meanwhile, there are very few studies in the northern two-thirds of the South American continent, including the Atacama desert in northern Chile (PAGES-2K Network, 2013).~~

Studying the climate of northern Chile is key to understanding how extremely sensitive arid environments respond to climatic variations. Furthermore, the natural resources and ecosystem of northern Chile have been put under ever increasing ~~pressure~~ stress by the accelerating economic development of the region (Messerli et al., 1997). It is, therefore, of paramount importance to understand the long-term climatic variations of the region. There have been some regional paleoclimatic studies in northern Chile with the majority of them addressing the mid-Holocene paradox. ~~, a period ≈4-9 ky BP where it is uncertain whether the climate of the Atacama desert and the Central Andes was dry or humid (Bobst et al., 2001; Grosjean et al., 2003). Paleosoils, groundwater, abiotic proxy data, and aquatic plant pollen from lake sediments imply a very humid early Holocene and an extremely dry mid Holocene (Bobst et al., 2001; Grosjean et al., 2001), while terrestrial plant pollen from lake sediments does not (Betancourt et al., 2000; Latorre et al., 2002; Gayo et al., 2012). These studies have not addressed the recent climate variations. but recent climate variations have not been addressed.~~ In order to study the climate of northern Chile and South America of the past 500 years, we have compiled and collected borehole temperature depth profiles, interpreted these data and determined ground surface temperature variations, and compared our results with climate reconstructions from other proxies and with climate model simulations.

~~Earth's subsurface thermal regime is governed by the outflow of heat from Earth's interior and long term changes in ground surface temperature (GST). If there are no temporal changes in GST, subsurface temperature increases linearly with depth. When persistent temporal GST variations occur, they diffuse downward and are recorded as perturbations to Earth's steady-state geotherm (see, e.g., Hotchkiss and Ingersoll, 1934; Birch, 1948; Beck, 1977). The time of occurrence, duration, and amplitude of GST changes govern the extent to which they are recorded. Attempts to infer past climate from these borehole temperature-depth profiles began in the 1930s (Hotchkiss and Ingersoll, 1934). It was, however, only in the 1970s that systematic studies to infer past climate were undertaken (Cermak, 1971; Sass et al., 1971; Beck, 1977). As of the 1980s, the technique became more widespread due to~~ The use of borehole temperature depth profiles to determine past changes in ground surface temperature (GST) and study past climate is relatively recent and was motivated by the concerns about rising global temperatures (Lachenbruch and Marshall, 1986; Lachenbruch, 1988). Over the years, many global, regional, and local reconstructions of GST have been undertaken (Huang et al., 2000; Harris and Chapman, 2001; Pollack and Smerdon, 2004; Jaume-Santero et al., 2016; Pickler et al., 2016). ~~However, the majority of these studies have focused on the Northern Hemisphere with little attention to the Southern Hemisphere and South America due to the scarcity of adequate data.~~ These studies have relied almost exclusively on temperature depth profiles collected for heat flow measurements with two caveats: (1) Not all the data are suitable for climate studies, and (2) Heat flow data are very unevenly distributed with the vast majority being located in the northern hemisphere. A recent compilation of conventional land heat flow measurements shows that out of 17,232 heat flow values, 16,062 are found in the northern hemisphere and only 1,170 in the southern hemisphere (Francis Lucazeau, personal communication, see also (Jaupart and Mareschal, 2015)). The compilation includes a total of 261 values for the entire South American continent where several large regions are void of measurements (Figure 1). ~~(Watanabe et al., 1980; Uyeda and Watanabe, 1982; Hamza and Muñoz, 1996; Springer and Förster, 1998). The first heat flow measurements date back to the mid sixties before the marked warming observed in the Northern Hemisphere. Uyeda and Watanabe (1970) conducted a preliminary study of heat flow in South America. The majority of thermal gradients are normal or subnor-~~

~~mal over the continent with high values in the Andes and low values on the Pacific coast and along the Amazon River. Uyeda and Watanabe (1982) examined 25 heat flow measurements from western South America to investigate heat flow in the subduction plate boundary area of the region. They found low heat flux near the trench and high heat flux on the volcanic arc, similar to the trends observed in other arc-trench systems. Only a few of these borehole temperature profiles are useful for climate studies because of their insufficient depth range and inadequate sampling. Furthermore, the only accessible archive of the temperature profiles are the publication figures. Springer and Förster (1998) made 74 heat flow measurements across the central Andes subduction zone in Chile and Bolivia to study large scale heat flux variations and confirmed the conclusions of the previous studies.~~ Beginning in the late 1960s, studies were conducted on the western margin of the continent to understand the heat flow of the arc-trench system (Uyeda and Watanabe, 1970; Watanabe et al., 1980; Uyeda and Watanabe, 1982). Unfortunately, most of the temperature profiles are too shallow and too coarsely sampled to be useful for climate studies. In addition, there are no digital archives of these data, but only figures in publication. More recently, Springer and Förster (1998) conducted a new heat flow study based on 74 temperature depth profiles measured in Bolivia and northern Chile. We have selected some of these data to include in our analysis. Measurements were also made in Brazil (Vitorello et al., 1980) but some of the data are in publications of limited accessibility (Hamza et al., 1987). ~~The uneven distribution of available and suitable borehole temperature measurements has left several parts of South America void of measurements.~~ Despite the uneven sampling, Huang et al. (2000) inferred a cumulative temperature increase of 1.4 K over the past 500 years in South America from their global reconstruction of ground surface temperature variations in the continents. Because this study relied on only 16 borehole temperature-depth profiles for South America, additional data are needed to confirm its conclusions. Hamza and Vieira (2011) selected and analyzed in terms of GST variations more than 30 temperature-depth profiles deeper than 200m from eastern Brazil, the Amazon region, the Cordilleran region of Colombia, and the Cordilleran region of Peru. They inferred a warming of 2-3.5°C from the early 20th century to present and observed similar trends in tropical and subtropical zones. Meanwhile, a warming of 1.4-2.2°C from the late 19th century to present was inferred for the semi-arid zones.

In an attempt to enlarge the South American borehole temperature data set, we have collected 31 borehole temperature-depth profiles measured in 1994, 2012, and 2015 in northern Chile, a region that was void of data, and reconstructed the GST history for the past 500 years. We compare these reconstructions with meteorological data for the region, past climate inferences based on proxy data, and model simulations for central Chile and southern South America to determine climate trends for northern Chile and assess their robustness.

2 Ground surface temperature reconstructions from borehole temperature profiles

To determine GST histories from temperature-depth profiles, we use a physical model of heat diffusion in the subsurface. We assume that Earth is a half-space where physical properties vary solely with depth, heat is transported only by vertical conduction, and changes in the surface temperature boundary condition propagate into the subsurface and are recorded as temperature perturbations, $T_t(z)$, of the steady state (reference) temperature profile. The temperature, $T(z)$, at depth z can then be written as (Jaupart and Mareschal, 2011):

$$T(z) = T_o + q_o R(z) - \int\limits_0^z \frac{dz'}{\lambda(z')} \int\limits_0^{z'} H(z'')dz'' + T_t(z) \tag{1}$$

where T_o is the steady state (reference) ground surface temperature, q_o is the reference heat flux, $\lambda(z)$ is the thermal conductivity, $H(z)$ is the radioactive heat production, and $T_t(z)$ is the temperature perturbation at depth z due to time variations in surface temperature. The effect of heat production is usually negligible for shallow depth. $R(z)$ is the thermal ~~depth~~ resistance, which is defined as:

$$R(z) = \int\limits_0^z \frac{dz'}{\lambda(z')} \tag{2}$$

The temperature perturbation, $T_t(z)$, can be written as (Carslaw and Jaeger, 1959):

$$T_t(z) = \int\limits_0^\infty \frac{z}{2\sqrt{\pi\kappa t^3}} \exp\left(\frac{-z^2}{4\kappa t}\right) T_o(t)dt \tag{3}$$

where κ is the thermal diffusivity, and $T_o(t)$ is the surface temperature at time t before present. For a stepwise change ΔT in surface temperature at time t before present, the temperature perturbation, $T_t(z)$, is given as (Carslaw and Jaeger, 1959):

$$T_t(z) = \Delta T \operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right) \tag{4}$$

where erfc is the complementary error function. In order to parameterize the variations in surface temperature, $T_o(t)$, we approximate them by their average values, ΔT_k, during K time intervals (t_{k-1}, t_k). The perturbation, $T_t(z)$, is then obtained as follows:

$$T_t(z) = \sum_{k=1}^{K} \Delta T_k \left(\operatorname{erfc}\frac{z}{2\sqrt{\kappa t_k}} - \operatorname{erfc}\frac{z}{2\sqrt{\kappa t_{k-1}}}\right) \tag{5}$$

The ΔT_k values represent the difference between the average GST during the time interval (t_{k-1}, t_k) and T_o.

2.1 Inversion

In order to reconstruct the GST history, equation 3 (where heat production is neglected) and 5 are combined to obtain one linear equation for each measured depth (z) with $K+2$ unknowns, T_o, q_o, and ΔT_k. The inversion involves solving the system of equations for the unknown parameters. This can be done either by: (1) solving for the $K+2$ unknown parameters simultaneously, or by (2) determining independently T_o and Γ_o, the reference ground surface temperature and ~~quasi-steady state~~ reference temperature gradient. We have made tests to compare the two techniques and found no significant differences between the results. For this study, we have used the second technique. T_o and Γ_o are calculated by linear regression of the lowermost 100 m of the temperature-depth profile. The lowermost 100 m of the temperature-depth profile is used since it is sufficiently deep to be unaffected by short period (<100years) surface temperature perturbations and represent the geothermal steady state on a ≈ 100 years timescale. Furthermore, we made tests to check that the reference ground surface temperature is stable and the reference heat flux does not vary with depth interval selected. An estimate of the maximum error at a 95% confidence interval of T_o and Γ_o is also provided by the linear regression and are the upper and lower bounds of the geothermal quasi-steady state, referred to as the extremal steady states. The temperature anomaly or perturbation T_t, is then obtained by subtracting the linear fit from the data. If N temperature measurements were made, we obtain a system of N linear equations with K unknowns: the K values of ΔT_k. Regardless of the actual values of K and N, this system of equations is ill-conditioned and its solution is unstable. To stabilize the solution, various ~~inversion~~ regularization techniques have been used (~~Bayesian methods,~~ singular value decomposition, Backus-Gilbert inversion, Tikhonov regularization ~~Monte-Carlo methods~~) and applied to GST history reconstructions (e.g., Mareschal and Beltrami, 1992; Vasseur et al., 1983; Wang et al., 1992). We use singular value decomposition (SVD) (Lanczos, 1961) because its application to GST ~~reconstructions~~ inversion is straightforward. See Mareschal and Beltrami (1992) and Clauser and Mareschal (1995) for more details.

2.2 Simultaneous inversion

Simultaneous inversion is used at sites with multiple profiles. If the same ~~surface~~ temperature variations have affected the surface of the site, the profiles are expected to show consistent subsurface temperature anomalies. If the noise is random, inverting these profiles simultaneously for a common GST history results in increasing the signal to noise ratio and reinforcing consistent trends in the temperature anomalies. This technique has been widely used and is discussed further in Beltrami and Mareschal (1992), Clauser and Mareschal (1995) and Beltrami et al. (1997).

3 Data collection and selection

Thirty-one borehole temperature-depth profiles varying in depth from 118 m to 557 m ~~were logged~~ have been obtained at 11 ~~different~~ sites in northern Chile (Figure 2). One site includes one or several boreholes within a radius of 1 km or less. All the sites used in this study are located in the Atacama desert, an arid region with little to no vegetation, and the holes had been drilled for mining exploration purposes. The temperature profiles were measured during three different campaigns in 1994, 2012, and 2015 (Springer, 1997; Springer and Förster, 1998; Gurza Fausto, 2014; Pickler et al., 2017). The data were obtained using different measurement techniques. Fibre-optic distributed temperature sensing (DTS), used for some holes in 1994 and 2015, is based on the measurement of a backscattered laser light pulse through a fibre-optic cable (Förster et al., 1997; Förster and Schrötter, 1997). It allows the continuous measurement of the entire profile once the cable has been completely lowered into the borehole. A detailed description of this methodology can be found in Förster et al. (1997), Förster and Schrötter (1997), Hausner et al. (2011) and Suárez et al. (2011). The remaining profiles were measured using the conventional method of lowering a calibrated thermistor into the borehole and measuring temperature with depth. In 2012, temperature was measured continuously by lowering the thermistor into the borehole at an average speed of ≈10-15 m/min. In 1994 and 2015, temperature was measured at 2 m and 10 m intervals, respectively with a precision of ±0.01K. For the analysis, all profiles were re-sampled at 10 m intervals to ensure they were weighted evenly. Förster et al. (1997) and Wisian et al. (1997) ran tests to verify the consistency between the DTS and conventional methods. An offset between the temperature-depth profiles was detected and attributed to the calibration of the measurement tools. This effect is considered unimportant when examining temperature differences but must accounted for to avoid an offset of the reference surface temperature. ~~Technical details on~~ Information about all the profiles, including their locations, depths, elevations, ~~are summarized~~ is provided in Tables 1, 2, and A1. ~~For the analysis, all profiles were re-sampled at 10 m intervals to ensure they were weighted evenly. Förster et al. (1997) and Wisian et al. (1997) ran tests to ensure verify the compatibility of the DTS and conventional method. An offset between the temperature-depth profiles was detected and attributed to the calibration of the measurement tools. This effect is considered unimportant when examining temperature changes but must be taken into consideration to avoid an offset of the reference surface temperature.~~

We used several selection criteria to determine whether the borehole temperature-depth profiles are suitable for climate studies, and ended up rejecting 20 profiles (Table A1 in Appendix). In the tectonic setting of the active central Andean orogeny, uplift and erosion occur that can alter the temperature gradient (Jeffreys, 1938; Benfield, 1949; Jaupart and Mareschal, 2011), but these effects take place on a much longer timescale than the 500 years period studied here and they can be considered negligible. In order to reconstruct 500 years, boreholes must be at least 300 m deep and, to detect the recent changes, they must include measurements in the topmost 100 m. ~~Many of the boreholes that had been drilled in sedimentary rocks had collapsed and could not be logged all the way to the end of hole. In other holes, reliable measurements could not be made in the upper part of the hole because it was above the water table.~~ Profiles less than 300 m deep and/or without measurements in the upper 100 m were rejected. Also, profiles were visually inspected to ensure that they show no discontinuities, signs of water flow, or other perturbations that would make them unsuitable for climate reconstructions. As topography ~~is known to~~ distorts the temperature isotherms (Jeffreys, 1938), ~~profiles from boreholes near significant topography were also rejected.~~ profiles on or near a slope steeper than 5% over a distance comparable to borehole depth were rejected. This left only eleven profiles suitable for climate studies. However, two of the retained profiles are repeat measurements and do not provide independent information. The ~~original and repeat~~ measurements of ~~the borehole~~ temperature ~~data~~ at the Vallenar site (ala1110/ala1110-2) used the same technique (conventional method with continuous sampling) and yielded identical profiles. We arbitrarily retained profile (ala1110-2). ~~The second profile with repeat measurements was that of borehole DDH2489A (1501) at the Inca de Oro site where the temperature data were obtained with two different techniques: conventional thermistor and DTS. Because the DTS measurements have a lower temperature resolution (0.1K) than the conventional method, we discarded the DTS profile (DDH2489A).~~ At the Inca de Oro site, where hole DDH2489A was logged by conventional thermistor and DTS, we retained the conventional measurements (1501) because they have better temperature resolution (0.01K) than the DTS (0.1K).

Following this selection, we retained nine independent profiles ~~for climate reconstructions~~ suitable for inversion (Figure 4). We truncated the profiles at 300 m to ensure that we were ~~studying~~ referring to the same time period, and we calculated the temperature anomalies (Figure 4). These profiles are distributed between four sites: one (Michilla) in northern coastal Chile was measured in 1994, and a group of three (Inca de Oro, Totoral, Vallenar) in north-central Chile were measured in 2012 and 2015 (Figure 2). Northern coastal Chile and north-central Chile are more than 500 km apart. The three Michilla boreholes are located in a relatively flat area near the Michilla open pit mine, ≈10 km from the coast. The dominant lithologies crossed by the holes are andesite and diorite (Springer, 1997; Springer and Förster, 1998). The other three sites (Inca de Oro, Totoral, Vallenar) are located ~~in north-central Chile~~ between 26°S and 28°S. Four boreholes were logged in the center of a flat basin between two ranges ≈ 5km away near the town of Inca de Oro, less than 100km from the coast. The Totoral borehole is located in a relatively flat area, ≈75 km south-west of the city of Copiapó and ≈50 km from the coast. The borehole at Vallenar is located between two hills, ≈20 km south-west of the city of Vallenar and ≈40 km from the coast. All the holes that we logged in North central Chile had been drilled through sediments and penetrated only a few meters in the crystalline basement. The only lithological log available (for borehole RC370, Totoral) shows that a dominant lithology of sandstone with no significant lithological changes. Cuttings picked near the Inca de Oro boreholes showed similar lithologies.

Previous heat flow measurements made in Chile in 1969 included several holes in the region of Vallenar (Uyeda et al., 1978; Uyeda and Watanabe, 1982). A digital archive of these measurements could not be found and the profiles are too shallow (<200m) to be very useful in climate studies. The Vallenar data show small temperature gradients (≈ 10K/km) and very low heat flux ($\approx 20\mathrm{mWm}^{-2}$), which are consistent with our measurements.

For measurements made in 1994, Springer and Förster (1998) found a mean thermal conductivity of 2.04 WmK^{-1} for the three Michilla boreholes and noted no significant thermal conductivity variations. Because the holes had been drilled by percussion no continuous core was retrieved from the holes at the Inca de Oro and Totoral sites measured in 2012 and 2015 and we could not make conductivity measurements. The calculated temperature gradients showed no obvious signs of thermal conductivity variations. For the borehole RC370, no major change in conductivity with depth is consistent with the lithological log that shows no significant change in lithology.

4 Inversion results

The GST histories of the past 500 years relative to the measurement date were inverted for the four retained sites (Michilla, Inca de Oro, Totoral, Vallenar). For the inversion the GST history was parameterized by using a model consisting of 25 time-intervals of 20 years with constant temperature (Figures 5-8). We tried different parameterizations with intervals of varying sizes and found no significant differences between all the inversions. We have carried out individual inversions for each of the retained holes, but we only shall show the results of simultaneous inversions of all the profiles for the sites with multiple boreholes (Michilla and Inca de Oro). The main inferences of the inversions for all the sites are summarized in Table 2. Because we expect meteorological trends to be correlated over distances <500 km, we have also inverted simultaneously the six borehole temperature-depth profiles from north-central Chile ~~(Inca de Oro, Totoral, Vallenar)~~ (Figure 9). ~~Three singular values were retained for all the inversions, eliminating the unstable part of the solution that is most affected by noise~~ For all the inversions, we have used a high singular cutoff value which resulted in retaining only three singular values. This yields a stable solution for the retained singular values which correspond to the long trends, but at the expense of resolution of shorter variations corresponding to lower singular values (Mareschal and Beltrami, 1992). ~~The inversion results are summarized in Table~~ 2.

The GST history of northern coastal Chile (Michilla) shows no warming or cooling for the past 500 years (Figure 5). The temperature anomalies of the three Michilla profiles show very weak and inconsistent ~~climate~~ signals (Figure 4). Two of the temperature anomalies are slightly negative (≈-0.2 K) indicating a cooling, while the other anomaly is positive and consistent (≈0.5 K) with a warming. The small amplitudes of the anomalies and inconsistencies point to the absence of a signal above the level of noise (0.1-0.2K) and no resolvable change in ground surface temperature. On visual inspection, these profiles measured with DTS appear very noisy (Figures 3 and 4) with oscillations of ±0.2K around the mean trend, which may be due to the poor resolution of the DTS. In such noise, a weak climate signal cannot be resolved. However we can infer that, for the past 100 years, surface temperature changes cannot exceed 0.5K This ~~absence of signal~~ nul result differs from the trends ~~observed~~ inferred in north-central Chile. ~~which is plausible~~ Such a difference is not unlikely since the two regions are over 500 km apart.

In contrast, the profiles in north central Chile show a negative temperature gradient and a positive temperature anomaly near the surface, indicative of recent warming, followed by a ~~regular~~ linear increase in temperature with depth. The presence of noise in these data, shown by the irregular variations in temperature gradient, lowers the resolution of the inversion. The temperature anomalies are well marked on all the profiles from Inca de Oro and Totoral; the temperature anomaly at Vallenar is not so well defined because the uppermost 40 m of the profile could not be measured and is missing (Figure 4). The anomalies suggest that all three sites have experienced warming and that ground surface temperature is higher now than in the past. This conclusion is supported by the inversion of GST histories for all the sites (Figures 6-8), but marked differences exist between Totoral on the one hand and Vallenar and Inca de Oro on the other. The warming at Inca de Oro and Vallenar is very recent, beginning after 1960, and appears to follow a long cooling period from 1800 to 1960, while Totoral shows no cooling but warming starting much earlier, ≈1800. The amplitude of warming varies from 0.4 K at Vallenar to 2.2 K at Inca de Oro. The maximum temperature is reached at present (2015) for Inca de Oro and Vallenar. However, at Totoral, the maximum temperature, a warming of 1.7 K, was reached in 1980 and followed by a cooling of ≈1 K until present. The robustness of this conclusion is questionable as there is no obvious sign of very recent cooling in the temperature anomaly and it may be a consequence of the limited resolution of the inversion with 3 singular values. ~~outside the resolution of our reconstructions~~. For the sites Inca de Oro and Vallenar, the inversions show a cooling of ≈ 1K between 1800 and 1980, followed by a strong warming (1.5K at Inca de Oro and 2.5K at Vallenar). Cooling followed by warming can also be inferred by visual inspection of the temperature anomalies at these sites. The inversion of the temperature profile at Totoral shows a warming trend by about 2K between 1800 and present. ~~Between ≈1800 and 1980, cooling by 0.9 K and 1.1 K is found at Inca de Oro and Vallenar, respectively. The cooling can also be inferred from visual inspection of the temperature anomalies for Vallenar and Inca de Oro, excluding borehole 1505 (Figure~~ 4). For Totoral, the cooling is not present in the GST history and no sign of it can be seen in temperature anomaly.

Despite the differences between the GST inversions of the three sites in north-central Chile, they all show a consistent warming trend. The simultaneous inversion of the six north-central Chile ~~borehole~~ temperature-depth profiles yields a GST history similar to those of Inca de Oro and Vallenar (Figure 9). There is no warming or cooling between 1500 and ≈1800. A cooling of 0.6 K is inferred between ≈1800 and 1980, followed by a warming of 1.9 K until present.

5 Discussion

5.1 Comparison with other borehole temperature studies in South America

A recent climate warming of ≈0.5-2 K with respect to the long-term GST has been detected for all the sites in north-central Chile. The sites are located in the Atacama Desert, a region with little to no vegetation. In such region with very low population density and without agriculture, changes in land use are insignificant and could not have generated a fake warming signal. Also, the amplitude of the inferred climate warming is in the range suggested by Huang et al. (2000) for the South American continent (1.4 K) and comparable with the warming of ≈1.4-2.2 K starting in the late 19th century inferred for semi-arid regions of South America (Hamza and Vieira, 2011). The timing of the warming in the latter study coincides with that of the Totoral site but it is much earlier than the very recent warming (past 40 years) at Inca de Oro, Vallenar, and for the entire north-central Chile region. There is also no evidence of prior cooling in the GST for semi-arid South America, suggesting that this cooling episode may be a local feature of north-central Chile. Records from a meteorological station located near the Copiapó airport, that cover only the second half of the 20^{th} century, show a very strong cooling period (-3K) between 1950 and 1960. This cold period also appears in the CRUTEM4 compilation of meteorological records on a 5×5^o grid. The effect of such a cooling event on the inversion of the temperature anomaly will be discussed when we compare our results with meteorological records. Huang et al. (2000) did not include any borehole temperature-depth profiles from northern Chile in their global study, but they analyzed four borehole temperature depth profiles from the semi-arid region of Peru. Only two of these profiles meet our selection criteria (LM18 and LOB525), the other two (LOB527 and PEN742) being too shallow. We have determined the GST history for the selected Peruvian boreholes by simultaneous inversion of the temperature anomalies ~~(following the technique outlined in section~~ 2.1) from the profiles cut at 300 m and retaining 3 singular values. We then compared the Peruvian and north-central Chile GST histories although they do not cover exactly the same time period (Figure 10). The GST history of the Peruvian profiles ends in 1979, the year of measurement. Both the Peruvian and the north-central Chile GSTs show no warming nor cooling for the period between 1500 and ≈1800. Following this period, the Peruvian GST shows warming by 1.6 K until 1979. The amplitude of this warming signal is similar to that of north-central Chile (1.9 K) but it starts much earlier and ~~there is~~ the simultaneous inversion shows no cooling period. ~~However, we~~ We also inverted each profile individually and we noted that for LM18, the Peruvian site closest to the border with Chile and at the northern edge of the Atacama desert, a cooling of $\approx$0.5 K is present from $\approx$1800 to 1950, similar to that observed in north-central Chile. We cannot rule out that this apparent cooling is an artifact of the noise and the limited resolution of the inversion, however the similarity of the results suggests that the cooling are real and reflect regional differences in the response of the climate system to warming. ~~This leads us to hypothesize that this cooling is spatially variable.~~

5.2 Comparison with meteorological data

In order to compare our results with meteorological records, we have used the worldwide compilation of air surface temperature records on land included in the CRUTEM4 data set (Jones et al., 2012). These records are averaged on a 5×5^o grid but we have used the records of individual stations. We have also used the complete meteorological record of the station at Copiapó. ~~Air surface temperature records on land have been compiled on a 5×5^o grid in the CRUTEM4 data set (Jones et al., 2012)~~. For northern coastal Chile, the CRUTEM4 data include stations at Iquique ($\approx$260 km north of Michilla), Mejillones ($\approx$55 km south of Michilla) and Antofagasta Cerro ($\approx$80 km south of Michilla) and covering the the period 1900-2016 with very important gaps. There appears to be a marked cooling around 1940, but there are gaps in the data between 1930 and 1960. A warming of $\approx$1 K is observed around 1980. Such warming is inconsistent with the nul result of the GST history inferred for the region. Because the temperature profiles obtained by DTS are quite noisy, we cannot rule out very weak temperature variations (< 0.5K), but our analysis of the temperature profiles suggests no significant climate warming for northern coastal Chile.
In north central Chile, the CRUTEM4 data include stations at La Serena, Vallenar, Copiapó, and Caldera but cover only the years 1940 to 2016. The mean yearly temperature from all the stations does not show a marked increase over the period, but it does show large amplitude variations including a marked cooling period from 1960 to 1970 similar to that at the Copiapó weather station. After 1970, there is modest warming consistent with, but with much less amplitude than the warming in the GST history for this region.

Examination of meteorological data from Copiapó, a city ~~with a population of 100,000,~~ less than 100 km away from Inca de Oro, shows a temperature decrease of $\approx$2.5 K between 1960 and 1970. To determine whether this cooling could be resolved in the GST reconstruction, ~~a test was run for~~ we have generated a synthetic profile for a cooling of 2.5 K between 1950 and 1960 that we inverted for a GST history of the last 500 years using the same parameters as in the study above (intervals of 20 years, retaining 3 eigenvalues). The inversion yielded a cooling of 0.5 K between 1800 and 1960, suggesting that a strong ~~period of~~ cooling event between 1950 and 1960 could appear as the cooling trend in the north-central GST history. ~~An unexpected feature of the GST history for central Chile (Figure~~ 9) is the long cooling trend preceding a very short and strong warming. This cooling event might explain the long cooling trend preceding a very short and strong warming seen in the GST history for central Chile (Figure 9). We believe that this "result" might be an artifact of the lack of resolution of our inversion procedure. With only the three largest singular values retained, the inversion does not resolve short period signals regardless of their strength. That such short period signals might have been present and affected the temperature profiles is suggested by the temperature record at the Copiapó airport meteorological station. This short (1950-present) weather record shows an 8 years interval (1960-1968) with temperature ≈2K colder than the mean (Figure 11). We have calculated the perturbation of a 300m deep temperature profile caused by a surface temperature variation identical to that of Copiapó's weather station and we inverted it retaining only the 3 largest singular values (Figure 11). We note that the resulting GSTH exhibits a very long trend of decreasing temperature followed by a very sharp increase not dissimilar to the surface temperature history inferred for north central Chile.

5.3 Comparison with other climate proxies

The north-central Chile GST history was also compared with the linear regression 5-year smoothed austral summer surface air temperature reconstruction from sedimentary pigments at Laguna Aculeo, central Chile (von Gunten et al., 2009) and the southern South America austral summer surface air temperatures inferred from 22 annually resolved predictors from natural and anthropogenic archives (Neukom et al., 2011) (Figure 12). Although there have been paleoclimatic studies in northern Chile, they do not focus on the recent climate, i.e. the last 1000 years (e.g., Bobst et al., 2001; Grosjean et al., 2003), leading to the comparison with the von Gunten et al. (2009) and Neukom et al. (2011) data. This also provides insight to whether the trends in northern Chile are regional or extend through central Chile and southern South America. From 1500 to 1700, there is no warming or cooling observed in any of the proxy climate reconstructions. Decadal variations, which cannot be resolved in the GST, are observed from 1700 to 1900 in the climate reconstruction for central Chile and southern South America. The climate reconstructions for the three regions show a recent climate warming but differences are noted with respect to the timing of its onset and its amplitude. In southern South America and central Chile, a recent warming of ≈0.5 K starting ≈150 years BP is inferred. In northern Chile, the warming begins significantly later, ≈20-40 years BP, and reaches a maximum of 1.9 K with respect to the long-term GST. No cooling trend is observed in the central Chile or southern South America climate reconstructions. These differences suggest that there are spatial and temporal variations in climate trends in Chile and southern South America. The cooling and greater amplitude recent warming are regional features of north-central Chile but the absence of warming or cooling from 1500 to 1700 is a climate trend for southern South America.

5.4 Comparison with models

The simulations of the last millennium for the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) provide insight to the climate of the last millennium (Braconnot et al., 2012; Taylor et al., 2012). The six models used to determine the multi-model mean surface temperature anomaly are outlined in Table 3. The multi-model mean surface temperature anomaly from the last millennium PMIP3/CMIP5 simulations for the gridpoints of northern coastal and north-central Chile show similar trends. Between 1500 and 1900, there is no warming or cooling. From 1900 to present, there is a warming of ≈1 K. This supports the absence of climate signal in the GST history of northern coastal Chile. Similarities are observed between the multi-model mean surface temperature anomaly for the north-central Chile gridpoint and the GST history for the region (Figure 13). Both infer no warming or cooling between 1500 and

≈1800 followed by recent warming. The warming of the PMIP3/CMIP5 surface temperature simulation is half and starts earlier than that reconstructed by the GST history. No cooling is observed in the PMIP3/CMIP5 surface temperature simulation for the north-central Chile gridpoint. This further suggests that the cooling trend and the greater amplitude recent warming are local trends for north-central Chile that cannot be resolved on the PMIP3/CMIP5 gridpoint scale.

6 Conclusions

We collected and analyzed 31 temperature-depth profiles in north-central and northern Chile but only 9 independent profiles were retained for inversion of the ground surface temperature history for the past 500 years.

For northern coastal Chile, the inversion of the temperature depth profiles shows little or no climate variations (warming or cooling) over the past 500years.

In north central Chile, the inversions of 6 profiles from 3 different sites yield some consistent conclusions: no warming or cooling can be resolved between 1500 and 1800 for all sites; all sites show recent (<50 years) and pronounced (0.5-2K) warming; for 2 of the sites, some cooling may have preceded this recent warming, but we can not discriminate between short (10 years) and strong (3K) cooling episodes and a long cooling trend (150 years).

The amplitude of warming in north central Chile in consistent with that inferred from other borehole temperature studies in other parts of South America. The warming is greater than that calculated in the PMIP3/CMIP5 surface temperature simulation for the northern coastal and north-central Chile gridpoints.

A cooling episode is also inferred from the study of 1 borehole in Peru at the northern edge of the Atacama desert. A short and strong cooling episode is consistent with the CRUTEM4 compilations of meteorological records, but these are unfortunately too short for comparing long term trends.

Our study suggests the presence of spatial and temporal climate variations in northern Chile, at a scale which cannot be well resolved by the simulations or by the limited data sets available.

7 Data Availability

The borehole temperature-depth profiles measured in 2012 and 2015 were uploaded to Figshare (https://figshare.com/articles/ChileData_zip and published with doi:10.6084/m9.figshare.5220964.v2. The temperature-depth profiles from 1992 were obtained from Andrea Förster and can be found in Springer (1997) and Springer and Förster (1998).

Appendix A: Boreholes not suitable for climate

The borehole temperature-depth profiles that did not meet the selection criteria for climate studies are displayed in Figure A1. The reason for eliminating these holes is given in TableA1. The majority of borehole temperature-depth profiles were rejected because they were deemed too shallow, i.e. they were less than 300 m deep or had no measurements in the top 100 m. This was frequent because measurements above 100m could not be made when the water table was too deep, and/or because the end of hole could not be reached in the many holes that had collapsed due to seismic activity. Some profiles were also eliminated due to discontinuities, signs of water flow, or other perturbations through visual inspection of the profiles. Some sites were excluded because of the topography when they are located on or near a steep slope. ~~since it is known to distort the temperature isotherms (Jeffreys, 1938)~~.

A1 El Loa

The site is mountainous and includes two boreholes. This is the furthest east and has the highest elevation (3950 m) among all the sites in this report. The lithology of the boreholes is primarily grandiorite and rhyolite (Springer, 1997; Springer and Förster, 1998). The temperature-depth profiles were too shallow for climate studies. They indicated high heat flux in the region (Figure A1), which could be attributed to the proximity of two volcanoes, the Miño Volcano (≈6 km) and the Cerro Aucanquilcha (≈20 km).

A2 Mansa Mina

The Mansa Mina borehole is located in a relatively flat region in sediments and granodiorite (Springer, 1997; Springer and Förster, 1998). It is <10 km from Chuquicamata open pit mine, ~~which is by extracted volume the largest open pit mine in the world,~~ and ≈10 km from the city of Calama. It is too shallow for climate studies.

A3 Sierra Limon Verde

Six borehole temperature-depth profiles were measured in Sierra Limon Verde. They are shallower than 300 m ~~and~~, found within 25 km and sediments make up the main lithology (Springer, 1997; Springer and Förster, 1998). Boreholes MODD37 MODD38, and MODD45 lie on top of a ≈400 m high hill. SLV-A and SLV-B are situated on the southern flank of this hill and MODD34 on the northern slope. The site is ≈25 km from the city of Calama and ≈35 km from the Mansa Mina borehole.

A4 Sierra Gorda

The two boreholes, ≈9 km apart are located in a relatively flat region, close to the Sierra Gorda open pit mine and ≈30 km south-east of the village of Sierra Gorda. One hole was too shallow to be retained for climate studies. For the other (JVC2641), the 100 topmost meters are missing and the change in the gradient at about 300m depth is indicative of a change in thermal conductivity. ~~They are ≈9 km apart and close to the Sierra Gorda open pit mine~~.

A5 Vallenar

This site, ≈ 20 km from Vallenar and ≈40 km from the coast, has two boreholes that have been measured twice using the same measurement technique. The repeat measurements were not included in order to not bias the reconstructions and only borehole ala1110 was retained for climate studies. The temperature-depth measurement of borehole ala0901 was discarded for being too shallow. Borehole ala0901 is ≈300 m from borehole ala1110 and is located between two hills, ≈ 20 km from Vallenar and ≈40 km from the coast. This site is about 40 km north of the Vallenar site reported by Uyeda et al. (1978).

A6 Copiapó

Two boreholes, ≈200 m apart, were measured ~~at Copiapó~~ ≈10 km east of the city of Copiapó. The temperature-depth profile of borehole 1507/DDH009 was measured twice using different techniques, conventional and DTS. The two boreholes were rejected because they are in an area of significant topography. ~~≈10 km east of the city of Copiapó. Since topography distorts temperature isotherms, the temperature-depth profiles were rejected.~~ Obviously, the strong discontinuities visible in the profiles of boreholes 1506 and 1507 are sufficient cause to reject them. Water flow is strongly suspected for both holes. An incident occurred during the logging of 1507, where the cable experienced a very strong downward pull that lasted for several seconds, likely caused by a slump of mud within the borehole. ~~Two sites near Copiapó, Elisa mine and Sierra Negro Norte, reported by Uyeda et al. (1978) are located 40km west of our measurements.~~

A7 Totoral

The site is in a relatively flat area, ≈75 km south-west of Copiapó, and ≈50 km from the coast. Two temperature-depth profiles for borehole 1509/RC370 were obtained using the conventional method and DTS. The profile obtained using DTS was retained, while that measured using the conventional method showed discontinuities probably caused by instrumental problems and was rejected.

A8 Punta Diaz

The site is on top of a ≈100 m hill and ≈3 km from the town of Punta Diaz. Signs of water flow are present in the temperature-depth profile, which lead to its exclusion.

A9 San José de Coquimbana

The site is on the side of a small hill, ≈40 km from Vallenar and ≈30 km from the coast. Using DTS and the conventional method, two temperature-depth profiles were measured for borehole 1511/RC363. Both profiles show signs of water flow and were discarded.

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Table 1. Location and technical information concerning the borehole temperature-depth profiles measured in 1994 by Springer (1997) and Springer and Förster (1998), in 2012 by Gurza Fausto (2014) and in 2015, where the column "suitable climate?" indicates if it passed the selection criteria outlined in Section 3.

Site	Log ID	Measurement Technique	Measurement Year	Latitude (S)	Longitude (W)	Depth Range (m)	Elevation (m)	Suitable climate?
El Loa				21°09.1′	68°39.1′		3950	
	LOA3587	Thermistor (2 m)[*]	1994			20-222		no
	LOA3622	Thermistor (2 m)[*]	1994			30-176		no
Mansa Mina	MM3205	Thermistor (2 m)[*]	1994	22°22.3′	68°54.9′	58-182	2423	no
Sierra Limon Verde	SLV-A	Thermistor (2 m)[*]	1994	22°49.1′	68°54.8′	86-206	2516	no
	SLV-B	Thermistor (2 m)[*]	1994	22°49.1′	68°54.8′	42-118	2516	no
Michilla				22°40.7′	70°10.9′		849	
	na12	DTS[†]	1994			20-455		yes
	p398	DTS[†]	1994			20-408		yes
	z197	DTS[†]	1994			20-446		yes
Sierra Limon Verde	MODD34	Thermistor (cont.)[‡]	2012	22°35.308′	68°54.865′	42-196	2704	no
	MODD37	Thermistor (cont.)[‡]	2012	22°41.059′	68°54.619′	43-135	2931	no
	MODD45	Thermistor (cont.)[‡]	2012	22°43.223′	68°55.441′	50-131	2910	no
	MODD38	Thermistor (cont.)[‡]	2012	22°43.660′	68°55.723′	65-228	2980	no
Sierra Gorda	ox10	Thermistor (cont.)[‡]	2012	23°0.454′	69°5.021′	60-185	2368	no
	JCV264	Thermistor (cont.)[‡]	2012	23°4.765′	69°5.666′	102-485	2379	no
Vallenar	ala901	Thermistor (cont.)[‡]	2012	28°39.855′	70°54.505′	60-207	490	no
	ala901-2	Thermistor (cont.)[‡]	2012	28°39.855′	70°54.505′	53-204	490	no
	ala1110	Thermistor (cont.)[‡]	2012	28°39.979′	70°54.624′	48-411	521	yes
	ala1110-2	Thermistor (cont.)[‡]	2012	28°39.979′	70°54.624′	41-412	521	yes
Inca de Oro	DDH2457	DTS[◇]	2015	26°45′10.8″	69°53′38.4″	39-413	1628	yes
	1501	Thermistor (10 m)[**]	2015	26°45′14″	69°53′42″	26-398	1621	yes
	DDH2489A/1501	DTS[◇]	2015	26°45′14″	69°53′42″	20-422	1621	yes
	1504	Thermistor (10 m)[**]	2015	26°45′20″	69°53′42″	26-309	1626	yes
	1505	Thermistor (10 m)[**]	2015	26°45′20″	69°53′38″	26-420	1630	yes
Copiapo	1506	Thermistor (10 m)[**]	2015	27°22′49″	70°13′25″	26-297	679	no
	1507	Thermistor (10 m)[**]	2015	27°22′55″	70°13′27″	20-550	703	no
	DDH009/1507	DTS[◇]	2015	27°22′55″	70°13′27″	20-557	703	no
Totoral	1509	Thermistor (10 m)[**]	2015	27°58′51″	70°36′60″	20-310	400	no
	RC370/1509	DTS[◇]	2015	27°58′51″	70°36′60″	20-298	400	yes
Punta Diaz	RC151	DTS[◇]	2015	28°01′56.3″	70°38′44.2″	20-365	480	no
San José de Coquimbana	1511	Thermistor (10 m)[**]	2015	28°15′35″	70°51′27″	36-335	354	no
	RC363/1511	DTS[◇]	2015	28°15′35″	70°51′27″	20-314	354	no

[*] Value in parenthesis indicates sampling interval and yields temperature measurements with a precision of 0.01°C.

[†] Temperature measurements with a precision of 0.3°C.

[‡] Value in parenthesis indicates continuous sampling and yields temperature measurements with an accuracy of 0.05°C.

[**] Value in parenthesis indicates sampling interval and yields measurements with a precision better than 0.005 K and an accuracy on the order of 0.02 K.

[◇] Temperature measurements with a precision of 0.3°C.

Table 2. Summary of inversion results where T_o is the long-term surface temperature, Γ_o is the quasi-steady state temperature gradient and ΔT is the difference between the maximal temperature and the temperature at 1500 years CE.

Site	Log ID	year	T_o ($^{\circ}C$)	Γ_o (km^{-1})	ΔT (K)
Michilla					0.1
	na12	1994	20.9±0.01	9.9±0.1	
	p398	1994	20.9±0.01	8.8±0.2	
	z197	1994	22.0±0.01	10.4±0.3	
Inca de Oro					2.2
	DDH2457	2015	22.4±0.01	12.9±0.1	
	1501	2015	22.5±0.02	14.0±0.5	
	1504	2015	22.9±0.02	12.3±0.3	
	1505	2015	22.4±0.01	14.6±0.3	
Totoral	RC370	2015	20.8±0.01	11.3±0.2	1.7
Vallenar	ala1110-2	2015	23.5±0.00	6.6±0.01	0.4

Table 3. Summary of models used to calculate the multi-model mean surface temperature anomaly from the PMIP3/CMIP5 simulation

Model	warming	Reference
BCC-CSM1.1	1.8K	(Li et al., 2014)
CCSM4.0	1.6K	(Gent et al., 2011)
GISS-E2-R	1.0K	(Schmidt et al., 2014)
IPSL-CM5A	1.7K	(Mignot and Bony, 2013)
MPI-ESM	1.6K	(Giorgetta et al., 2013)
MRI-CGCM3	1.0K	(Yukimoto et al., 2012)

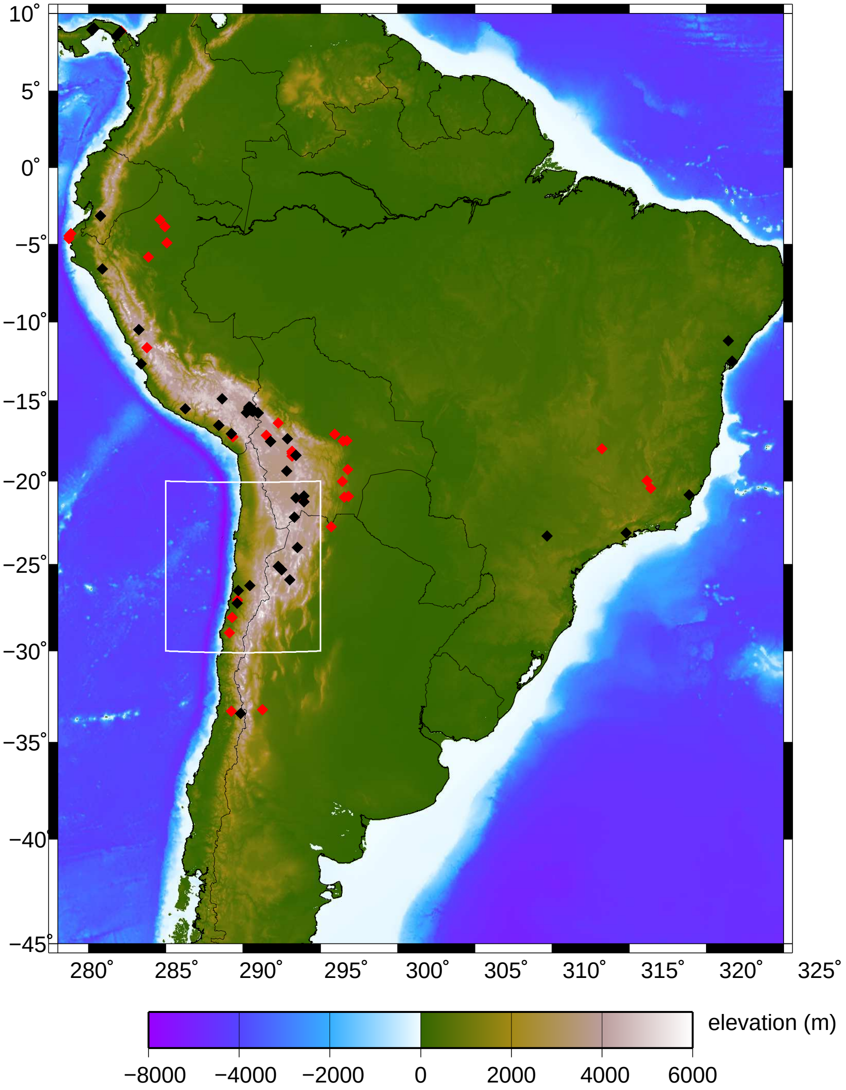

Figure 1. Map of South America including locations of borehole temperature measurements for heat flow studies from the updated International Heat Flow Commission (IHFC) (IHFC (2011), http://www.heatflow.und.edu/index2.html) database. Red diamonds represents boreholes deeper than 200 m, while black are boreholes shallower than 200 m. More than 100 bottom-hole temperature measurements, mainly in Brazil, are not included as they are not useful for climate studies. The rectangle indicates the study region of northern Chile.

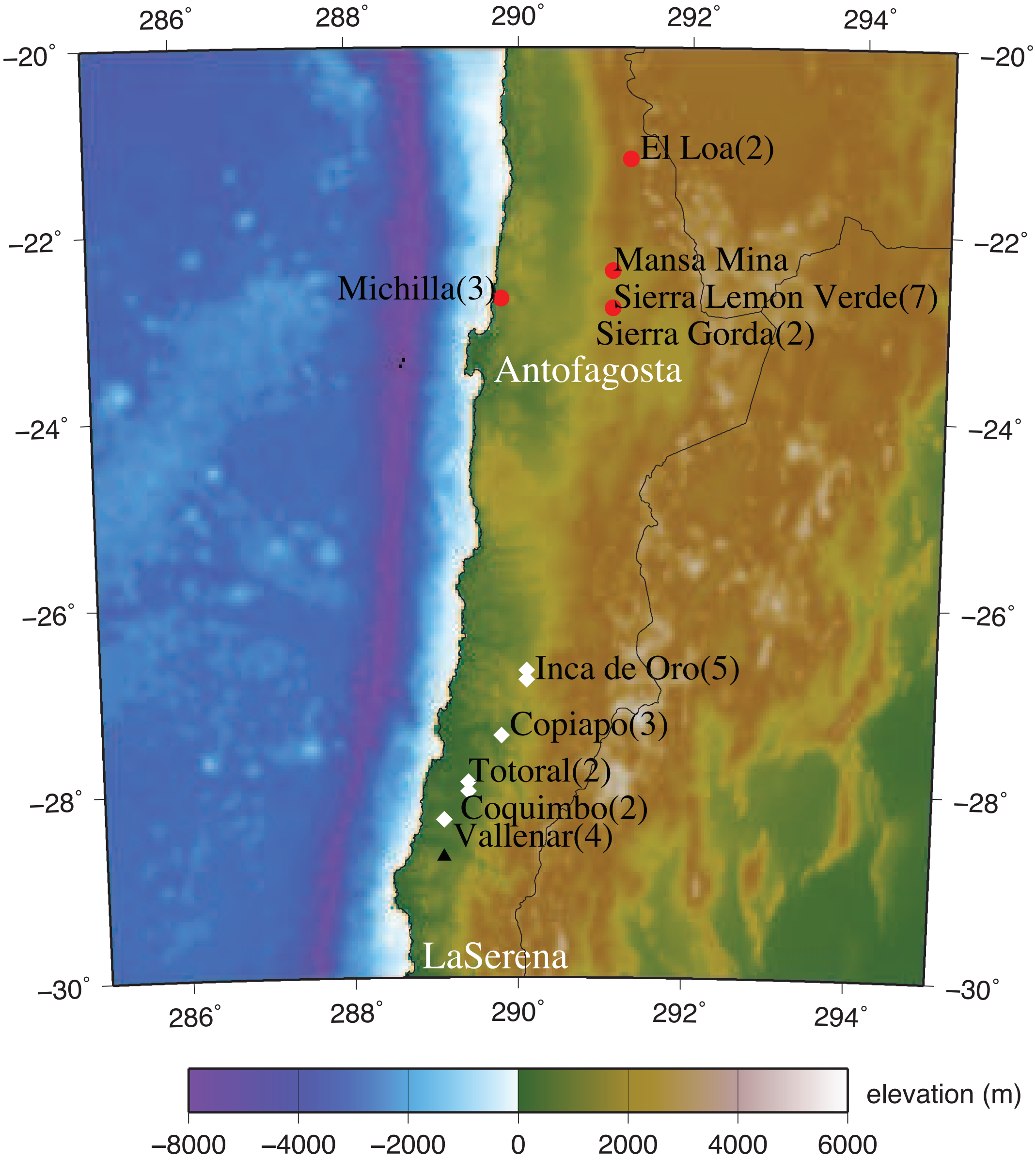

Figure 2. Map of northern Chile with locations of boreholes used in this study. The number of boreholes at each site is indicated in parenthesis. Red circles indicate borehole temperature-depth profiles measured in 1994, black triangles are measured in 2012, and white diamonds are measured in 2015. Sites with borehole temperature-depth profiles deemed suitable for climate are Michilla, Totoral, Inca de Oro, and Vallenar.

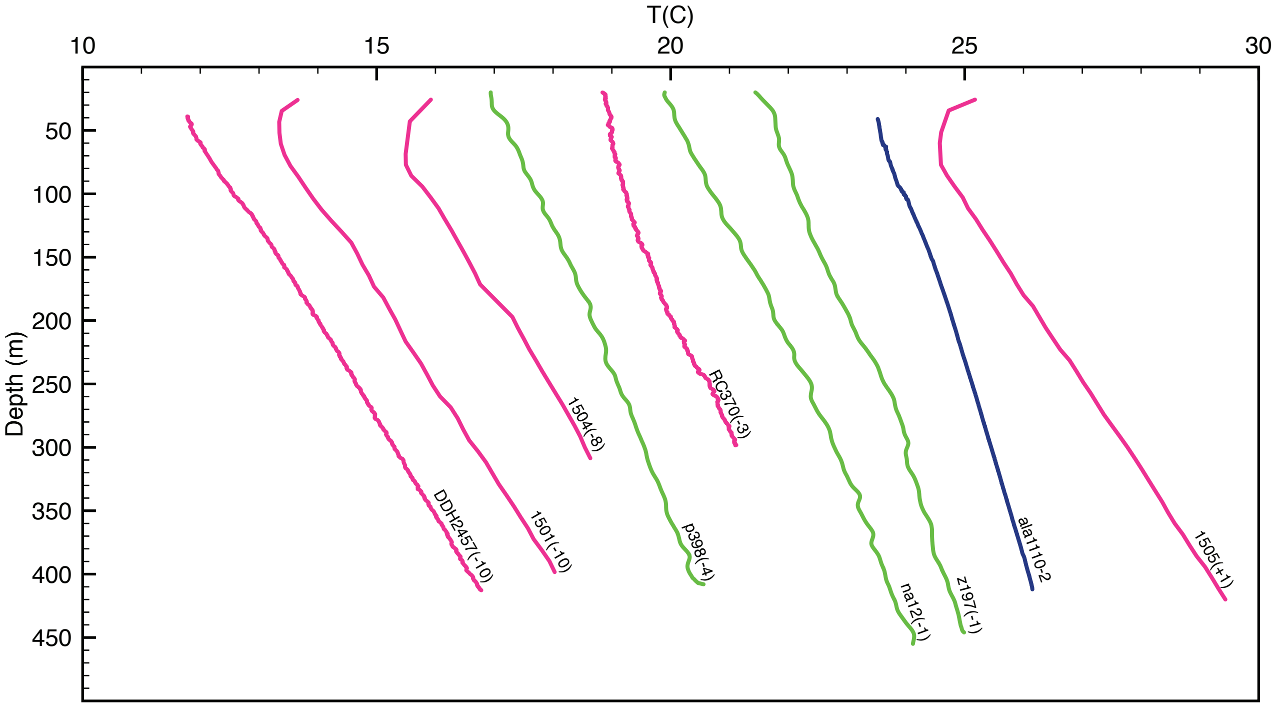

Figure 3. Retained temperature-depth profiles measured in 1994 (green), 2012 (blue), and 2015 (pink). Temperature scale is shifted as indicated in parenthesis. The profiles from Michilla measured with DTS (in green) appear to be noisier than those obtained from conventional methods.

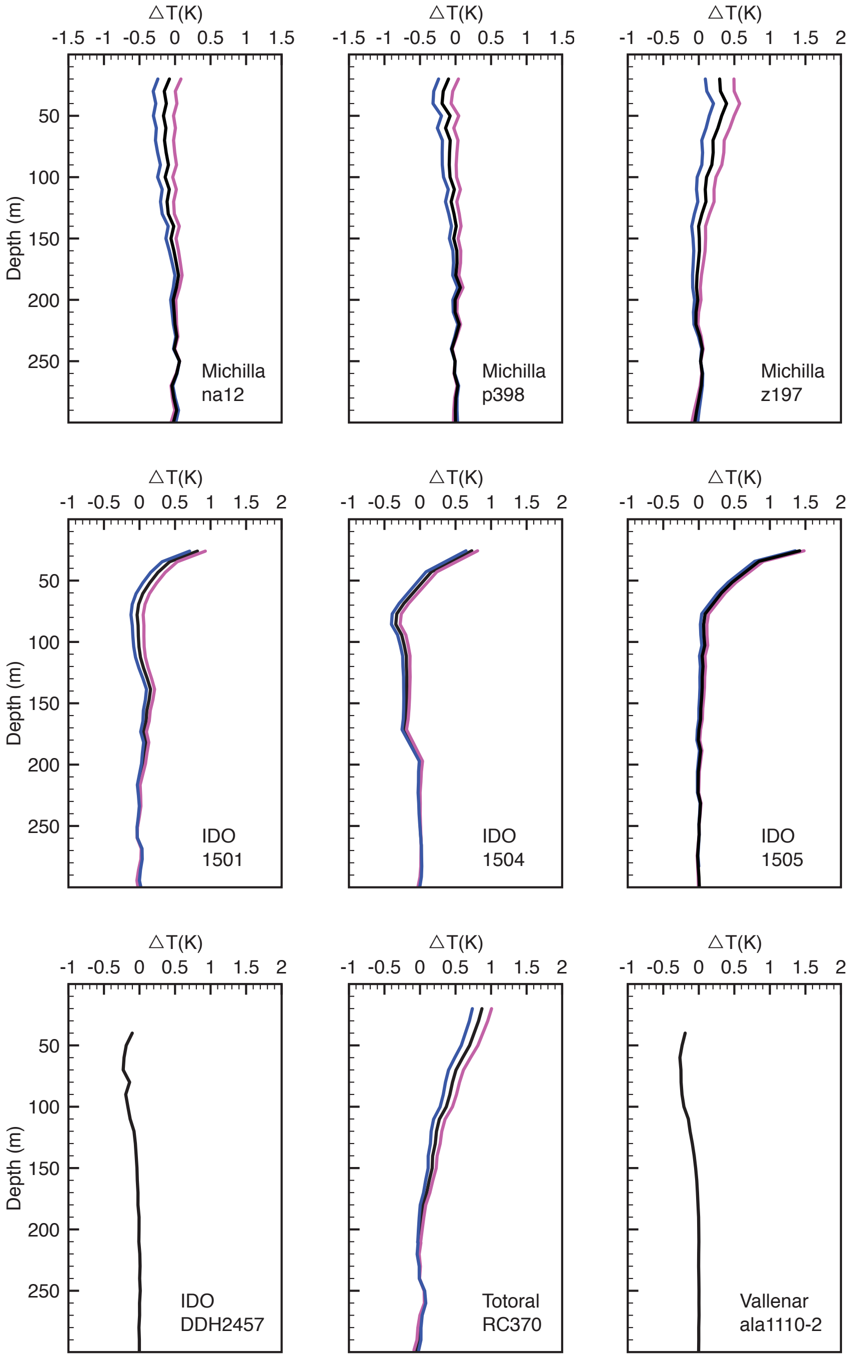

Figure 4. Temperature anomalies for the retained temperature-depth profiles, where IDO is Inca de Oro. The pink and blue lines represent the upper and lower bounds of the temperature anomaly. These are not visible at IDO-DDH2457 and Vallenar ala1110-2 because they are superimposed.

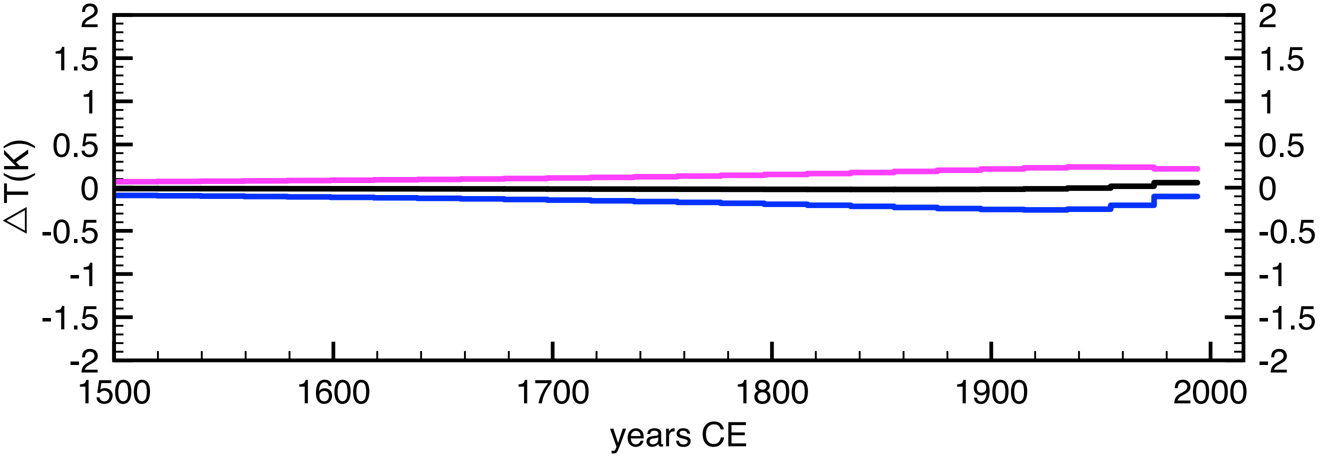

Figure 5. GST history for northern coastal Chile (Michilla) determined for its period of measurement (1994) from the simultaneous inversion of na12, p398, and z197, where 3 eigenvalues are retained. The pink and blue lines represent the inversion of the upper and lower bounds of the temperature anomaly or the extremal steady states.

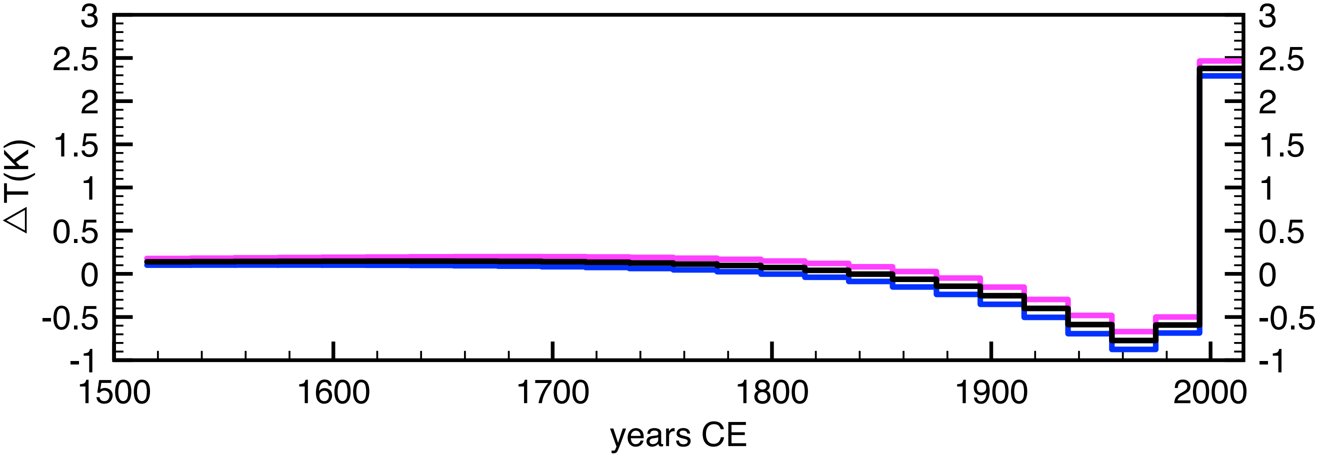

Figure 6. GST history for Inca de Oro determined from the simultaneous inversion of DDH2457, 1501, 1504, and 1505, with 3 eigenvalues retained. The pink and blue lines represent the inversion of the upper and lower bounds of the temperature anomaly or the extremal steady states.

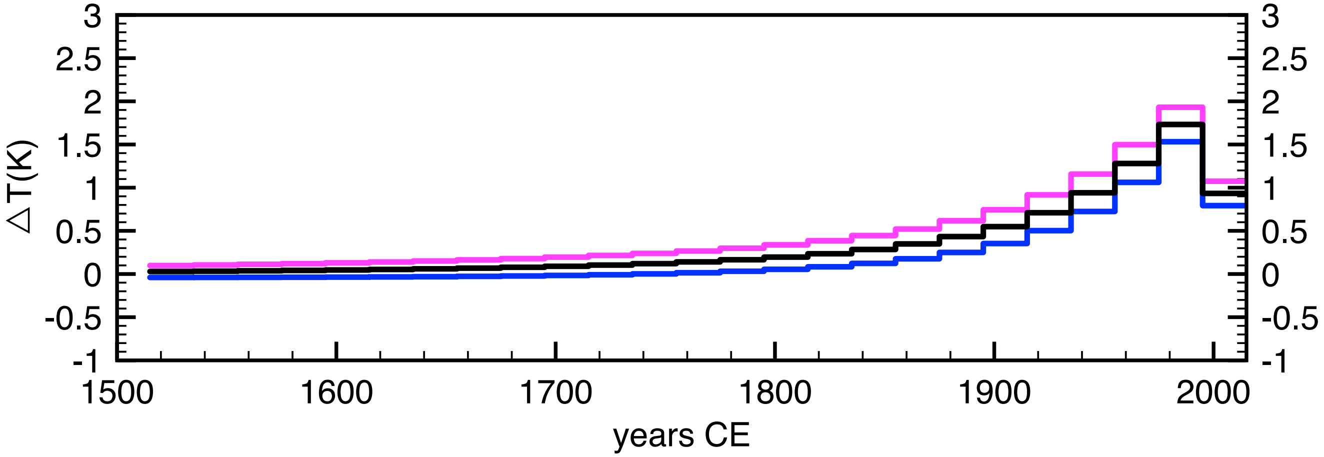

Figure 7. GST history for Totoral (RC370), with 3 eigenvalues retained. The pink and blue lines represent the inversion of the upper and lower bounds of the temperature anomaly or the extremal steady states.

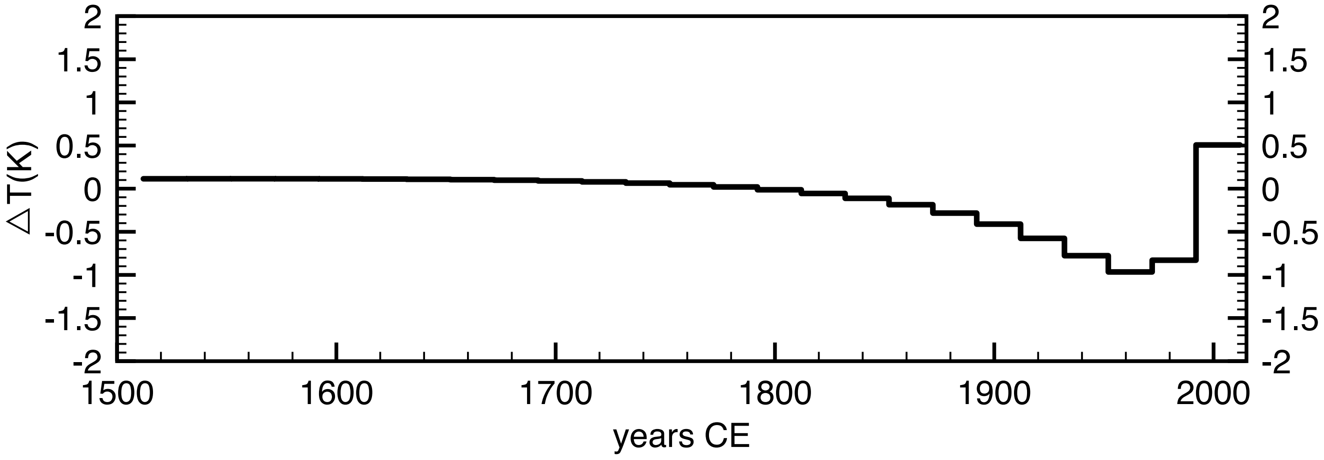

Figure 8. GST history for Vallenar (ala1110-2), with 3 eigenvalues retained. The inversion of the upper and lower bounds of the temperature anomaly or the extremal steady states are not visible because the three lines are superimposed.

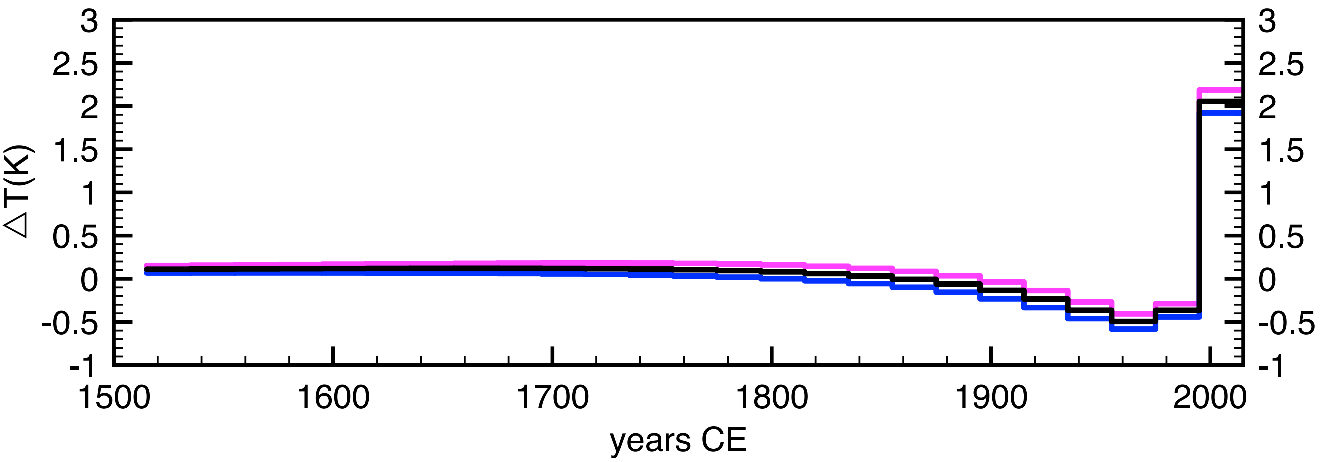

Figure 9. GST history for north-central Chile determined by the simultaneous inversion of DDH2457, 1501, 1504, 1505, RC370, and ala1110-2, with 3 eigenvalues retained. The pink and blue lines represent the inversion of the upper and lower bounds of the temperature anomaly or the extremal steady states.

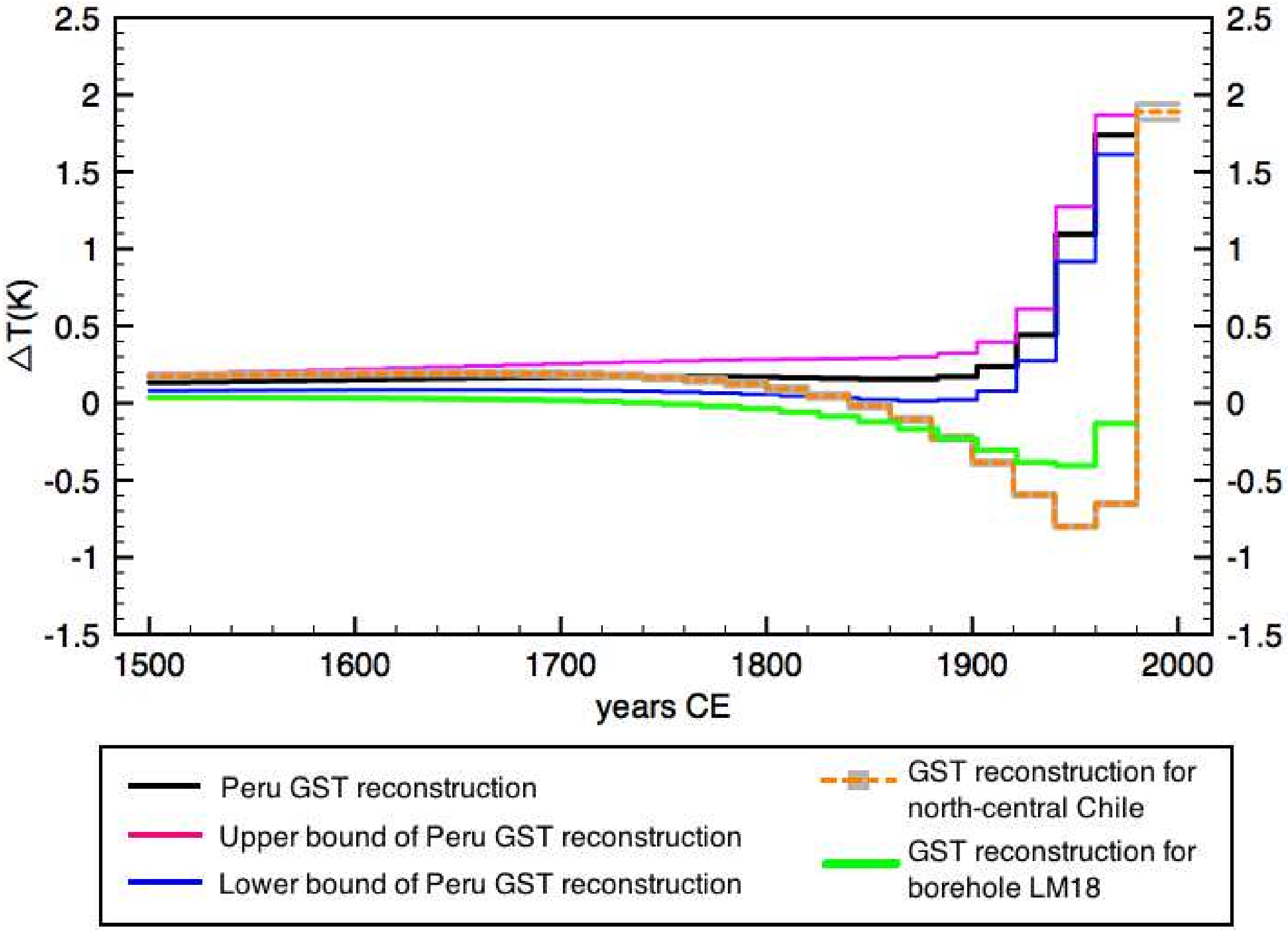

Figure 10. Comparison of GST histories for Peruvian boreholes (black), Peruvian profile LM18 (in green), and north-central Chile (orange) with its upper and lower bounds (grey shaded area). The GST for the Peruvian boreholes ~~is reconstructed~~ was obtained by the simultaneous inversion of LM18 and LOB525 and is relative to the measurement time (1979). Inversion of LM18 shows a cooling similar to that observed in north-central Chile. ~~and obtained by the simultaneous inversion of LM18 and LOB525.~~ The inversions of the upper and lower bounds of the temperature anomaly for the Peruvian boreholes are represented by the pink and blue lines, respectively.

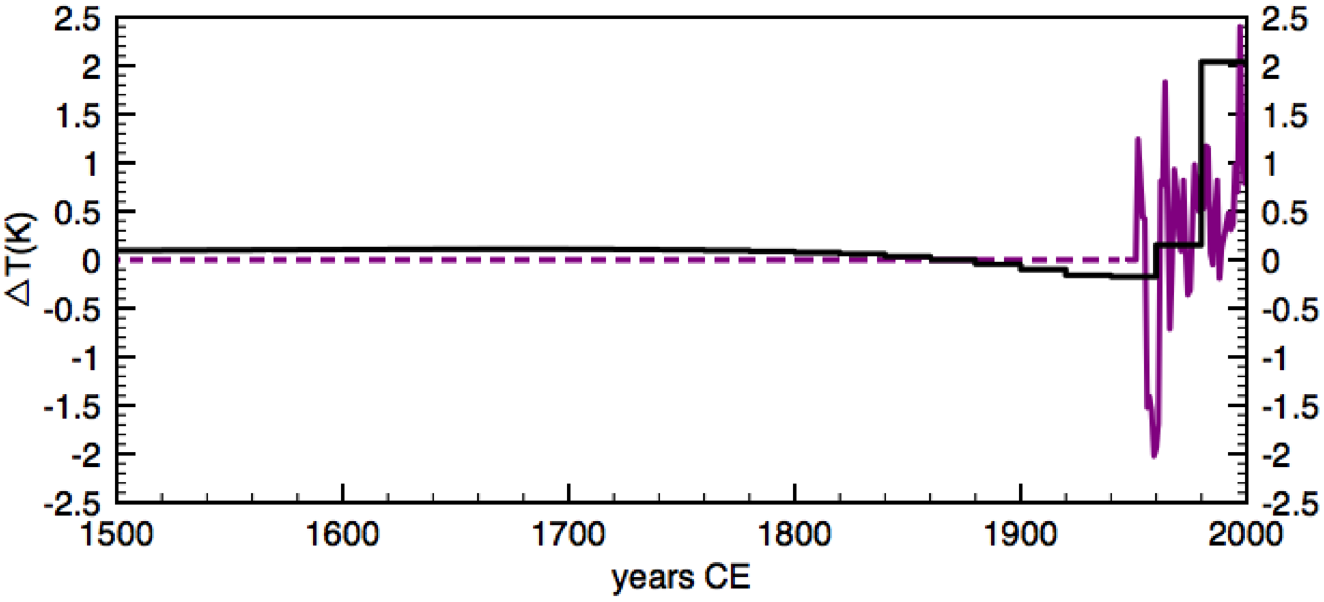

Figure 11. Meteorological record from Copiapo airport (in purple) used as input for calculating a synthetic temperature anomaly and result of its inversion ~~of the corresponding temperature profile~~ using 3 singular values (in black). The solid purple line is the actual meteorological record (1950-2014), the dashed horizontal line is an extrapolation of the mean temperature of the record.

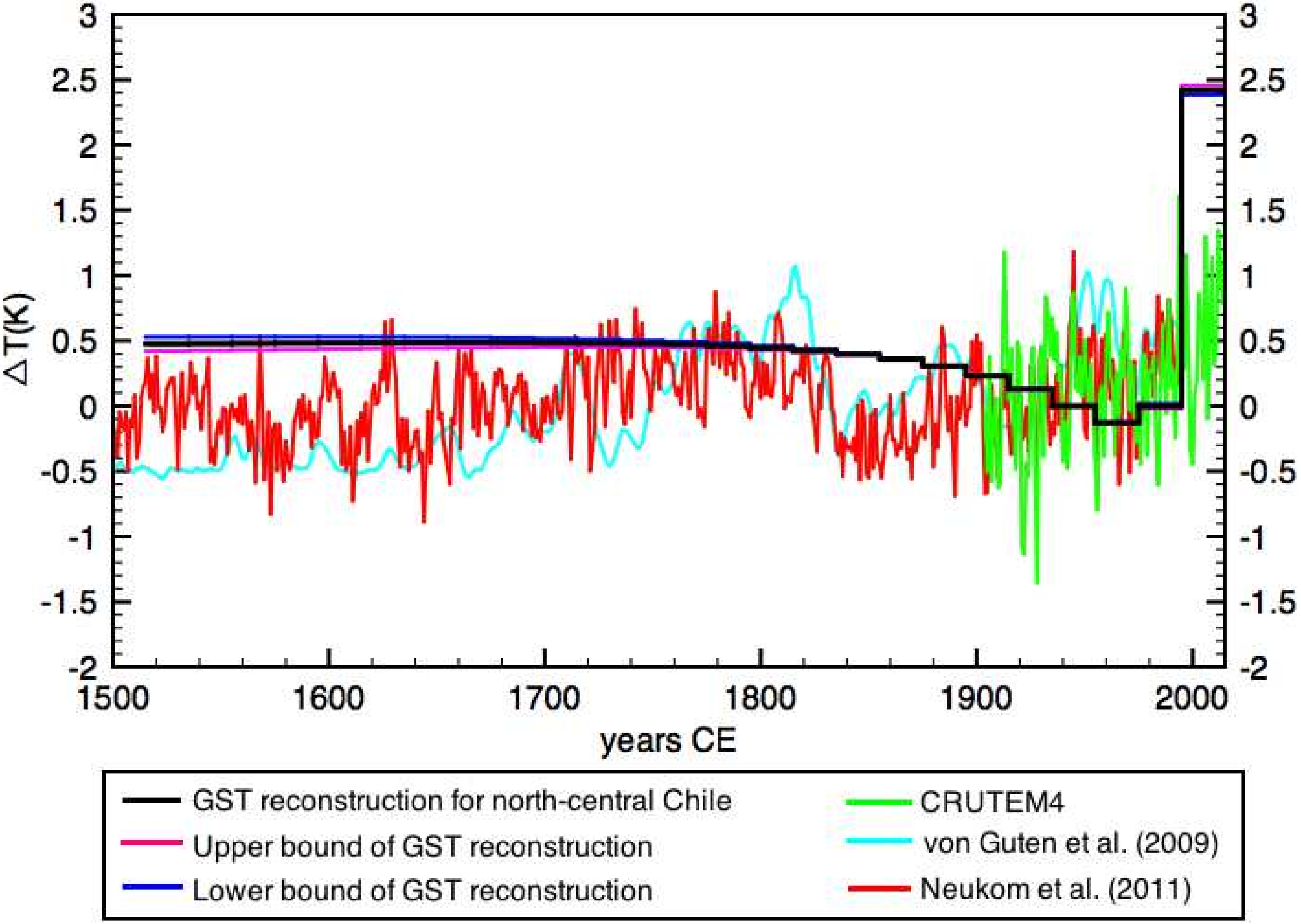

Figure 12. Comparison of GST history for north-central Chile (black) along with the upper and lower bounds of the inversion (pink and blue lines, respectively), the CRUTEM4 data for the north-central Chile gridpoint (green) (Jones et al., 2012), the austral summer surface air temperature reconstruction from sedimentary pigments for the past 500 years (aqua) at Laguna Aculeo, central Chile (von Gunten et al., 2009), and the austral summer surface air temperature reconstruction for southern South America (red) with its 2σ standard deviation (grey shaded area) (Neukom et al., 2011). They are all presented as temperature departures from the 1920-1940 mean.

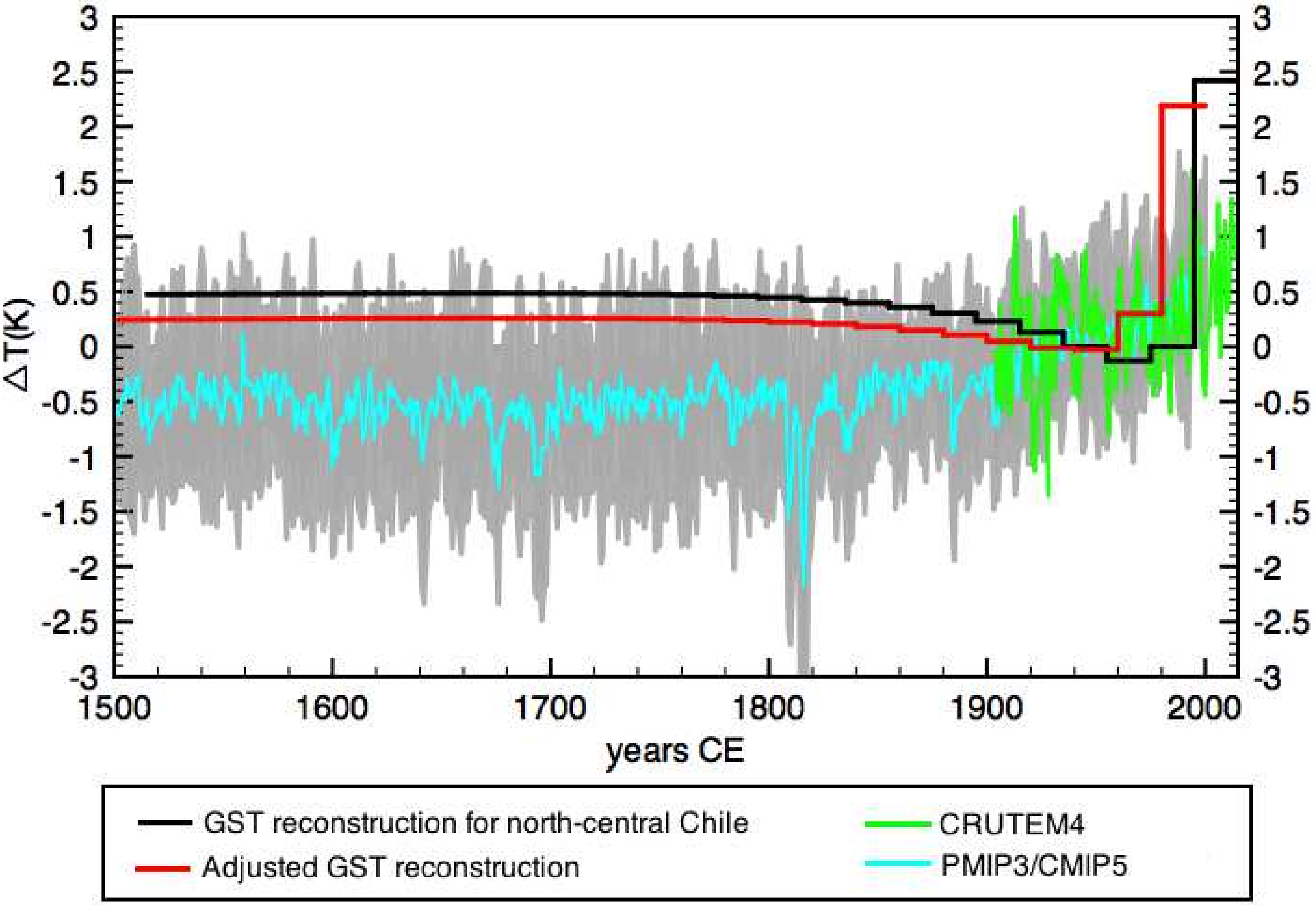

Figure 13. Comparison of two GST histories for north-central Chile (black and red lines) with the CRUTEM4 data for the north-central Chile grid point (Jones et al., 2012), and the multi-model mean surface temperature anomaly reconstruction for the PMIP3/CMIP5 (aqua) with its 2σ standard deviation (grey shaded area). They are all presented as temperature departures from the 1920-1940 mean. The black line is the result of the inversion of all the temperature profiles; the red line is the same ~~inversion~~ adjusted to remove the effect on the inversion of a hypothesized short marked cooling (-2K) event between 1950 and 1960.

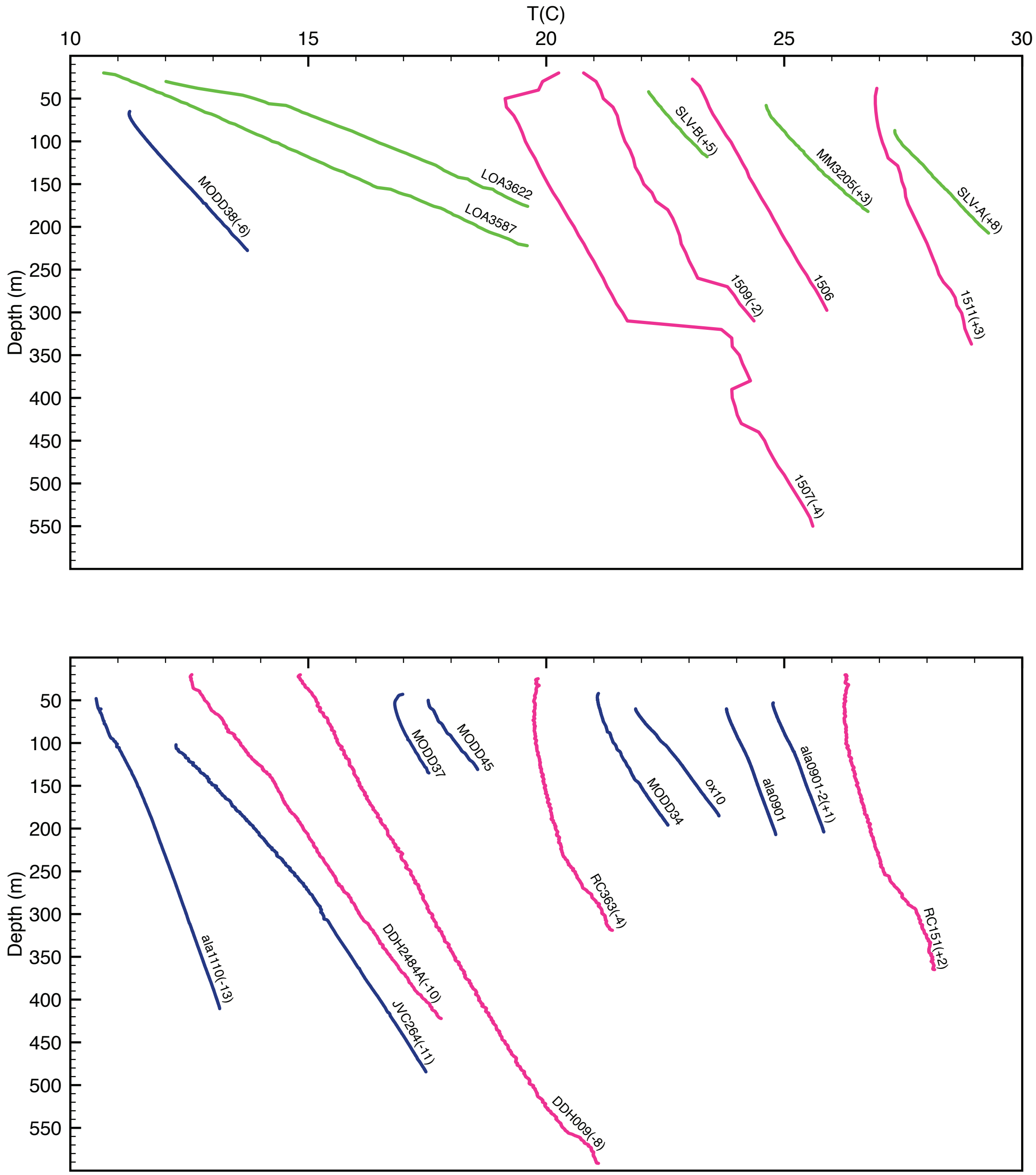

Figure A1. Rejected temperature-depth profiles measured in 1994 (green), 2012 (blue), and 2015 (pink). Temperature scale is shifted as indicated in parenthesis.

Table A1. Technical information concerning boreholes not suitable for this study

Site	Log ID	Year Measured	Remark	Reference
El Loa	LOA3587	1994	Too shallow	(Springer, 1997; Springer and Förster, 1998)
El Loa	LOA3622	1994	Too shallow	(Springer, 1997; Springer and Förster, 1998)
Mansa Mina	MM3205	1994	Too shallow	(Springer, 1997; Springer and Förster, 1998)
Sierra Limon Verde	MODD34	2012	Too shallow	(Gurza Fausto, 2014)
	MODD37	2012	Too shallow	(Gurza Fausto, 2014)
	MODD45	2012	Too shallow	(Gurza Fausto, 2014)
	MODD38	2012	Too shallow	(Gurza Fausto, 2014)
	SLV-A	1994	Too shallow	(Springer, 1997; Springer and Förster, 1998)
	SLV-B	1994	Too shallow	(Springer, 1997; Springer and Förster, 1998)
Sierra Gorda	ox10	2012	Too shallow	(Gurza Fausto, 2014)
	JCV264	2012	Top 100 m absent	(Gurza Fausto, 2014)
Inca de Oro	DDH2489A	2015	Remeasurement of 1501 by DTS	-
Copiapo	1506	2015	Topography, Discontinuity	-
	1507	2015	Topography, Discontinuity	-
	DDH009	2015	Topography	-
Totoral	1509	2015	Discontinuity	-
Punta Diaz	RC151	2015	Water Flow	-
San José de Coquimbana	1511	2015	Water Flow	-
	RC363	2015	Water Flow	-
Vallenar	ala901	2012	Too shallow	(Gurza Fausto, 2014)
	ala901-2	2012	Too shallow, Duplicate of ala0901	(Gurza Fausto, 2014)
	ala1110	2012	Duplicate of ala1110-2	(Gurza Fausto, 2014)