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- Trends depend on latitude and choice of reference period
- Recent coastal cooling is consistent with a PDO-analog model
- High-elevation warming signal outside of 1σ model spread

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Impact of the global warming hiatus on Andean temperature

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Abstract The recent hiatus in global warming is likely to be reflected in Andean temperature, given its close dependence on tropical Pacific sea surface temperature (SST). While recent work in the subtropical Andes has indeed documented a cooling along coastal areas, trends in the tropical Andes show continued warming. Here we analyze spatiotemporal temperature variability along the western side of the Andes with a dense station network updated to 2010 and investigate its linkages to tropical Pacific modes of variability. Results indicate that the warming in tropical latitudes has come to a halt and that the subtropical regions continue to experience cooling. Trends, however, are highly dependent on elevation. While coastal regions experience cooling, higher elevations continue to warm. The coastal cooling is consistent with the observed Pacific Decadal Oscillation (PDO) fingerprint and can be accurately simulated using a simple PDO-analog model. Much of the PDO imprint is modulated and transmitted through adjustments in coastal SST off western South America. At inland and higher-elevation locations, however, temperature trends start to diverge from this PDO-analog model in the late 1980s and have by now emerged above the 1σ model spread. Future warming at higher elevation is likely and will contribute to further vertical stratification of atmospheric temperature trends. In coastal locations, future warming or cooling will depend on the potential future intensification of the South Pacific anticyclone but also on continued temperature dependence on the state of the PDO.

1. Introduction

The recent slowdown in global warming has spurred a debate regarding its underlying causes. While some have suggested that climate sensitivity may have been overestimated [*Otto et al.*, 2013], others have pointed to incomplete global coverage of the observational temperature data and stronger than average warming in regions not covered by this database [*Cowtan and Way*, 2014] or changes in solar variability and stratospheric or tropospheric aerosols that may have lead to the stagnant temperature trend over the past decade [*Solomon et al.*, 2011; *Kaufmann et al.*, 2011; *Santer et al.*, 2014]. Much of the evidence, however, suggests that the surplus energy has been stored in the world's oceans [*Meehl et al.*, 2011; *Guemas et al.*, 2013], in particular the equatorial Pacific [*Kosaka and Xie*, 2013] related to the cool phase of the Pacific Decadal Oscillation (PDO) and strengthened trade winds [*Trenberth and Fasullo*, 2013; *England et al.*, 2014; *Meehl et al.*, 2014]. Nowhere on Earth does this recent halt in warming appear to be more obvious than along the extratropical west coast of central and northern Chile (17°S–37°S), where temperature rose significantly during much of the twentieth century [*Rosenblüth et al.*, 1997], but then started to drop, resulting in a sustained cooling of up to −0.20°C/decade over the past 20–30 years [*Falvey and Garreaud*, 2009; *Schulz et al.*, 2012]. *Falvey and Garreaud* [2009] partially attributed the observed cooling to changes in Pacific decadal variability and suggested that the projected intensification of the South Pacific anticyclone (SPA) and related enhanced upwelling of cold water from below the thermocline will help cool the region in the future. Despite this offshore cooling, however, Andean glaciers continue to retreat faster than at any time since they reached their neoglacial maximum extent [*Rabatel et al.*, 2013], which has spurred a reanalysis of temperature data in some mountain regions of the Andes [e.g., *Schauwecker et al.*, 2014]. At the same time, temperature along the west coast of tropical South America (Peru and Ecuador) was reported to show maximum warming rates during the second half of the twentieth century [*Marengo et al.*, 2011; *Vuille and Bradley*, 2000; *Vuille et al.*, 2003, 2008a]. Other more regional studies also document significant warming trends in the second half of the twentieth century in the Peruvian Andes [*Mark*, 2002; *Mark and Seltzer*, 2005; *Racoviteanu et al.*, 2008; *Bradley et al.*, 2009; *Lavado*

Casimiro et al., 2013; *Salzmann et al.*, 2013], the Andes of Bolivia [*Gilbert et al.*, 2010; *Thibeault et al.*, 2010; *Seiler et al.*, 2013], and Colombia [*Quintana-Gomez*, 1999; *Poveda and Pineda*, 2009].

A common theme emerging from all these studies is that there appear to be large differences in observed temperature trends between tropics and extratropics and between inland warming and offshore marine cooling; yet up to now, these different results have not been reconciled in an overarching study combing data from the entire South American west coast. Hence, it remains uncertain whether the recent anomalous cooling affects only the midlatitudes of the South American west coast or whether it also extends into the tropics. Earlier studies from the tropics did not detect this cooling [*Vuille and Bradley*, 2000], but this may also reflect the fact that they relied on 20th century temperature data only, not including the most recent cooling period. One of the main objectives of this article is therefore to shed some light on the spatiotemporal characteristics of temperature variations along the entire west coast of South America from the equator to Patagonia using an extended data set and consistent analyses.

A second topic of outmost relevance is to document whether there are large elevation dependencies of the observed temperature trends as initially proposed by *Vuille and Bradley* [2000]. Glaciers along the Andes continue to retreat; yet it is unclear whether this trend continues despite a slowdown of the warming in the Andes or whether the reported cooling is limited to lower elevations near coastal areas but not affecting the highest elevations of the Andes where glaciers are located. Model projections of future warming in the Andes based on Coupled Model Intercomparison Project phase 3 and regional climate model simulations [*Bradley et al.*, 2006; *Urrutia and Vuille*, 2009] suggest such an elevation-dependent warming to become very pronounced during the course of the 21st century, but the observational evidence is not as clear. *Vuille and Bradley* [2000] in their analysis found stronger warming along the lower elevations of the west coast of northern Chile, Peru, and Ecuador, with a decreased rate of warming at higher elevations, although the warming trend was still significant at the 95% confidence level, even at the highest elevations. Temperature changes at high altitude are generally difficult to detect, given the paucity of in situ data. Several studies therefore made use of reanalysis or radiosonde data to document changes in the 0°C isotherm (freezing level) of the free atmosphere, assuming that free-air and near-surface temperature trends at a similar elevation are comparable [*Pepin and Seidel*, 2005]. *Diaz et al.* [2003] and *Rabatel et al.* [2013] analyzed changes in freezing level height over the Andes based on reanalysis data and documented a significant increase since the middle of the 20th century. *Falvey and Garreaud* [2009], using radiosonde data in north central Chile, also reported lower- and middle-tropospheric warming over land.

The third objective of this study is to shed some light on the relative roles of natural and anthropogenic forcings related to temperature change and hence glacier retreat in the region. While global warming is usually seen as the main culprit for the shrinking Andean cryosphere [*Vuille et al.*, 2008a; *Rabatel et al.*, 2013], it is also well understood that tropical Pacific sea surface temperatures (SSTs) in particular significantly affect Andean glacier mass balance [*Francou et al.*, 2003, 2004; *Vuille et al.*, 2008b]. El Niño years are generally characterized by a more negative glacier mass balance due to warm and dry conditions (see also Figure 1c), while the cooler and wetter La Niña years [*Vuille et al.*, 2000a, 2000b; *Garreaud et al.*, 2009] often lead to a neutral or sometimes even slightly positive mass balance on glaciers in Bolivia, Peru, and Ecuador [*Wagnon et al.*, 2001; *Francou et al.*, 2003, 2004; *Vuille et al.*, 2008a; *Rabatel et al.*, 2013]. Hence, it remains an unanswered question whether this sensitivity to tropical Pacific SST on interannual time scales translates into significant cumulative mass changes on time scales of decades or longer or whether the observed glacier retreat is instead solely driven by an anthropogenically forced temperature increase in the region.

At the same time, the recent cooling along coastal areas may also largely reflect processes in the tropical equatorial Pacific. On a global scale, the change in the phase of the PDO after the 1997/1998 El Niño event has been linked to the recent hiatus in global warming [*Meehl et al.*, 2011; *Trenberth and Fasullo*, 2013]. Given the close relationship between PDO and surface temperature along the South American west coast (Figure 1d) [see also *Garreaud et al.*, 2009], the PDO may also be responsible for the lack of a significant temperature increase along parts of the South American west coast. Answering these questions requires a decomposition of temperature trends into natural and anthropogenically forced components. The only existing study addressing this issue, to our knowledge, was performed by *Vuille et al.* [2003], who used a

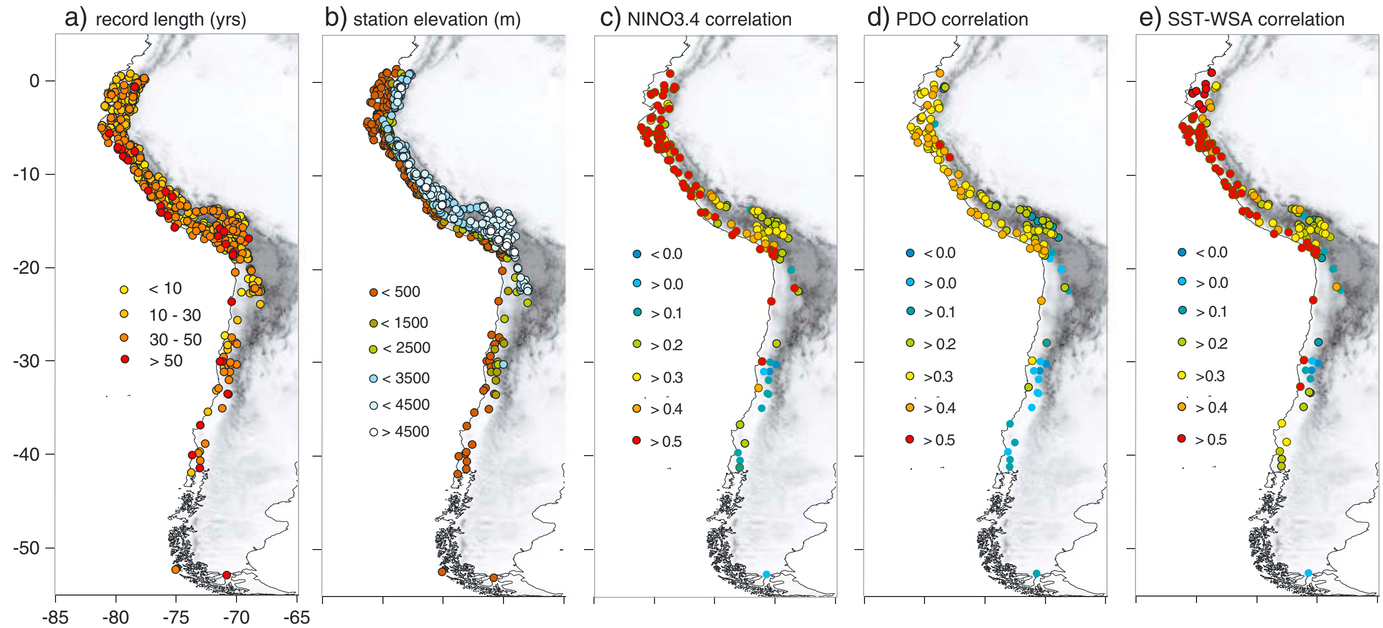

Figure 1. Map with location of all stations used, with color coding indicating (a) record length in years, (b) station elevation in meter, and (c) correlation coefficient between station temperature anomalies and Niño 3.4 index. (d) Same as in Figure 1c but for correlation with PDO. (e) Same as in Figure 1c but for correlation with SST-WSA index. Correlations in Figures 1c–1e are calculated over the period of 1971–2000, with symbols outlined in black indicating correlations significant at $P < 0.05$.

high-resolution version (T106) of the European Centre/Hamburg model 4 atmospheric general circulation model to diagnose the contribution of the El Niño–Southern Oscillation (ENSO) phenomenon to the overall warming trend in the tropical Andes between 1979 and 1998. According to their results, roughly 50–70% of the simulated warming along the Pacific coast is linearly congruent with the Niño 4 index. However, since these results are entirely model based and calculated for a 20 year period which includes the two strongest ENSO events of the century (1982/1983 and 1997/1998), they need to be interpreted with caution, and a reanalysis over a longer time period, using observational data and considering other modes of variability that can affect temperature along the South American west coast [*Garreaud et al.*, 2009], seems warranted.

To address all these questions, we rely on updated monthly temperature data sets from Ecuador, Peru, and Chile, which were first published in *Vuille and Bradley* [2000] and then updated in *Vuille et al.* [2003, 2008a]. More details on this data set can be found in *Franquist* [2013]. In the following sections, we first introduce the data and methods we applied (section 2), then present the results (section 3), and finally discuss how these new results compare to previous studies and to what extent they offer any new insights into the questions posed above (section 4).

2. Data and Methods

Monthly mean surface temperature data from 626 stations, (1.3°N–62.5°S) ranging from 0 to 4800 m along the western slopes and coastlines of Ecuador, Peru, and Chile, were used for analysis in this study (Figures 1a and 1b). These data were provided by the Global Historical Climatology Network (GHCN) [*Lawrimore et al.*, 2011]; the Dirección General de Aguas (DGA) in Arica, Antofagasta, and Santiago (Chile); the Servicio Nacional de Meteorología e Hídrologia (SENAMHI) and the former Instituto de Recursos Naturales in Lima (both Peru); and the Instituto Nacional de Meteorología e Hídrologia (INAMHI) in Quito (Ecuador). The GHCN database covers mainly stations from coastal areas and larger cities, while the National Meteorological Services (SENAMHI, INAMHI, and DGA) provided data for most middle-and high-elevation stations from smaller localities.

In addition, we make use of the Niño 3.4 index, obtained from the National Center for Atmospheric Research Climate Analysis Section, the Pacific Decadal Oscillation (PDO) index provided by the Joint Institute for the

Study of the Atmosphere and Ocean, and the Southern Annular Mode (SAM) index provided by the NOAA Climate Prediction Center. The mechanism by which temperature along the western slopes of the Andes is affected by modes of variability such as ENSO, SAM, or the PDO likely involves changes in the SST off the coast of western South America (Figure 1e). We therefore also created a coastal SST index, named SST-WSA (sea surface temperature off western South America) by averaging SST from the NOAA Enhanced Reconstructed Sea Surface Temperature version 4 [*Huang et al.*, 2015] data set over the domain (12°S–28°S/276°E–290°E). The relationship of this index with large-scale modes of climate variability and with Andean temperature variability and trends was assessed to better understand to what extent the transmission of the PDO, ENSO, or SAM signals involves changes in local SST off the coast of South America.

Most station data have been published in previous studies [*Vuille and Bradley*, 2000; *Vuille et al.*, 2003, 2008a] and already undergone quality control. Data sets obtained from the National Meteorological Services SENAMHI, INAMHI, and DGA after the publication of *Vuille et al*. [2008a] were additionally quality controlled as described in *Vuille and Bradley* [2000], and outlier data were removed using a procedure described below.

In all records, years with less than 9 months of data were discarded. Data gaps during the remaining years were filled using linear regression with data from a nearby station as predictor. This predictor station was chosen based on the highest correlation achieved among neighboring stations. The regression analysis was performed using monthly anomalies, and the resulting anomalous values were added to the long-term monthly mean for that station to fill in the missing raw temperature value.

Annual mean temperature series were created for each station from this base data set by averaging the 12 months of the calendar year. Since only a few station records share a common and long enough time frame to be chosen as a reference period, using a conventional anomaly-averaging method to create a regional average time series would have led to a significant loss of available data. Therefore, the *first difference method* was chosen [*Peterson et al*., 1998] rather than the conventional anomaly method. This method has been successfully applied in the Andes in previous studies [*Vuille and Bradley*, 2000; *Vuille et al*., 2003, 2008a] and allows the use of all available data without referencing it to a common base period. Using this method, an annual temperature difference from one year to the next was computed for each individual station record ($\delta T_i = T_i - T_{i-1}$, where the subscript i is for the year). To avoid a spatial bias due to uneven station distribution, δT_i for all 626 stations were gridded into 2° latitude × 2° longitude boxes by averaging all station values within each grid box for each year. Outlier values were removed separately for each grid box, if a station's annual difference value was outside 2 standard deviations from the grid box's annual mean difference for that year. The time series from all grid boxes were then area averaged into two first difference time series representative of the tropical (2°N–18°S) and extratropical (18°S–42°S) Andes. This subdivision into tropical and extratropical Andes was motivated by the fact that previous studies show a different temperature regime during the second half of the 20th century in the tropical Andes [*Vuille and Bradley*, 2000], when compared to the region further to the south [*Falvey and Garreaud*, 2009]. Due to sparse data coverage, the high-latitude region south of 42°S was not considered in this analysis. A starting year of 1950 was chosen for this analysis since station data were sparse prior to that time in the southern Andes. The cumulative sums of these two area-averaged first difference time series were calculated by setting the value for the initial year to zero and then adding up the values. This effectively yields an anomaly time series with 1950 as a reference year. In a last step, the time series were converted into an anomaly series with 1961–1990 as the reference period, by subtracting the mean of the cumulative sum time series for that period from every year in the time series. As a result, two time series were created that show the average temperature anomaly with respect to the 1961–1990 reference period for the tropical and extratropical regions west of the Andes, respectively. Uncertainties of the annual mean temperature estimates are expressed as two standard errors of estimate (2 standard deviations of the gridded temperature deviations divided by the square root of the number of grid boxes) on either side of the annual average.

We also investigated the dependence of temperature trends on latitude. Because of sparse data in the southern region and since the main discrepancies between the studies by *Vuille and Bradley* [2000] and *Falvey and Garreaud* [2009] appear to be related to the lowest elevations, we limited this analysis to elevations below 500 m along the coastal zone. The latitudinal range for this analysis was 2°N–48°S. The first difference method was applied again, and stations were divided into 10°×10° grid boxes. The analysis was repeated for three separate time intervals (1961–1990, 1971–2000, and 1981–2010, respectively) to assess whether results were sensitive to the time

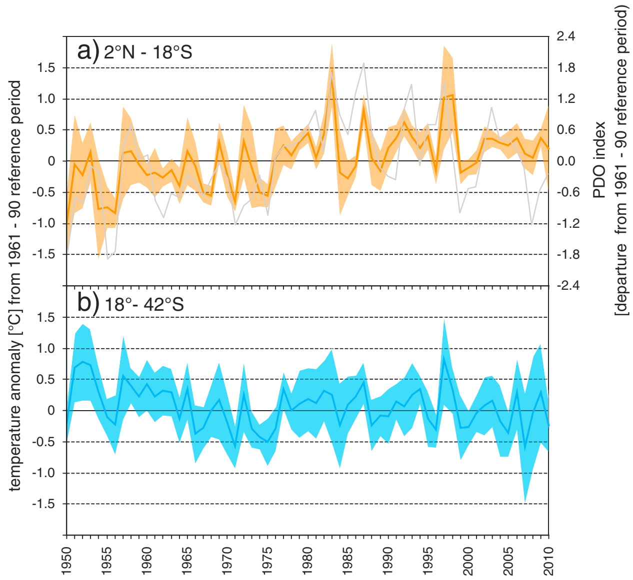

Figure 2. Annual mean temperature departures from 1961 to 1990 reference period for (a) tropical (2°N–18°S) and (b) extratropical region (18°S–42°S). The gray line in Figure 1a indicates PDO. The color shading represents two standard errors of estimate (2 standard deviations of the gridded temperature deviations divided by the square root of the number of grid boxes on either side of the estimate).

period analyzed. Analyzing trends prior to 1961 was not possible in this and all subsequent analyses due to an insufficient number of stations that have 30 year long continuous records.

Trends for individual stations were also calculated using ordinary least squares regression. Given the varying record lengths, trends were calculated for the same three 30 year time periods as above (1961–1990, 1971–2000, and 1981–2010). For each period, only station records with data that were at least 80% complete were included. Histograms displaying the range and frequency of temperature trends were created for each period in order to assess potential changes in the distribution of temperature trends over time.

Temperature trends from individual station were also used to test whether Andean warming rates are elevation dependent, as suggested in previous studies. Student's *t* test and a two-sample Kolmogorov-Smirnov (KS) test were applied to assess the statistical significance of differences in arithmetic means and the cumulative distribution functions between low- and high-elevation stations. In addition, the mean warming/cooling rate was calculated separately for each 1000 m elevation bin, with a 500 m overlap between bins, as the average from all station trends in that elevation zone. This analysis was restricted to the region 2°N–18°S, since data were too sparse farther south to allow for an elevation-dependent analysis.

Finally, we performed a simple empirical attribution study by calculating the temperature trend at each station that is linearly congruent with the suspected dominant climate modes influencing the region, ENSO, PDO, SST-WSA, and SAM, respectively [*Garreaud et al.*, 2009]. This yielded an estimate of the fraction of the temperature trends that can be attributed to forcing from each of these modes, respectively [see *Thompson and Solomon*, 2002]. The analysis was performed by first calculating the regression coefficient between the standardized monthly temperature time series at each station and the monthly climate index anomaly ($T^*_i = \alpha + \beta \cdot \mathrm{CI}_i$, where CI is the climate index in year *i*). This calculation was again performed only on stations, which reported at least 80% complete data and with outliers outside of the 2 standard deviations from the monthly mean removed. The resulting regression coefficients were then multiplied by the trend in the monthly climate index anomaly, resulting in temperature trends linearly congruent with the natural forcing, which can be compared with the observed trend (that is ΔT versus $T^* = \beta \cdot \Delta\mathrm{CI}$, where Δ stands for the linear trend in the period).

All significance levels given in this paper are at the $P < 0.05$ level, unless noted otherwise.

3. Results and Discussion

3.1. Spatiotemporal Temperature Trends

The first difference temperature time series for the tropical Andes (2°N–18°S) indicates a significant warming trend of 0.13°C/decade over the past 61 years (1950–2010) (Figure 2a), very similar to the global mean warming rate of 0.12°C/decade between 1951 and 2012 [*Intergovernmental Panel on Climate Change* (*IPCC*), 2013]. In the extratropical Andes (18°S–42°S), however, the trend is negative and significant over the same period (−0.05°C/decade; Figure 2b). The uncertainties are generally larger in the extratropics, reflecting the

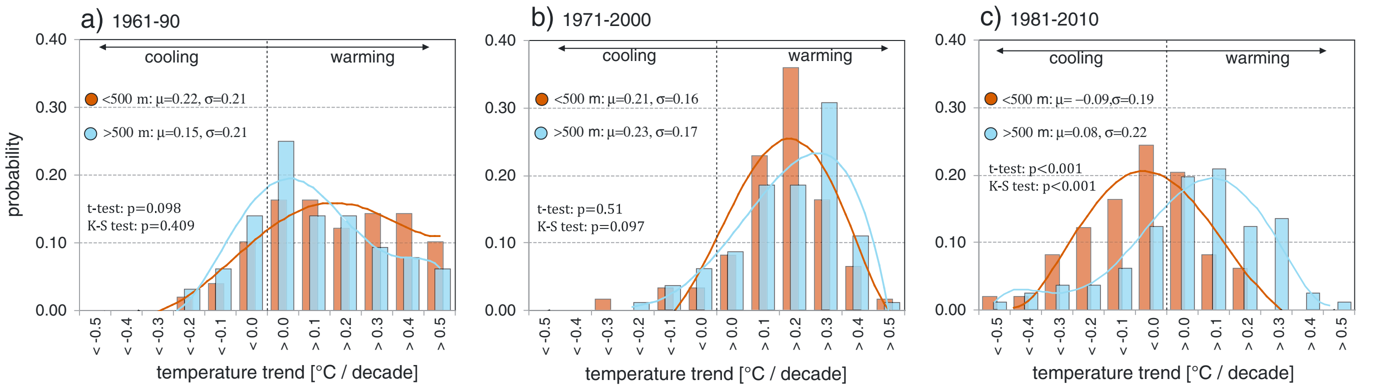

Figure 3. (a–c) Histograms and probability density functions of temperature trends (in °C/decade) for three different 30 year segments, separated by stations located above (light blue) or below 500 m (brown). Parameters μ and σ indicate arithmetic mean and standard deviation (in °C/decade), respectively. For interpretation of *t* test and K-S test results, see text.

lower station density. The discrepancies in the temperature trends between tropical and extratropical regions are consistent with previous results reporting warming in the tropics [*Vuille et al.*, 2008a] and cooling in the extratropics [*Falvey and Garreaud*, 2009; *Schulz et al.*, 2012]. If only the last 30 years are considered (1981–2010), the trends are negative, but insignificant, in both regions (−0.02°C/decade in the tropics and −0.09°C/decade in the extratropics), indicating that the warming in the tropical region has also come to a halt.

The recent tendency toward stagnant or even negative temperature trends seen in Figure 2 is also confirmed by the analysis of individual temperature trends, plotted in Figure 3. The histograms of the individual station trends show a clear shift from predominant warming (1961–1990 and 1971–2000) to near-neutral conditions during the most recent period (1981–2010). During 1961–1990, 81% of the analyzed stations showed a positive temperature trend, a number that rose to 90% during 1971–2000, but then dropped to 57% for the most recent three decades, 1981–2010 (Figure 3). It is noteworthy, however, that the halt in Andean warming during the most recent period (1981–2010) is primarily a result of low-elevation cooling. The average temperature trend at stations located below 500 m dropped from 0.22°C/decade (1961–1990) to −0.09°C/decade (1981–2010).

To further investigate the significance of the difference in trends at high and low elevation, we performed both a Student's *t* test and a two-sample Kolmogorov-Smirnov (KS) test. The *t* test gives a probability measure of the likelihood that the arithmetic means of the two samples are different from one another, while the KS test measures the discrepancy between the two sample cumulative distribution functions. Results are listed in Figure 3 and indicate that both mean and distribution of the two populations are significantly different from one another ($P < 0.001$) in the last period (Figure 3c) but that mean and distribution functions at high and low elevations are indistinguishable from one another during 1961–1990 and 1971–2000 when warming occurred almost everywhere in our domain.

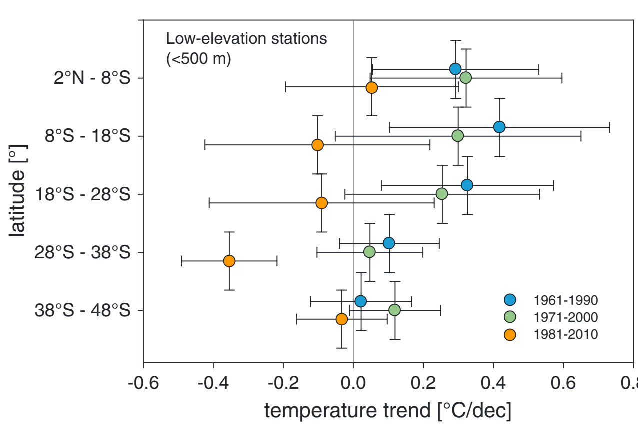

Figure 4. Temperature trends (in °C/decade) in coastal areas below 500 m (lower western slopes) as a function of time period and latitude. Trends for 1961–1990 and 1981–2010 are plotted with a slight latitudinal offset to increase clarity.

The recent cooling at low elevations also appears to be highly dependent on latitude. The analysis of temperature trends along coastal areas (below 500 m) reveals that the warming is strongest in equatorial regions and gradually weakening toward midlatitudes (Figure 4). Indeed, the warming was highly significant at low latitudes during 1961–1990 and 1971–2000 but mostly insignificant at

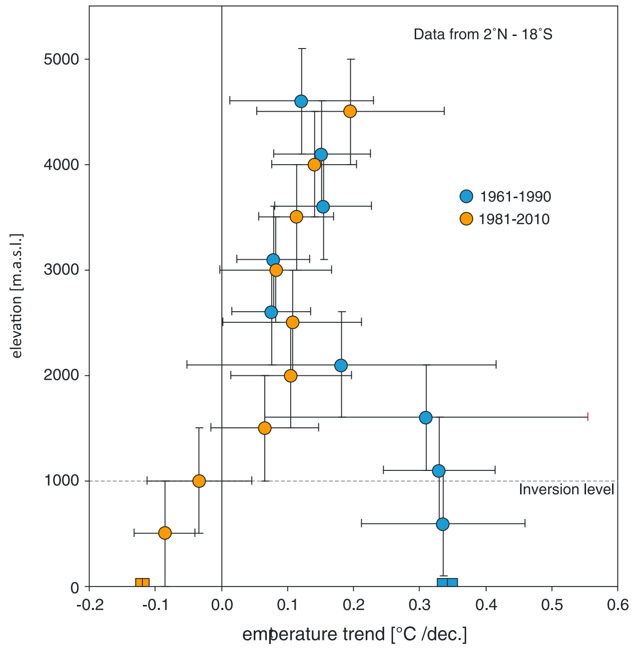

Figure 5. Temperature trends versus altitude along western tropical Andean slopes (2°N–18°S) for 1961–1990 (blue circle) and 1981–2010 (orange circle). The horizontal bars represent 95% confidence limits based on one sample *t* test. Trends are significant at 95% level if horizontal bars do not intersect 0°C/decade vertical line. The vertical bars indicate 1000 m elevation range used to calculate trends. For clarity, trends for 1961–1990 are offset by 100 m. The color bars at 0 m indicate trend (black vertical line) ±95% confidence limits for SST-WSA index for 1961–1990 (blue bar) and 1981–2010 (orange bar), respectively.

higher latitudes. Over the past 30 years (1981–2010), a significant anomalous cooling trend (weakened warming) occurred at all latitudes, leading to mostly insignificant trends except between 28°S–38°S, where significant cooling occurred. Hence, this analysis confirms both the results in *Vuille and Bradley* [2000] and *Falvey and Garreaud* [2009] and reconciles the different results along the South American west coast, seen in these two studies. The significant warming detected by *Vuille and Bradley* [2000] along the lowest elevations of the western Andean slopes can be explained by their focus on tropical latitudes and reflects their temporal limitation using data up to 1998 only. *Falvey and Garreaud* [2009] on the other hand analyzed temperature trends farther south along coastal Chile, where the cooling is significantly more pronounced and used data for a more recent time period when this effect has been much more evident.

3.2. Elevation-Dependent Temperature Trends

Modeling studies suggest that higher-elevation sites in the Andes may experience stronger future warming as compared to lower elevations [e.g., *Bradley et al*., 2006; *Urrutia and Vuille*, 2009], with significant repercussions for the Andean cryosphere [e.g., *Vuille et al*., 2008a; *Rabatel et al*., 2013]. *Rangwala and Miller* [2012] discuss the various feedbacks, such as snow-albedo feedback, cloud feedback, water vapor/downward longwave radiation feedback, or aerosol feedback, which could potentially lead to enhanced warming at higher elevations, but it is not yet fully understood to what extent these may be relevant for the Andean region. Observational evidence suggests that in the past, temperature trends were not simply elevation dependent but also differ between eastern and western slopes [*Vuille and Bradley*, 2000; *Vuille et al*., 2003]. The fact that temperature below the Pacific inversion level, located at roughly 1000 m above sea level [e.g., *Rahn and Garreaud*, 2010], is thermodynamically separated from the air masses aloft further complicates such an analysis. Here we repeat the earlier work by *Vuille and Bradley* [2000] with the more recent data updated through 2010 but focus exclusively on the western slopes. Figure 5 shows temperature trends as a function of elevation in 1000 m bins from sea level up to 5000 m. For clarity, only results for 1961–1990 and 1981–2010 are shown, and due to low station density, we limit this analysis to latitudes north of 18°S. A clear trend toward cooler temperatures during 1981–2010 as compared to 1961–1990 at elevations below 2000 m is evident in Figure 5, consistent with the results in Figures 3 and 4. Above 2000 m, however, temperature trends remain positive and for the most part significant. As a result, the elevation-dependent warming now features stronger warming at higher elevations as compared to coastal areas, while in the 1961–1990 period, the opposite was the case (Figure 5). Hence, it appears that the strong vertical stratification of temperature trends in the atmosphere, as documented along the Chilean coast by *Falvey and Garreaud* [2009], now extends northward to the equator. The color bars at 0 m in Figure 5 represent the 95% confidence levels of the observed SST trends in the WSA box off the coast of western South America. A remarkable coherence is notable between the observed SST trends off the coast and air temperature trends in the lowest elevation bin (0 m–1000 m). From the 1961–1990 to the 1981–2010 period, the WSA region has undergone a significant change with the average SST trend switching from

+0.34°C/decade to −0.12°C/decade, consistent with the change seen in low-elevation air temperature. This coherent change nicely documents the first-order control of low-level temperature trends below the inversion layer by coastal SST.

3.3. To What Extent Can Natural Variability Explain Observed Trends?

The results of our empirical trend attribution study are shown in Figure 6. While the analysis was again performed for the same three 30 year long periods, we here focus our discussion on the results from the two periods, 1961–1990 and 1981–2010, only. The results for 1971–2000 are qualitatively similar to the period of 1961–1990.

Our analysis did not yield any significant results for either the SAM or ENSO (not shown). As far as the SAM is concerned, this is not too surprising given that the influence of the SAM on temperature variations in South America is limited to the southernmost part of the continent [*Garreaud et al*., 2009]. Maybe more interesting is the lack of influence of ENSO on temperature trends given the strong covariance on interannual time scales (Figure 1c). Over the time periods analyzed, however, ENSO does not show a clear trend in either direction, which results in low congruence with the observed temperature trends in the Andes. Hence, it appears that *Vuille et al*. [2003] may have overestimated the role of ENSO when they attributed 50–70% of the warming in the tropical Andes to Pacific SST. The disagreement with the results in this study likely stem from the fact that *Vuille et al*. [2003] used a 20 year period with very strong El Niño activity and a strong positive trend in tropical Pacific SST (1979–1998) and because the results were based on an atmospheric general circulation model with prescribed SST, which have been shown to overestimate the coupling between tropical SST and land surface temperature over South America during ENSO events [e.g., *Barreiro and Diaz*, 2011; *McGlone and Vuille*, 2012].

The results for the SST-WSA index and for the PDO (Figure 6), however, suggest a significant influence on Andean temperature during the second half of the 20th century, in particular along the coastal areas. During the 1961–1990 period, almost the entire Andes are warming (Figure 6a), which is consistent with the SST-WSA and the PDO fingerprint (Figures 6b and 6c). It is noteworthy that the fingerprints of the PDO and the WSA index on Andean temperature are almost identical, highlighting that the PDO influence is primarily transmitted through adjustments in local SST off the coast of South America, which subsequently affect temperatures along the western Andean slopes and the coastline. The PDO and the WSA are indeed highly correlated over this 30 year time period ($r = 0.57$, $P < 0.01$, using monthly anomalies). The strong influence of the PDO during this period is likely related to the Pacific climate shift in 1976/1977, which coincided with a regime change of the PDO from its negative to its positive polarity and lead to a strong positive trend in the PDO during this period. Indeed, the PDO can be associated with a positive temperature trend of more than 0.2°C/decade at many stations in the tropics (Figure 6b). In the most recent decades (1981–2010), however, a clear separation between coastal cooling and high-elevation warming has occurred (Figure 6d), in particular in the tropics. During this period, the trends in both the PDO and the SST-WSA index are slightly negative; hence, their contribution is to lower Andean temperature wherever the regression coefficients with local temperature are high. The correlation between the two indices is weaker over this period, but still significant ($r = 0.38$, $P < 0.01$, using monthly anomalies), confirming that the local SSTs off the South American west coast are partially a regional expression of the PDO. While the low-level cooling is consistent with the notion of a strong PDO and SST-WSA influence, the continued warming at higher elevations such as southern Peru (~15°S) or central Chile (~30°S) is in stark contrast to the PDO and SST-WSA imprints in those areas (Figures 6e and 6f). In fact, more than half of all stations still report positive temperature trends during this period (Figure 3c), with some showing warming rates of more than 0.2°C/decade (Figure 6d). Clearly, the PDO does not provide much explanatory power for this behavior, indicating that the positive temperature trends at higher elevation are the result of other, possibly anthropogenic, forcing.

To further investigate this aspect, we examine the individual response of temperature at selected coastal and inland/high-elevation stations over a longer, 51 year period from 1960 to 2010. We analyze whether the observed temperature in any given year is consistent with expectations based on a simple analog model [e.g., *Yiou et al*., 2007] using the PDO as only predictand. Specifically, we calculate for each year the PDO-analog temperature by averaging the temperature over the 5 years, which feature the most closely related PDO values. Tests with averages calculated from 8 to 10 years produced qualitatively similar

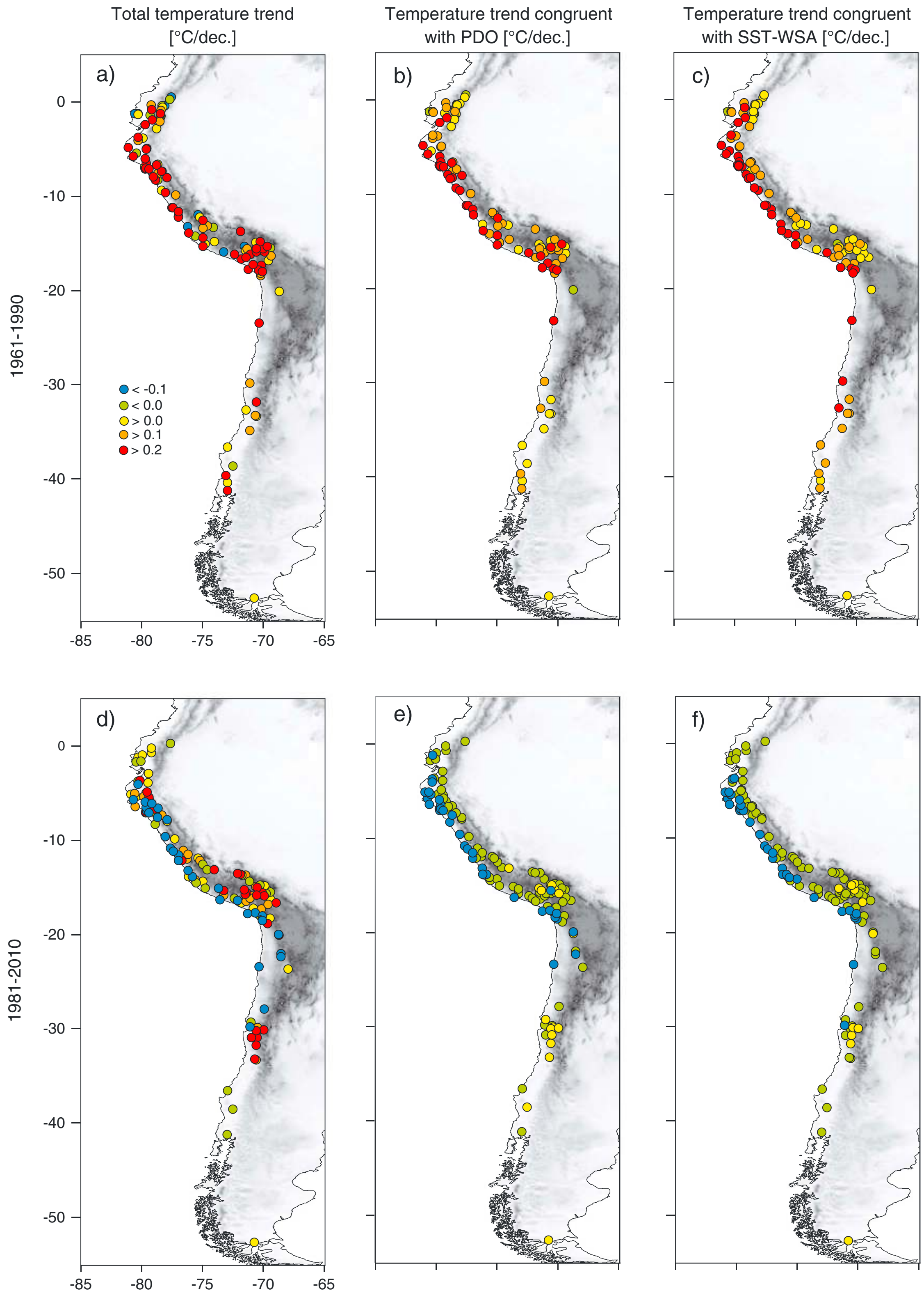

Figure 6. (a) Map of total observed temperature trend (in °C/decade) during 1961–1990, (b) trend attributed to PDO during 1961–1990, and (c) trend attributed to SST-WSA index during 1961–1990. (d–f) Same as in Figures 6a–6c but for 1981–2010.

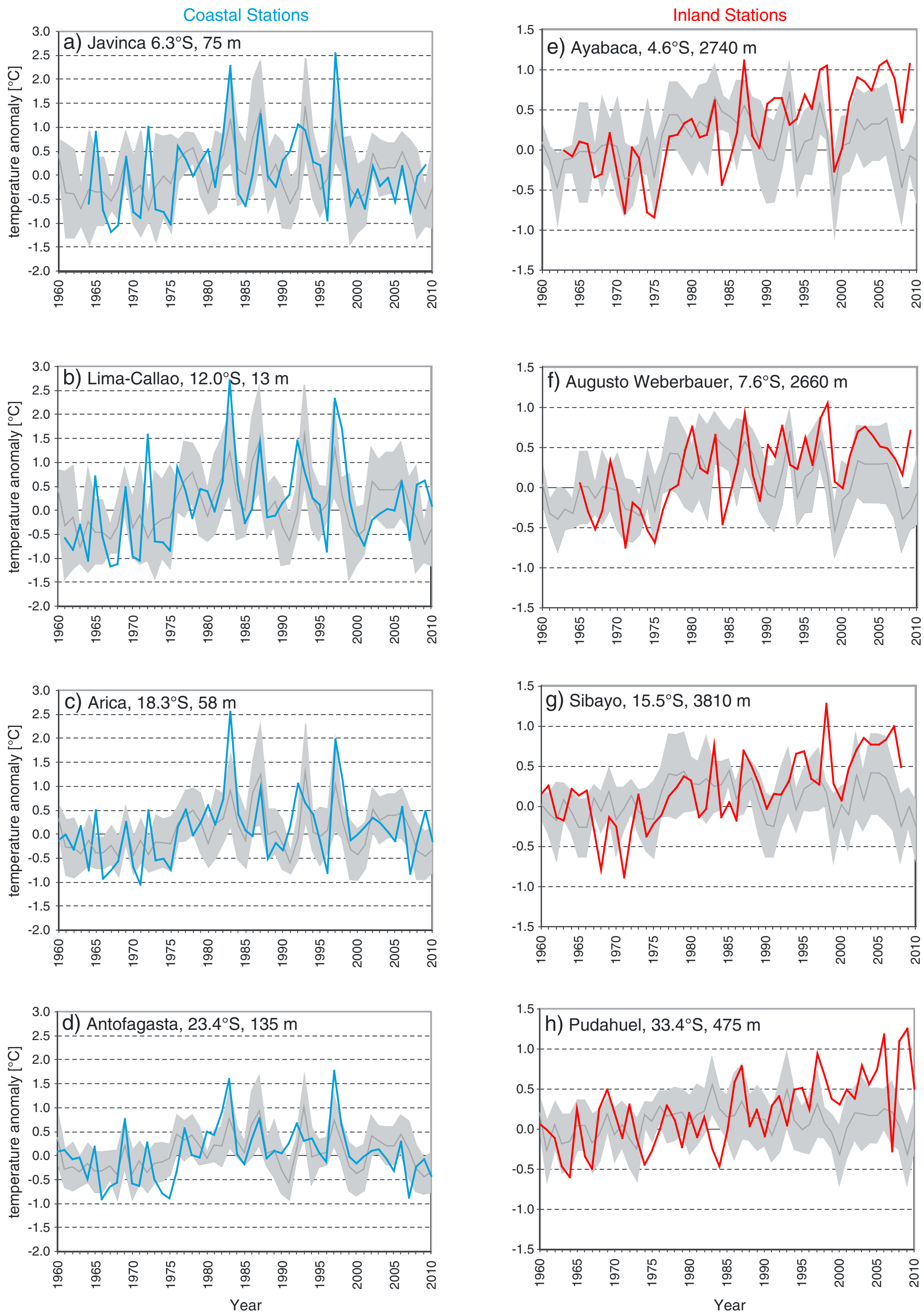

Figure 7. Annual mean observed and PDO-analog temperature anomalies for (a–d) four lowland/coastal stations and (e–h) four inland/high-elevation stations between 1960 and 2010. Anomalies are with respect to the 1961–1990 mean. Observed temperature is shown by blue (red) line for coastal (inland) stations. PDO-analog temperature anomaly (gray line) and its spread (gray shading) represent average temperature anomaly calculated from 5 years with most similar PDO value, ±1 standard deviation.

results (not shown). This methodology yields an estimated temperature based on the state of the PDO only and is useful to assess to what extent station temperature is slaved to the PDO forcing. Figure 7 shows the observed temperature trends for four coastal and four inland/high-elevation stations, each ranging from the inner tropics to the southern midlatitudes. The coastal stations all show a similar behavior with an upward tendency in temperature until the 1980s, after which temperatures start to decline (Figures 7a–7d). This behavior is consistent with the expected temperature from the PDO-analog model, as temperature generally resides within the spread encompassed by the 5 years with the most similar PDO value. Inland stations, however, show a continued warming after the 1980s, with a tendency for temperature to be warmer than the PDO-analog temperature (Figures 7e–7h). In fact, temperature has been above the PDO-analog mean for at least 18 out of the past 20 years at all four inland stations. The divergent trends between observed and PDO-analog temperature at inland locations start to emerge in the late 1980s/early 1990s. By 2010, the difference has become large enough for the observed temperature to surpass the 1σ analog spread. In some sense, however, this discrepancy between coastal and inland stations is not such a big surprise. After all, the relationship of Andean temperature variations with the PDO and the SST-WSA index is generally weaker at higher elevation (Figures 1d and 1e); hence, the higher altitudes of the Andes are not as strongly affected by the Pacific cooling over the past few decades.

4. Summary and Conclusion

The aim of this study was to provide a clearer picture of the magnitude, spatiotemporal characteristics, and the causes of surface air temperature changes along the western slope of the Andes using a dense station network from Ecuador, Peru, and Chile.

Our results show a significant warming trend between 1950 and 2010 for the tropical Andes, while the region south of 18°S has experienced cooling over the same time. If only the last 30 years are considered, trends are slightly negative in both regions. This highlights that multidecadal variability strongly affects results from studies on temperature trends and that caution must be exercised when choosing an appropriate time period for analysis. The strong dependence of temperature trends on the time period analyzed and the latitude over which stations are considered reconciles the different results obtained by *Vuille and Bradley* [2000], who reported maximum warming rates at tropical coastal sites in the 20th century with the findings of *Falvey and Garreaud* [2009], who identified a significant cooling trend along the Chilean coast over the past three decades.

The analysis of tropical Andean temperature trends as a function of elevation indicates that the higher elevations have seen continued warming, while a distinct change from strong warming to stagnant temperatures or even cooling has been observed along coastal areas. Natural multidecadal variability, expressed by the strong congruence between observed trends and the PDO fingerprint, appears to be the most relevant factor in explaining the recent stall of temperatures along lower-elevation coastal areas. This cooling influence of the PDO during the past decades is noteworthy as the switch of the PDO to its cool phase after the 1997/1998 El Niño has also been associated with the hiatus in warming on a global scale [e.g., *Meehl et al.*, 2011]. Analysis of the relationship between a coastal SST index, the PDO, and Andean temperature suggests that much of the PDO imprint is modulated and transmitted through adjustments in coastal SST off the coast of western South America. At higher elevations, however, there is a notable divergence between the observed temperature increase and the contribution of the PDO and coastal SST, which show a negative trend over the past 30 years and hence would have acted to reduce temperature. One could argue that the observed high-elevation warming might be related to other processes such as deforestation, urbanization or land use change in general, or other changes in the station environment. Nevertheless, the observed warming occurs on such a large scale that it leaves little room for local to regional scale influences as the main driver, and it is of similar magnitude as the observed global mean warming over the same period [*IPCC*, 2013]. While positive feedbacks, such as snow-albedo or downward longwave radiation feedback [e.g., *Rangwala and Miller*, 2012], may have amplified the warming at high elevation, anthropogenic radiative forcing due to increased greenhouse gas concentrations remains the most likely factor in explaining the overall continued warming, consistent with model-based evidence over the South American continent [*Bindoff et al.*, 2013]. Given the continued projected increase in radiative forcing due to greenhouse gas emissions, the warming at higher elevations will likely continue. In coastal areas, however, our results suggest that temperature trends may depend on the future state of the PDO but also be influenced by changes in the intensity of the South Pacific anticyclone (SPA). Most climate models simulate a continued strengthening of the SPA as a result of greenhouse gas forcing [*Garreaud and Falvey*, 2009], which may lead to continued and enhanced vertical stratification of temperature trends and strongly reduced lapse rates along the western Andean slopes.

An important caveat in our distinction between PDO and anthropogenic forcing is that natural modes of variability such as ENSO or the PDO might themselves be affected by greenhouse gas and aerosol emissions. In this study we do not distinguish whether the recent trends in natural modes were themselves forced by anthropogenic emissions or whether they are the result of internal variability only. To more decisively attribute the observed warming to anthropogenic forcing would require a comparison of simulations from general circulation models forced with only natural (solar and volcanic) forcing with identical runs forced with anthropogenic forcing (greenhouse gases and aerosols). Such studies are in progress and will be reported elsewhere. Nonetheless, our empirical results imply that warming in the high Andes will likely continue, while along the coast, future cooling may hinge on the future intensification of the SPA but also on the response to the PDO once it switches back to its positive phase.

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