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# Mean Annual Temperature Trends and Their Vertical Structure In the Tropical Andes

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# Mean annual temperature trends and their vertical structure in the tropical Andes

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**Abstract.** Mean annual temperature trends in the tropical Andes were determined over the last six decades (1939-1998), to investigate the apparent inconsistency between the observed glacier retreat and the reported slight cooling trend in the lower tropical troposphere after 1979. Our results indicate that temperature in the tropical Andes has increased by 0.10° - 0.11°C/decade since 1939. The rate of warming has more than tripled over the last 25 years (0.32° - 0.34°C/decade) and the last two years of the series, associated with the 1997/98 El Niño, were the warmest of the last six decades. Temperature trends vary with altitude and show a generally reduced warming with increasing elevation. However, despite the lower rate of warming, the trend toward increased temperatures is still significant at the 95% confidence level, even at the highest elevations. Clearly high elevation surface stations in the Andes do not reflect the slight cooling trend observed in the tropical lower-troposphere.

## 1. Introduction

Recent radiosonde and satellite observations based on the microwave sounding unit (MSU) indicate that, following a period of rising freezing levels [ *Diaz and Graham,* 1996], a slight decrease of lower tropospheric temperatures occurred in the tropics during the last two decades [*Gaffen et al.*, 2000]. At the same time a dramatic glacier retreat can be observed all over the tropics [e.g. *Brecher and Thompson*, 1993; *Hastenrath and Ames*, 1995; *Kaser*, 1999]. Although this retreat could also reflect changes in the hydrologic regime of the tropics, it seems that it is at least partially a consequence of increasing air temperatures [*Kaser*, 1999]. One possible explanation for this apparent inconsistency is that surface conditions at high elevations in the tropics may differ from those of the surrounding free atmosphere [*Molnar and Emanuel*, 1999]. To test this hypothesis, we chose to analyze surface temperature trends at high elevation in the tropical Andes of South America, because 1) this region represents the largest and highest mountain range within the tropics, 2) it contains 99.7% of all tropical glaciers [*Kaser,* 1999], 3) it's a region where up to now adequate temperature information was not available, and 4) recent studies [*Vuille et al.,* 2000ab] show that no significant decrease in precipitation occurred over the last 30 years, thus changes in precipitation can be ruled out as a major contributing factor for the observed glacier retreat. Our study area covers the Andes of Ecuador, Peru, Bolivia and northernmost Chile (1°N-23°S, see Figure 1). Based on a newly established dense station database (268 stations) and using the first difference method, which allows station density to be maximized without the need for a common reference period, we here present temperature trends over the last 60 years and evaluate how those trends depend on elevation.



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## 2. Data and Methods

The temperature data consist of monthly means from 268 stations between 1°N and 23°S, ranging from 0 to 5000 m a.s.l. (Figure 1). All stations form part of the respective national meteorological networks in Ecuador, Peru, Bolivia, and Chile or were extracted from the Global Historical Climatology Network [*Peterson and Vose*, 1997]. All data were quality controlled, based on difference time series with homogenized reference stations [see *Peterson et al.*, 1998a for a comprehensive review] or with previously established principal component score time series [*Vuille et al.,* 2000a,b]. Individual station months that differ by more than 3 standard deviations (3σ) from the monthly mean of the respective station were omitted unless nearest neighbor stations, who usually are in close agreement with each other, showed similar anomalies. Data gaps of 3 months or less were filled by linear regression using neighboring stations. No adjustments for urbanization effects [*Hansen et al.*, 1999] were applied, since only a small fraction of the stations are located in towns larger than 10,000 inhabitants. Annual mean temperature series were created for each station by averaging the 12 months of the calendar year. The data were not stratified and analyzed for seasonal trends because of the small annual cycle of temperature in the tropics.

Since only a few station records share a common and long enough time-frame to be chosen as a reference period (i.e. 1961-1990), using the conventional anomaly method to establish the temperature time series, would have resulted in a significant loss of available information. We therefore chose to use the first difference method [*Peterson et al.*, 1998b] rather than the conventional anomaly method, which allowed us to include all available data without referencing it to a common base period. First, for each individual station record the annual difference $\delta_t$ is computed as:

$$\delta_t = T_t - T_{t-1} \tag{1}$$

where $T_t$ is the annual mean temperature $T$ in the year $t$. For example, the temperature value for 1990 ($\delta_{1990}$) of a first difference time series is calculated by subtracting the stations value in 1989 ($T_{1989}$) from its value in 1990 ($T_{1990}$). Next the $\delta_t$ time series of the 268 stations were gridded into 2°×2° boxes by averaging all station values within each grid-box for each year, which can easily be done because each value of $\delta$ for all stations is referenced to the same year. As a result we obtained a first difference time series for each grid box, indicating the temperature change from one year to the next. The

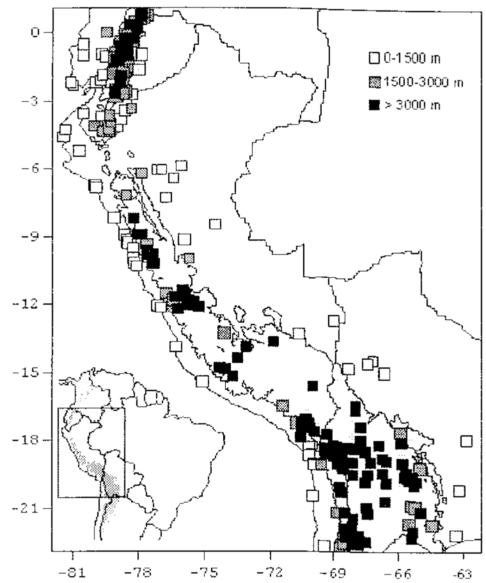


**Figure 1.** Location and altitudinal distribution of stations used in this study. Elevations above 2500 m are shaded gray. Location of the study area is shown in the inset (lower left).

time series from all grid boxes were then area-averaged into one single first difference time series representative of the Andean range between 1°N-23°S. Before 1959 the spatial coverage is incomplete, that is, a few grid boxes contain no temperature information and were therefore omitted. Finally, the cumulative sum of this area-averaged first difference time series was calculated by simply adding up all values. For example the value for 1990 is the sum of all previous annual temperature changes (annual temperature changes between 1939 and 1990). The initial level (temperature in year 1939) is conveniently set to zero. This final time series can now be considered as an anomaly time series with reference period 1939 (temperature anomaly in 1939 is zero). Thus it can easily be converted into a time series with a more common base period (i.e. 1961-1990) for easier comparison with other records. This is how we present our results in Figure 3. Overall the first difference method has a number of advantages over the conventional anomaly method, which are discussed in detail in *Peterson et al.* [1998b]. For our purpose, the most practical advantage was that it allows using all available data, including short records, which do not overlap, while the conventional anomaly method requires that all station records

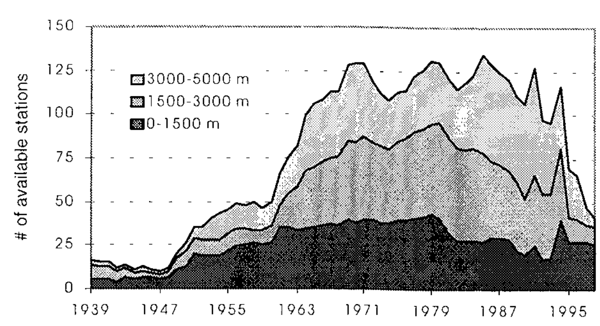


**Figure 2.** Number of stations with available temperature data per year and elevation zone.

have a common reference period (i.e. 1961-1990). We could thus rely on a very dense station network and thereby reduce the uncertainty associated with individual station records.

Since we were particularly interested to see whether the temperature trend changes with altitude, we next repeated the entire procedure but grouped all station $\delta_t$ time series into 1000 m elevation zones rather than into 2°×2° grid boxes. In addition, we separated the stations into an eastern and a western elevation zone below 2500 m, since the Andes are a powerful lower-tropospheric divide. This elevation-dependent analysis only covers the last 40 years (1959-1998) because the data coverage for this procedure was insufficient before 1959 (see Figure 2). Temperature trends for the entire region (area-averaged over the tropical Andes based on the 2°×2° grid) and for each elevation zone (1000 m intervals with 500 m overlap) were computed using both an ordinary least squares (OLS) and the more robust least absolute residuals (LAR) regression approach [i.e. *Li*, 1985]. Only the trends from the OLS regression are shown in Figures 3 and 4, but the corresponding trends of the LAR regression are given in Table 1 for comparison. The 95% confidence intervals for the trends are given by twice the standard error of estimate ($2\sigma_E$):

$$2\sigma_E = 2\frac{\sigma_T}{\sigma_N}\sqrt{\frac{1-r^2}{N'-2}} \qquad (2)$$

where $\sigma_T$ is the standard deviation of the 60 (40) years of temperature data, $r$ is the correlation of temperature with time, $\sigma_N$ is the standard deviation of the 60 (40) x-variate numbers and $N'$ is the effective sample size, taking into account the serial correlation of the data [*Angell*, 1999]:

$$N' = N\left(\frac{1-r_1}{1+r_1}\right) \qquad (3)$$

where $N$ is the 60 (40) years of data and $r_1$ is the autocorrelation at lag one.

**Table 1.** Temperature Trends (°C / Decade) in the Tropical Andes (1°N-23°S) for Different Time Periods and Elevation Zones (1959-1998 only). Trends are Based on Robust Least Absolute Residuals (LAR) and Ordinary Least Squares (OLS) Regressions. Trends Shown in Bold are Significant at the 95% Confidence Level (± twice the Standard Error of Estimate)

| | LAR | | | OLS | | |
|---|---|---|---|---|---|---|
| | East | Andes | West | East | Andes | West |
| 0-1000 m | -0.03 | - | **0.40** | 0.00 | - | **0.39** |
| 500-1500 m | **0.11** | - | **0.34** | **0.12** | - | **0.34** |
| 1000-2000 m | **0.15** | - | **0.25** | **0.16** | - | **0.29** |
| 1500-2500 m | **0.17** | - | **0.22** | **0.15** | - | **0.27** |
| 2000-3000 m | - | **0.19** | - | - | **0.21** | - |
| 2500-3500 m | - | **0.16** | - | - | **0.19** | - |
| 3000-4000 m | - | **0.18** | - | - | **0.19** | - |
| 3500-4500 m | - | **0.14** | - | - | **0.19** | - |
| 4000-5000 m | - | **0.09** | - | - | **0.16** | - |
| 1939-1998 | - | **0.10** | - | - | **0.11** | - |
| 1959-98 | - | **0.20** | - | - | **0.20** | - |
| 1974-98 | - | **0.32** | - | - | **0.34** | - |

## 3. Temperature trends and their vertical structure

Figure 3 shows the annual mean temperature deviation from the 1961-1990 average over the last 60 years (1939-1998). The vertical bars extend 2 standard errors of estimate (2 standard deviations of the gridded temperature deviations divided by the square root of the number of grid boxes) on both sides of the annual average. The lower number of available stations before 1959 and after 1995 (Figure 2) results in an increased uncertainty (larger vertical error bars) of the estimated temperature anomaly. Despite this uncertainty, there is a clear and significant positive overall trend of 0.11°C/decade between 1939 and 1998. However, this trend is far from linear but rather flat until the mid 1970's, when temperatures suddenly start to increase at a much faster rate, consistent with global observations [i.e. *Jones et al.*, 1999]. Indeed the warming trend has almost doubled over the last 40 years (0.20°C/decade) and more than tripled over the last 25 years (0.34°C/decade) as compared to the entire 60-year period. The results based on the robust regression approach (LAR) are slightly lower because of the reduced influence of outliers, but confirm the overall picture of an accelerated temperature increase over the last few decades (Table 1). The interannual variability is closely tied to sea surface temperature anomalies (SSTA) in the tropical Pacific domain. All major warm anomalies (1941, 1944, 1953, 1957, 1969, 1972, 1983, 1987, 1991 and 1997/98) are related to El Niño events and all major cold years (1950, 1955/56, 1964, 1971, 1974/75, 1984/85, 1989 and 1996) coincide with La Niña events, based on the definition of *Trenberth* [1997]. This is consistent with recent observations by *Vuille et al.* [2000a,b], who showed that temperature anomalies in the tropical Andes lag behind tropical Pacific SSTA by 1-2 months and that the temperature difference in the Andes between El Niño and La Niña events averages 0.7°-1.3°C. Despite this close relationship with tropical Pacific SSTA and the warm phase of the Pacific Decadal Oscillation (PDO) after the mid 1970's, it nonetheless seems that the background temperature has reached a generally higher level with El Niño years being more pronounced and La Niña years barely reaching negative values after 1976. Of the last 13 years only one (1996) was below average, and the last two years of the series, associated with the 1997/98 El Niño, were, despite the large standard error of estimate, most likely the warmest of the last six decades, even surpassing the record breaking temperatures of 1983.

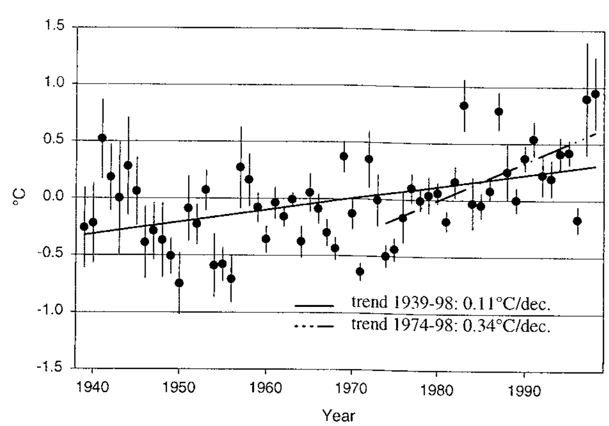


**Figure 3.** Annual temperature deviation from the 1961-1990 average in the tropical Andes (1°N-23°S) between 1939 and 1998. Trend estimates are based on ordinary least squares (OLS) regression. Vertical bars extend 2 standard errors of the mean either side of the annual average.

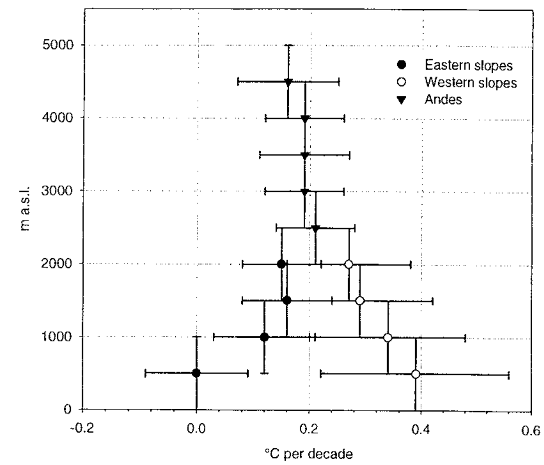


**Figure 4.** Temperature trend (°C/decade) as a function of elevation (m a.s.l.). Vertical bars indicate elevation range (±500 m) for which trend is valid. Horizontal bars are 95% confidence limits for the trend and extend two standard errors of estimate on either side (i.e. all trends whose horizontal bars

Over the last 4 decades (1959-1998) we further refined this picture by looking at trends in different elevation zones, based on 1000 m intervals (Figure 4). While the vertical bars represent the 1000 m elevation zone for which the established trend is valid, the horizontal bars indicate the 95% confidence limits for the trend and extend two standard errors of estimate on either side; that is, all trends whose horizontal bars do not intersect with the 0°C/decade trend abscissa are significant at the 95% level. While Figure 4 only shows the results based on the OLS approach, the results from the LAR regression are listed in Table 1 for comparison. Clearly, temperature trends in the tropical Andes vary with altitude and show a pronounced pattern of reduced warming with increasing elevation. The only exception is found along the lower eastern slopes, where no significant warming trend can be observed below 1000 m, and temperature trends increase up to an elevation of 2500 m. On the Pacific side of the Andes however, there is an almost linear decrease of the warming trend with elevation, ranging from 0.39°C/decade (LAR: 0.40°C/decade) below 1000 m to 0.16°C/decade (LAR: 0.09°C/decade) above 4000 m. This vertical structure of the temperature trend is different from what is observed in Tibet or the European Alps, where the warming is more pronounced at higher elevations [i.e. *Beniston and Rebetez*, 1996]. Although we don't have a conclusive answer for this dissimilarity, seasonal snow cover could play a prominent role. The mid-latitude mountain areas of the northern hemisphere experience a winter accumulation and a summer ablation season. Recent observations [i.e. *Groisman et al.*, 1994] show, that spring snow cover has significantly decreased in those areas, giving way to generally lower albedo values and higher absorption of solar radiation, which in turn lead to a positive feedback on temperature. In the tropics however, there are no 'winter' and 'summer' seasons. The accumulation ('rainy') season is also the ablation season and there is no seasonal snow cover, which could influence the thermal regime in a similar way as in the mid-latitudes [*Kaser and Georges*, 1999]. So even though the lower temperature increase at higher elevation is not reflected in similar studies at mid-latitudes, it is consistent with the observed differences in temperature trends between surface and lower-tropospheric levels in the tropics as seen in radiosonde data [*Oort and Liu*, 1993; *Angell*, 1999].

## 4. Summary and Conclusions

Based on a dense station network of 268 stations from 0 – 5000 m elevation, we present temperature trends over the last six decades (1939-1998) for the tropical Andes (1°N-23°S). Our results indicate a general warming trend of 0.10 - 0.11°C/decade since 1939. The rate of warming has more than tripled over the last 25 years (0.32 - 0.34°C/decade). Although there is a general decrease of the observed warming trend with increasing elevation, the trend toward increased temperatures is significant at the 95% confidence level, even at the highest elevations. This is consistent with the reported dramatic glacier retreat [e.g. *Brecher and Thompson*, 1993; *Hastenrath and Ames*, 1995; *Kaser*, 1999], the observed $\delta^{18}O$ enrichment in the uppermost part of tropical ice cores [*Thompson et al.*, 1993], and earlier radiosonde observations indicating rising freezing levels and lower-tropospheric warming at tropical latitudes [*Oort and Liu*, 1993; *Diaz and Graham*, 1996; *Vinnikov et al.*, 1996; *Angell*, 1999]. There is, however, a discrepancy between our results and the most recent observations from radiosondes and microwave sounding unit (MSU) satellite data indicating a reversal of the warming trend and decreasing lower-tropospheric temperatures in the tropics since 1979 [*Gaffen et al.*, 2000]. This inconsistency might be because a) the tropical Andes are not representative of the entire tropical latitudinal band, or b) the latter study did not include any radiosonde observations from the tropical Andes after 1979. Most likely however, it represents real differences in temperature and trends between high elevation surface stations and measurements in the free atmosphere [*Molnar and Emanuel*, 1999]. Thus lower-tropospheric temperature trends should be interpreted cautiously when characterizing climatic trends at high elevation locations. Our analysis provides evidence for significant warming after 1979, even above 4000 m (at lower- and mid-tropospheric levels). Unlike recent conclusions based on radiosonde and microwave sounding unit (MSU) satellite data, this is entirely consistent with observations of pronounced glacier retreat in the tropical Andes over recent decades.

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