



## Recent changes in freezing level heights in the Tropics with implications for the deglaciation of high mountain regions

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[1] The height of the freezing level in the tropical atmosphere (the free air 0°C isotherm) has increased across most of the region, particularly in the outer Tropics. In the tropical Andes, south of the Equator, high elevation surface temperatures and upper air data show a similar trend in temperature, of  $\sim 0.1^\circ\text{C}/\text{decade}$  over the last 50 years. Meteorological observations at 5680 m on the summit of the Quelccaya Ice Cap, the largest ice mass in the Tropics, indicate that daily maximum temperatures often exceed 0°C from October–May, and rise well above freezing for much of the year around the ice cap margin at 5200 m. This is consistent with observations of a rise in the percolation facies (an indicator of surface melting) in recent decades, and other observations of marginal recession, showing that the ice cap is rapidly losing mass. Similar conditions are likely to be affecting other high elevation ice caps and glaciers in Ecuador, Perú and Bolivia, with important implications for water supplies in the region. Over the Tropics as a whole, freezing level height (FLH) is closely related to mean SSTs, with inter-annual variations in FLH controlled by the phase of ENSO variability. More extensive monitoring of climatic conditions at high elevations in the mountains of the Tropics is urgently needed. **Citation:** Bradley, R. S., F. T. Keimig, H. F. Diaz, and D. R. Hardy (2009), Recent changes in freezing level heights in the Tropics with implications for the deglaciation of high mountain regions, *Geophys. Res. Lett.*, 36, L17701, doi:10.1029/2009GL037712.

### 1. Introduction

[2] The height of the freezing level (the free air 0°C isotherm) in the tropical atmosphere is a critical parameter that affects hydrological conditions in high mountains that reach above 4500 m in elevation [Coudrain *et al.*, 2005; Francou *et al.*, 2004; Harris *et al.*, 2000; Vuille *et al.*, 2008; see also Hoffmann, 2003]. In particular, the mass balance of glaciers is critically dependent on the extent of ice melting and sublimation, and on the balance of snowfall versus rain, which greatly affects albedo and thus net radiation. Previous research [Diaz and Graham, 1996] pointed out that there had been a significant rise in freezing level heights in the tropics over the period 1958–1990, and that this increase was related to sea-surface temperatures in the eastern Equatorial Pacific. In the American sector of the Tropics, the strongest relationship between freezing level height

(FLH) and SSTs is when SSTs lead FLH by about 3 months [Diaz *et al.*, 2003]. Other high mountain regions also exhibit significant warming in the last several decades, with the more recent decades displaying the largest FLH changes [Diaz *et al.*, 2003]. Here we look at temperature changes in the glacierized high mountains of the Tropical Andes, and more broadly at freezing level heights across the entire Tropical zone for the last three decades.

### 2. Data Sources

[3] Daily upper air data were obtained from the NCEP/NCAR reanalysis dataset [Kistler *et al.*, 2001]. The first seven levels (corresponding to 1000, 925, 850, 700, 600, 500, and 400 mb) were examined for a transition from a temperature above 0°C to a temperature at or below 0°C. The daily height of the freezing level was then obtained through linear interpolation between the geopotential heights of the transition levels; mean monthly and annual FLH were calculated.

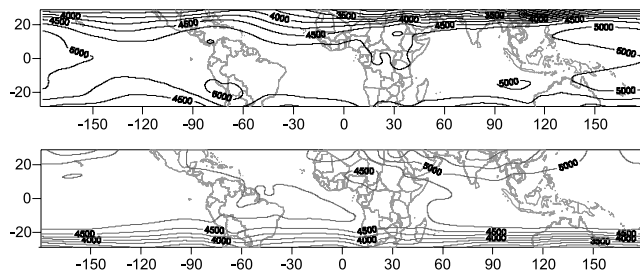
[4] Sea surface temperatures (SSTs) were obtained from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) Dataset v.3 [Smith *et al.*, 2008]. We also examined the HadISST 1.1 Global Sea Surface Temperature dataset [Rayner *et al.*, 2003], since they have somewhat different trends in the past few decades [Vecchi *et al.*, 2008] but we find very little difference in the relationships noted below in our analysis.

### 3. Analysis

[5] Figure 1 shows mean tropical freezing level heights for January and July. FLH decline steeply on the margins of the Tropics, but over the region from  $\sim 20^\circ\text{N}$  to  $20^\circ\text{S}$ , the freezing level is found within  $\sim 4800 \pm 300$  m for most of the year [Harris *et al.*, 2000]. Trends in FLH over the last  $\sim 30$  years (1977–2007) were computed and are shown in Figure 2 (left, units of m/yr), together with their zonal averages (Figure 2, right, units of m/decade). FLH in most of the tropics have increased, with zonal mean trends showing overall increases in FLH of 10–20 m/decade across the inner Tropics during this time, and even larger changes at the northern limit of the Tropics (near  $30^\circ$  latitude). However, over much of the Equatorial Pacific region and American sector close to the Equator, FLH have declined slightly over the last 31 years, although these changes are not statistically significant (Figure 2). South of the Equator, in southern Ecuador, Perú and Bolivia, surface temperature observations at stations up to  $\sim 4200$  m, and NCEP-derived 500 mb free air temperatures show similar upward trends in temperature, of  $\sim 0.1^\circ\text{C}/\text{decade}$ , over the last 50–60 years [Vuille *et al.*, 2008]

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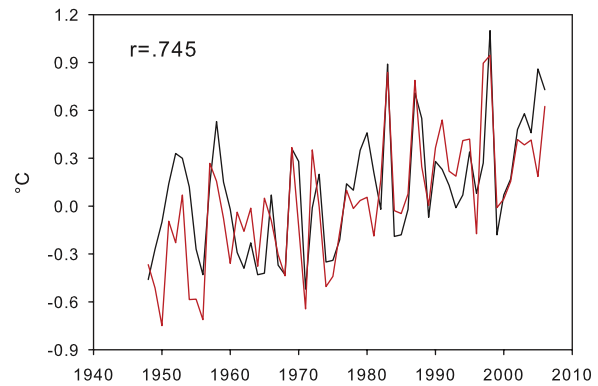
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**Figure 1.** Mean free air freezing level heights (GPH in meters) in (top) January and (bottom) July, based on NCEP reanalysis data for 1977–2007.

(Figure 3). Above 4200 m there are virtually no long-term meteorological stations, but since 2004 we have made temperature measurements at 5680 m on the summit of Quelccaya Ice Cap, the largest ice cap in the Tropics ( $13^{\circ} 55.7'S$ ,  $70^{\circ} 49.30'W$ ). These reveal the frequent occurrence of daily maximum temperatures above freezing during the period from September–May each year (Figure 4, top). (Sensors were ventilated by drawing air across them for two minutes prior to each measurement, to eliminate the effects of solar radiation on the measurements). Projecting the observed temperatures to the ice cap margin ( $\sim 5200$  m) using the observed free air lapse rate for this site (from NCEP data:  $5.4^{\circ}C\ km^{-1}$ ) shows that daily maximum temperatures have been persistently above freezing for much of the year, and it is therefore not surprising that even at this very high elevation, the ice cap is receding significantly around its margins [Thompson, 2000; Hardy and Hardy, 2008]. Glaciological observations at the ice cap summit show that the percolation facies (an indicator of surface melting) rose 130 m from 1976–1991 ( $\sim 8\ m\ yr^{-1}$ ) [Thompson et al., 1993] and the freezing level data suggest that this trend has continued. Similar conditions are likely to have affected other high elevation, glacierized areas of Perú and Bolivia, leading to significant glacier mass losses in recent years [cf. Soruco et al., 2009]. Regrettably, because there is no observational network in these high mountains, these changes are occurring without adequate monitoring, yet the consequences of the changes in glacier mass balance will have significant social and economic consequences far downstream, in lowland areas to which the glacier-fed streams and rivers drain [Vergara et al., 2007].

[6] Looking more broadly at the Tropics, it is clear that FLHs across the Tropics are strongly related to mean tropical SST variations, with the rising SSTs driving freez-



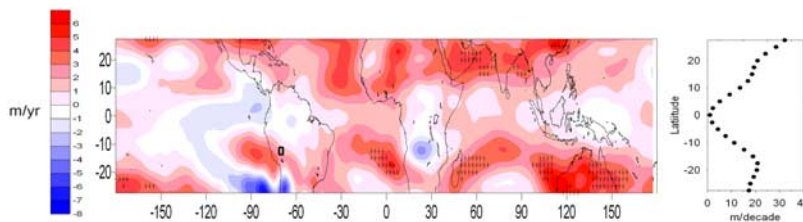
**Figure 3.** Black line: mean annual free air temperatures departures from the 1961–90 mean at 500 mb from the NCEP reanalysis data for the gridbox encompassing Quelccaya Ice Cap, S.E. Perú ( $13^{\circ} 55.7'S$ ,  $70^{\circ} 49.30'W$ ) (see box in Figure 2). Red line: Mean annual surface temperature departures from the 1961–90 mean for 279 high elevation observing stations in the Andes from  $1^{\circ}$ – $23^{\circ}S$  [from Vuille et al., 2008].

ing levels upward in the atmosphere (Figure 5). Regression of the FLH onto the SST change yields the relationship:

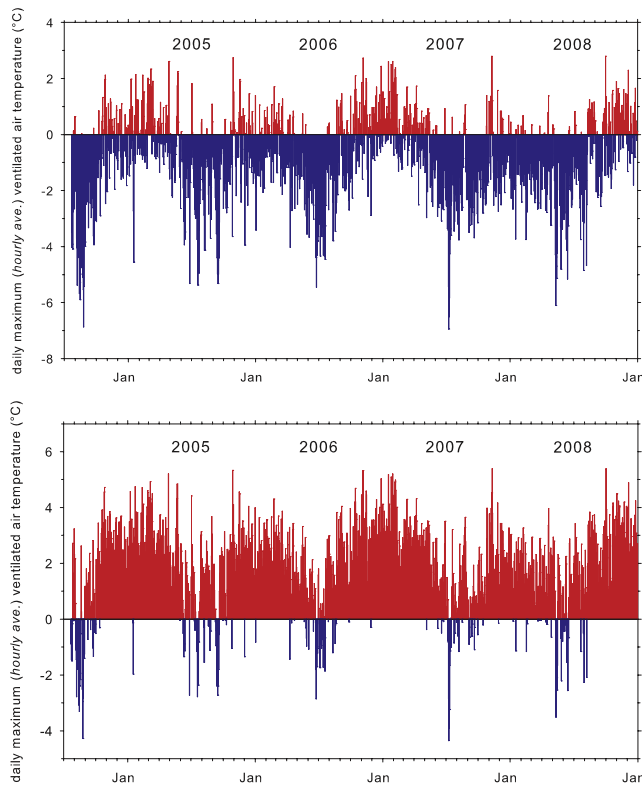
$$FLH = 252.7 * SST - 0.082$$

Over the last  $\sim 30$  years, freezing level heights across the Tropics have risen by  $\sim 45$  m, on average. If this same relationship prevailed during glacial times, a mean SST cooling of  $2$ – $3^{\circ}C$  (as most paleoceanographic proxies now suggest) would have led to a fall in the zero degree isotherm across the Tropics of  $\sim 500$ – $750$  m, with obvious effects on glacierization throughout the mountains of the region. Additional factors such as an increase in the fraction of precipitation falling as snow (and less as rain) and associated changes in albedo and absorbed solar radiation accompanying the change in FLH would have reinforced the effects of lower temperatures, leading to more positive mass balance regimes, and increased glacierization of the high mountains [Wagnon et al., 2001; Favier et al., 2004a; Vuille et al., 2008].

[7] Although the mean FLH is strongly related to mean SSTs across the Tropics, ENSO variations play a critical role in modulating FLH on an interannual basis across the entire region (Figures 6a and 6b) [cf. Vuille et al., 2000; Bradley et al., 2003; Favier et al., 2004b]. FLH across the

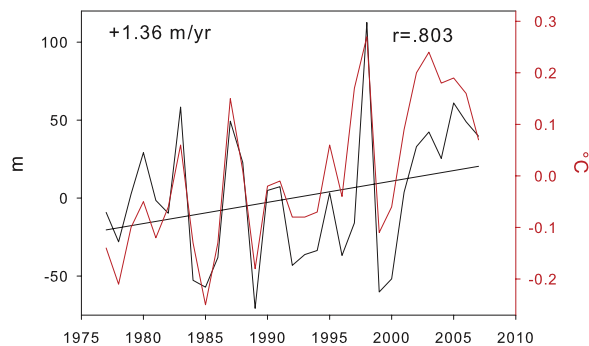


**Figure 2.** (left) Trends in freezing level heights, 1977–2007 in  $m\ yr^{-1}$ . Grid boxes with trends significant at the 95% level are indicated with + signs. 4.1% of the grid boxes in the tropical region shown had trends significant at the 95% level. Location of 500mb temperature record shown in Figure 3 is indicated by the box. (right) Zonal mean trends in freezing level height ( $m\ decade^{-1}$ ).

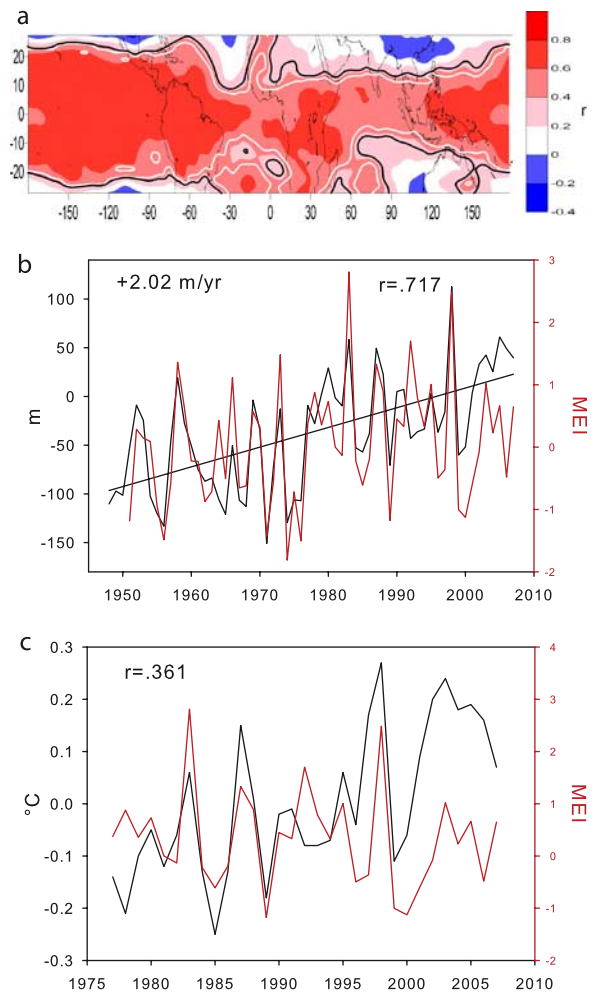


**Figure 4.** Daily maximum ventilated air temperatures (hourly averages) for (top) Quelccaya Ice Cap summit (5680 m) and (bottom) Quelccaya ice cap margin (5200 m). The latter was extrapolated using an observed free air lapse rate for the region of  $5.4^{\circ}\text{C km}^{-1}$  (based on NCEP reanalysis data).

Tropics has followed year-to-year variations in the Multi-ENSO Index (MEI) quite closely, except for the 2–3 years following the June 1991 eruption of Mt. Pinatubo (Figure 6b). However, there has been a distinct shift in the close relationship between the MEI and mean tropical SSTs since ~1999 (Figure 6c). We speculate that this may reflect an SST response to anthropogenic greenhouse gases in the atmosphere, which is not reflected in the MEI.



**Figure 5.** Mean freezing level height across the entire Tropics ( $28.75^{\circ}\text{N}$ – $28.75^{\circ}\text{S}$ ) compared to mean sea surface temperatures (ERSST data) in the same region (both expressed as departures from the 1977–2007 average in  $^{\circ}\text{C}$ ).



**Figure 6.** (a) Correlation coefficients between November–March multivariate ENSO index, MEI, and mean annual freezing level height departures from the 1977–2007 mean across the Tropics. Heavy black and white lines indicate 95% and 99% significance levels, respectively. (b) Mean freezing level height departures from the 1977–2007 mean across the entire Tropics ( $28.75^{\circ}\text{N}$ – $28.75^{\circ}\text{S}$ ) compared to the November–March multivariate ENSO index (MEI). (c) Mean tropical SST anomalies from the 1977–2007 mean (in  $^{\circ}\text{C}$ , left scale) compared to the November–March MEI. A distinct separation in the records is noticeable over the past decade.

[8] The latest IPCC late 21st century climate projections [IPCC, 2007] show warming of the tropical and subtropical atmosphere will be enhanced as greenhouse gases increase. Hydrometeorological observations in recent decades, together with geophysical evidence of wasting and rapidly receding mountain glaciers in the tropical Andes, suggest that high-elevation mountain regions are already experiencing the environmental effects of global warming. In previous papers [Bradley et al., 2004, 2006; Diaz et al., 2006], we have argued that the potential effects of an amplification of the global warming signal in mountain regions needs to receive greater attention from researchers and international funding agencies. A resumption of warming in the tropical Pacific in connection with ENSO will result in even more rapid



changes in many Andean mountain glacial systems with higher rates of mass wasting and further collapse of ice caps and glaciers.

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