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Temperature trends at high elevations: Patterns across the globe

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[1] Most climate models suggest amplification of global warming in high mountains, but observations are less clear. Using comprehensive, homogeneity-adjusted temperature records from over 1000 high elevation stations across the globe, we examine the causes of changing temperature trends with elevation, assessing the roles of free atmospheric change, topography (exposure and aspect), and cryospheric feedback. The data show that observed 20th century temperature trends are most rapid near the annual 0°C isotherm due to snow-ice feedback. Mountain summit and freely draining slope sites are dominated by free-air advection and thus have consistent trend magnitudes, with reduced inter-site variance in comparison with incised valley sites where local factors are more important. Thus, while there has been no simplistic elevational increase in warming rates, some generalizations can be made. Water resources and ecosystems near the 0°C isotherm in the extratropics are at increased risk from accelerated warming. The data also suggest that exposed mountain summits, away from the effects of urbanization and topographic sheltering, may provide a relatively unbiased record of the planet's climate. **Citation:** Pepin, N. C., and J. D. Lundquist (2008), Temperature trends at high elevations: Patterns across the globe, *Geophys. Res. Lett.*, *35*, L14701, doi:10.1029/2008GL034026.

1. Introduction

[2] Mountains make up close to 25% of continental surfaces [*Kapos et al.*, 2000] and snow-topped mountains provide water for roughly 25% of the global gross domestic product [*Barnett et al.*, 2005]. Around 40% of the world's population live in watersheds of rivers originating in mountains [*Beniston*, 2006]. These towers of snow and ice are very sensitive to warming temperatures, as has been documented in recent decades through observations of melting glaciers [*Meier et al.*, 2003], disappearing snowpacks [*Mote et al.*, 2005], and potential loss of biodiversity [*National Research Council*, 1999]. However, to project responses of mountain regions to future climate change requires not only an estimate of large-scale regional warming, as might be provided by a GCM, but also an estimate of if and how warming rates vary with elevation.

[3] This paper presents results from 1084 stations ranging in elevation from 500 m up to 4700 m (data further described by *Pepin and Seidel* [2005]), and explains how variations in free-air temperatures, large-scale circulation patterns, local topography, and snow-ice feedbacks can explain where on the Earth's surface we see the strongest temperature trends.

[4] Prior work has been inconclusive about whether high elevations around the globe have been warming faster or slower than nearby lower elevations or global averages [*Beniston et al.*, 1997; *Seidel and Free*, 2003]. *Diaz and Bradley* [1997] analyzed surface temperature records at 116 sites and found that many (although not all) high elevation sites showed enhanced 20th century warming. This has been substantiated by many regional examples including work in Tibet [*Liu and Chen*, 2000] and in the Swiss Alps [*Beniston and Rebetez*, 1996]. However, other studies show a decreased warming rate at high elevations [*Pepin and Losleben*, 2002; *Vuille and Bradley*, 2000] or the lack of any clear relationship between trend magnitude and elevation [*Vuille et al.*, 2003; *Pepin and Seidel*, 2005; *Liu et al.*, 2006; *You et al.*, 2008].

[5] On the other hand, nearly all global climate models report increased sensitivity to warming at high elevations [*Giorgi et al.*, 1997; *Chen et al.*, 2003] because melting snow and ice result in lower surface albedo, which in turn enhances further warming. This feedback should not consistently increase with elevation but should be strongest around 0°C. Because GCMs are run until equilibrium is reached far in the future, the elevational zone over which snow-ice feedback becomes critical is both enlarged and higher than in the present. Thus, care must be taken in relating model results to what is observed.

[6] This article uses observations to demonstrate where we see the most rapid temperature trends on a global scale. In addition to elevation, we consider the roles of a) the free atmosphere, b) snow-ice feedback, and c) topography (exposure and aspect), in controlling temperature trends. We use temperature trends derived from the extensive global dataset originally presented by *Pepin and Seidel* [2005]. This consists of monthly mean temperature anomalies at 1084 stations ranging in elevation from 500 m up to 4700 m from two global homogeneity adjusted datasets Global Historical Climate Network (GHCNv2) [*Peterson and Vose*, 1997] and Climate Research Unit (CRUv2) [*Jones and Moberg*, 2003]. Our selection of stations minimizes both urban and coastal effects. Trend magnitudes (1948–2002) were determined via the slope of an ordinary least squares regression line fitted to anomalies after inhomogeneities in the records had been adjusted. Topography was classified subjectively by reference to 1:1,000,000 Operational Navigation Charts as either mountain summit (MT), freely-draining hill-slope (HI), mountain valley (MV), or flat (FL). Urban stations were classified by reference to population estimates [*Peterson and Vose*, 1997]. For a map of

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stations readers are referred to auxiliary material.[1] Further details of statistical methods are given by *Pepin and Seidel* [2005].

2. Role of the Free Atmosphere

[7] Free atmospheric temperature trends provide a background to mountain trends. Radiosonde [*Lanzante et al.*, 2003; *Seidel et al.*, 2004] and/or satellite data [*Mears et al.*, 2003] trends show considerable variation depending on time period, atmospheric level and dataset. The tropics show less warming at higher elevations, particularly since 1979 [see *Karl et al.*, 2006], but there are no clear elevational contrasts in the extra-tropics. To an extent this pattern can also be seen in our surface data. Figure 1 shows the relationship between temperature trend magnitude (°C/decade) and elevation for (a) tropical and (b) extra-tropical stations from the GHCNv2 and CRUv2 datasets. Ignoring some outliers, there is a weak decrease in trend magnitude with elevation in the tropics but no relationship at higher latitudes, similar to the free atmosphere. The tropical relationship is strongest at urban stations, suggesting that rapid trends at some lower elevation tropical urban locations may influence the relationship. Free atmospheric temperature trends can only partially explain mountain climate changes, because temperatures at the mountain surface (and their trends) are not exactly the same as those at equivalent elevations in the free atmosphere [*McCutchan*, 1983; *Pepin and Norris*, 2005; *Seidel and Free*, 2003].

3. Snow and Ice Feedback

[8] Scatter plots of trend magnitude versus station mean annual temperature (derived from the whole record) show faster warming rates at lower temperatures, with particularly enhanced warming at temperatures near freezing. The result is stronger for flat and incised valley sites (Figure 2a), where surface characteristics such as snow cover exert a powerful influence, than for slope and summit sites (Figure 2b). Globally between −5°C and +15°C the correlation between trend magnitude and mean annual air temperature at valley sites is −0.445 (weaker trends at higher temperatures, $p < 0.001$). The relationship is weaker for mountain summit and freely draining slope sites ($r = -0.300$) but still apparent in the temperate zone. Mean trend magnitudes are significantly higher for the −5–0°C and 0–5°C mean annual temperature bands (Figure 2c). Indeed, the −10 to −5°C, −5–0°C, and 0–5°C bands have mean trends exceeding the global average rate of warming (horizontal line, Figure 2c). There is still great scatter within each class because mean annual temperature alone is a crude index of the annual time period when snow-ice feedback operates and because many other factors, such as latitude, location relative to local topography, and changing atmospheric circulation patterns, also play a role.

[9] Although the form of the relationship is independent of latitude, in the tropics due to fewer stations, it is less robust. In particular our data do not extend to high tropical elevations near the critical 0°C isotherm and unfortunately we cannot comment on snow-ice feedback effects at such locations.

4. Effects of Urbanization

[10] In addition to the snow-ice-albedo feedback, urbanization is expected to enhance warming. Although urban effects were minimised by restricting our analysis to stations over 500 m, there are some large cities above this elevation, especially in the tropics. Figure 3 shows that some of the warm urban stations (as measured by population estimates [*Peterson and Vose*, 1997]) show high warming rates, and that the negative relationship between mean annual temperature and warming rate discussed in section 3 does not exist at urban sites.

5. Surface Modification and the Role of Topography (Exposure and Aspect)

[11] Mountain climate is a balance between free-air advective influences and surface radiative-induced influences. Locations which are cloudy and/or windy, such as exposed mountain summits, which have minimized radiation and/or maximized advection, have surface temperatures most closely matching those of the free atmosphere [*Pepin and Norris*, 2005]. On the other hand, sites in topographic depressions are sheltered from the wind, and local radiative effects can cause extreme variations in local climate [*Whiteman et al.*, 2004].

[12] Mountain summit temperatures should therefore show a higher degree of affinity with each other (and with the free atmosphere), and their trends should show a reduced variance in magnitudes. On the contrary, temperature trends in valley locations will not follow a simplistic pattern, since local climate is dependent on the extent to which cold air pooling and/or local heating is facilitated by the combination of topography and synoptic conditions [*Neff and King*, 1989, *Whiteman et al.*, 2001]. For example, long-term changes in synoptic conditions could decrease the frequency of cold-air pooling, which would preferentially warm frost-hollow sites.

[13] Slope aspect can also result in trends of differing signs in very close proximity. *Lundquist and Cayan* [2007] give the example of the Sierra Nevada, where the east slope is cooling and the west slope warming due to decreased strength of the upper westerly flow.

[14] A division of trends (1948–2002) by topographic class supports the above arguments (Figure 4). For mountain summit sites (MT) and freely draining hillslope locations (HI), there is more consistency in trend magnitudes, particularly at the higher elevations. Flat locations (FL) and especially incised valley sites (MV), on the other hand, show a high degree of variation. The decreased variance in trend magnitudes at summit sites in comparison with the other topographic classes is statistically significant ($p = 0.0267$), reinforced further if slope/summit sites are contrasted with flat/incised valley sites (HI + MT vs. FL + MV) ($p = 0.0016$). The mean trend magnitude for mountain summit sites is also lower than for the other topographic classes (+0.049°C/decade vs. +0.113°C/decade for other sites combined, $p = 0.056$). Globally, since there are more

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034026.

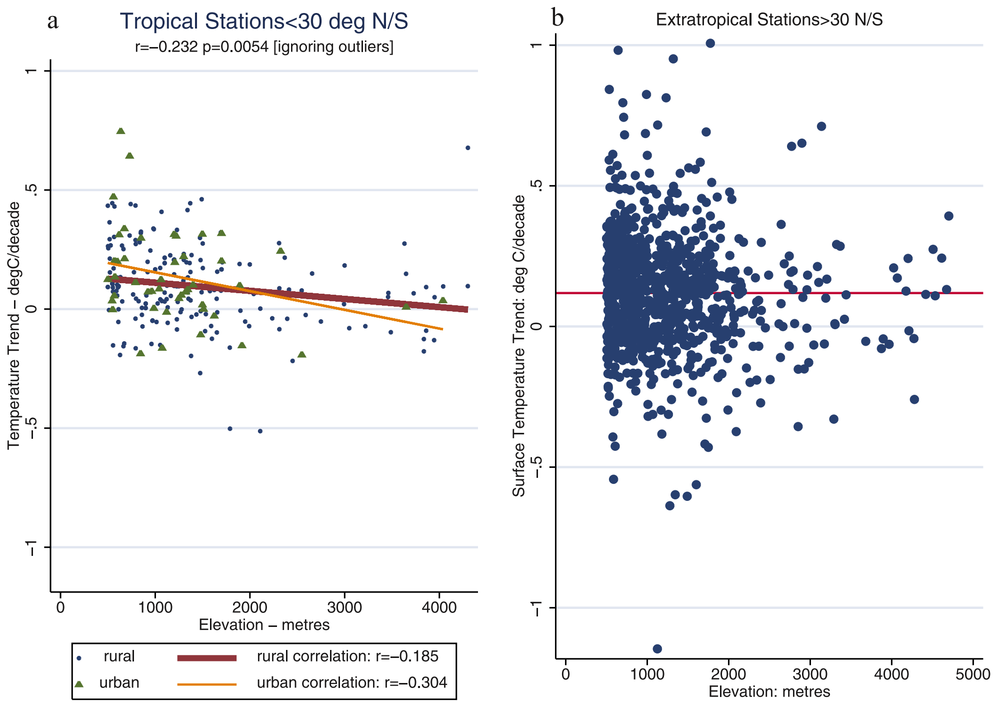

Figure 1. Relationships between temperature trend magnitude (1948–2002: °C/decade) and elevation for 1084 GHCN/CRU sites: (a) tropical stations (<30°N/S) and (b) extratropical stations (>30°N/S). Red horizontal line represents the mean global trend magnitude (+0.12°C/decade). For Figure 1a both urban and rural correlations are shown.

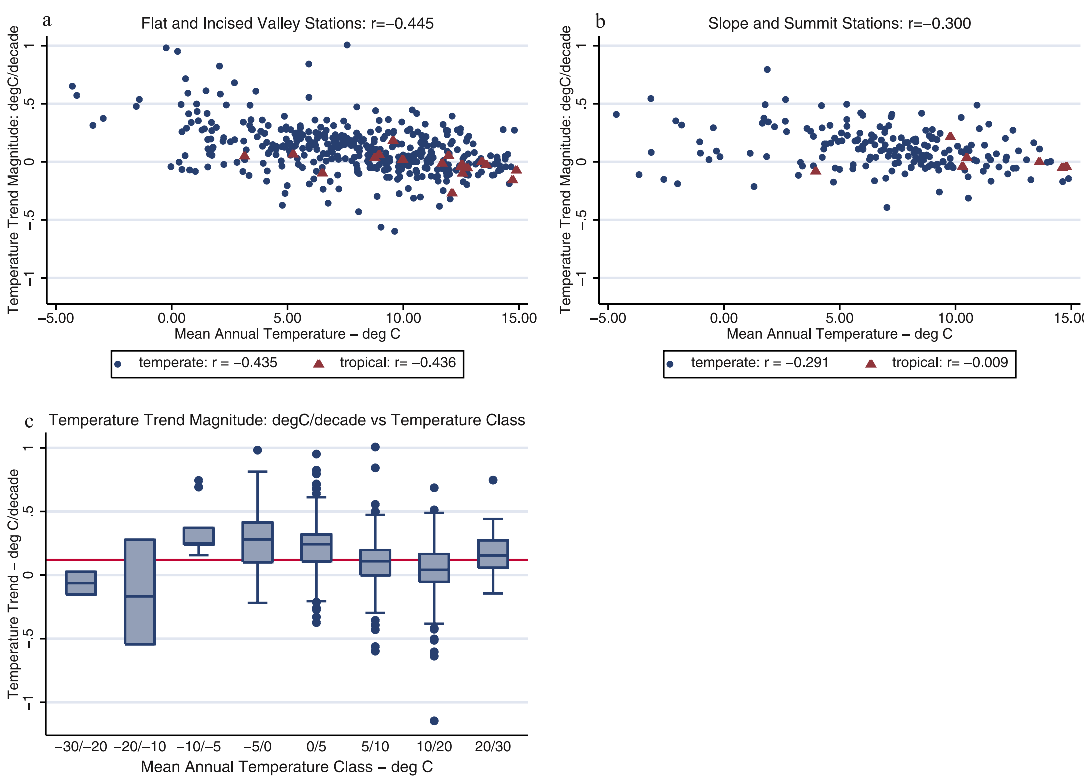

Figure 2. Relationship between temperature trend magnitude and mean annual temperature (−5°C to 15°C) for (a) flat and incised valley stations and (b) slope and mountain summit stations. (c) Box plots of temperature trend magnitudes for different mean annual temperature bands.

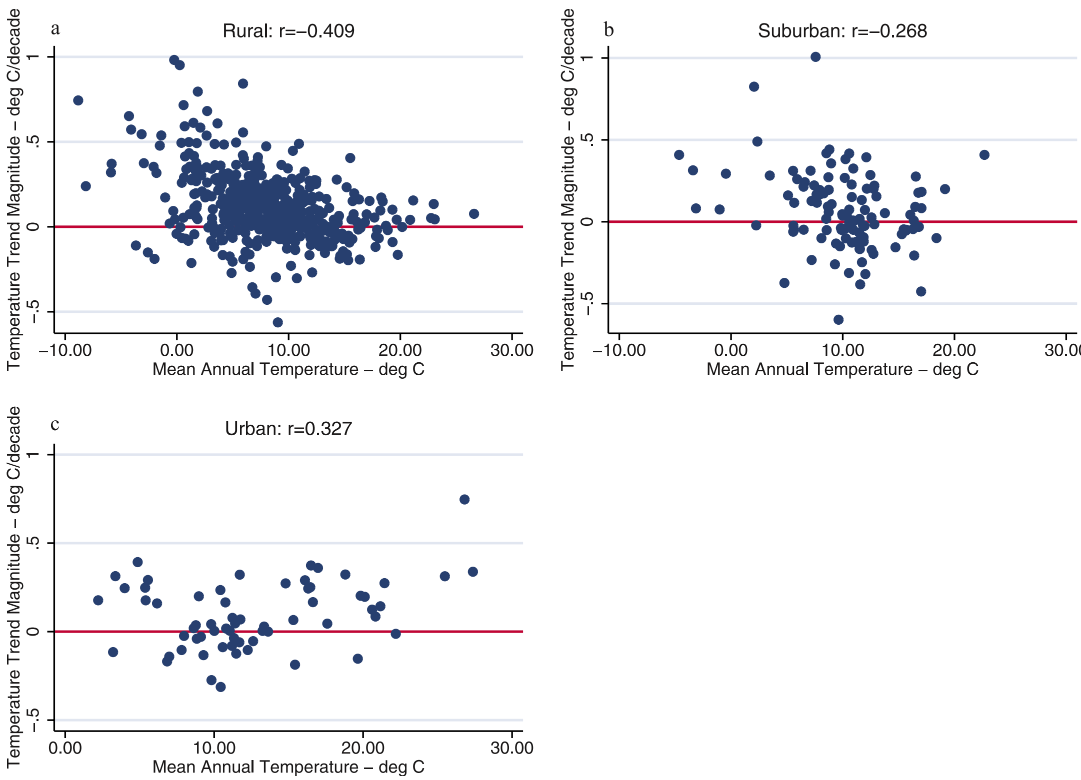

Figure 3. Relationship between temperature trend magnitude and mean annual temperature (−10°C to 30°C) for (a) rural, (b) suburban, and (c) urban stations.

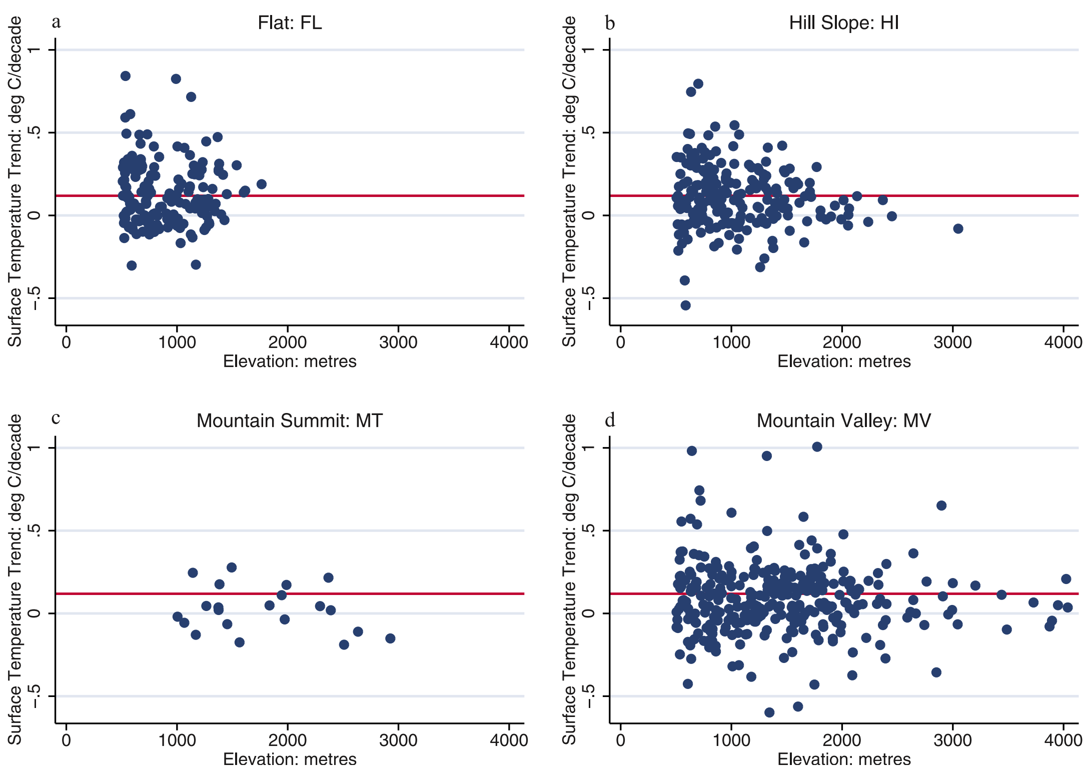

Figure 4. Temperature trend magnitude vs elevation for different topographical classes of station: (a) flat, (b) ridge/freely draining slopes, (c) mountain summits, and (d) incised mountain valleys. Red horizontal line represents the mean global trend magnitude (+0.12°C/decade).

valley sites than summit and hillslope locations (many high elevation stations being in mountain towns), any study not attuned to topography could reach contrasting conclusions.

[15] Unlike topographic exposure, it is hard to generalise about the impact of aspect on a global scale. Poleward-facing slopes will be cooler than the average for the elevation (and equatorward slopes warmer) because of contrasts in radiation load, but this difference depends on lack of cloud, and on latitudinally-specific solar geometry. In areas where it is often cloudy and/or windy and where advection plays a significant role in mountain climate, the critical aspect effect will be the contrast between windward and leeward slopes, but this depends on the prevailing winds in that locality (westerly in mid-latitudes, easterly in the tropics and polar cell). Analyses between trend magnitude and regional slope azimuth (not shown) therefore fail to show simple relationships, because local synoptic climatology is of great importance.

6. Concluding Remarks

[16] In our dataset, areas near the annual 0°C isotherm in the extratropics exhibit the strongest warming rates. This is consistent with other observational studies of cryospheric change [*Laternser and Schneebeli*, 2003; *Franssen and Scherrer*, 2007], which report rapid change at the lower margins of current snow/ice cover. A few urban mountain locations, which generally have mean annual temperatures over 15°C, also show enhanced warming rates.

[17] There are no global relationships between elevation and warming rates. However, mountain summit and freely draining slope sites show more spatially consistent temperature trends than incised valleys because the influence of the free-air is increased. Because summit locations rise above a sea of lower elevation noise, high mountains are therefore a good indicator of the state of the planet with regards to global warming. However, this is because of the increased global representativeness of trends at summit sites (less influenced by surface complexities) and not because of the enhanced sensitivity to warming and consequent rapid environmental change in mountains (e.g. melting glaciers) often exposed by the media. We monitor atmospheric CO_2 concentration on Mauna Loa (a mountain in the middle of an ocean) because it is remote from local influences which could contaminate the record [*Keeling et al.*, 1982]. Similarly, we should consider monitoring future temperature trends on isolated mountain summits.

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