Secular temperature changes in Hawai‘i

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[1] While the upward trend in global mean temperature has been intensively studied, some regional temperature trends are less well known. We document secular temperature changes in the Hawaiian Islands for the past ~85 years based on an index of 21 stations. Results show a relatively rapid rise in surface temperature in the last ~30 years, with stronger warming at the higher elevations. The bulk of the increase in mean temperature is related to a much larger increase in minimum temperatures compared to the maximum—a net warming about 3 times as large—resulting in a reduction of the diurnal range. For much of the period of record analyzed here, surface temperature in Hawai‘i has varied coherently with changes in the Pacific Decadal Oscillation (PDO). However, in recent decades, the secular warming has begun to predominate, such that despite the recent cooling associated with the PDO, surface temperatures in Hawai‘i have remained elevated. The greater warming trend at the higher elevations may have significant ecological impacts. **Citation:** Giambelluca, T. W., H. F. Diaz, and M. S. A. Luke (2008), Secular temperature changes in Hawai‘i, *Geophys. Res. Lett.*, *35*, L12702, doi:10.1029/2008GL034377.

1. Introduction

[2] The Hawaiian Islands enjoy one of the most equable climates on earth. Isolated from large landmasses, Hawai‘i has a very low annual temperature range. In contrast to the remarkable temporal constancy of temperature in Hawai‘i, spatial heterogeneity is great owing to the large elevation range. On tropical islands, global change concerns tend to focus more on sea level rise and possible shifts in precipitation than on temperature change. However, Hawai‘i’s terrestrial ecosystems, water supply, agriculture, and economic health are also sensitive to changes in temperature. While the human population is found mostly at lower elevations, temperature change in the mountains may have larger consequences on native biodiversity, water resources, and carbon sequestration. Accelerated warming at higher elevations, as has been shown for the western U.S. [*Diaz and Eischeid*, 2007] and predicted for the tropical Andes [*Bradley et al.*, 2004, 2006], may have severe impacts on Hawai‘i’s threatened and endangered bird species, for example, by allowing disease-carrying mosquitoes to reach the last remaining safe havens for these birds [*Benning et al.*, 2002].

[3] Recent studies of climatic variations in the Hawaiian Islands have focused on changes in rainfall [*Chu and Chen*, 2005] and the association with large-scale modes of climate variability, such as the Pacific Decadal Oscillation (PDO), the slow oscillation in North Pacific sea surface temperature (SST) patterns [*Mantua et al.*, 1997]. Temperature change in Hawai‘i was reported by *Nullet and Ekern* [1988], who found that significant warming had taken place at Honolulu and Hilo between the 1950s and 1980s, coincident with warming of adjacent ocean waters. In this paper, we examine recent historical variations in temperature in Hawai‘i, to determine whether significant warming has occurred throughout the Islands, whether other types of temporal variability can be detected, and how temperature changes differ according to elevation.

2. Methods

[4] A total of 21 temperature stations were selected based on length of record (see Table S1 in the auxiliary material[1]). Five of the stations (labeled 86.1, 87, 703, 1020, and 1020.1 in Table S1) are located in Hawai‘i’s population centers Līhu‘e, Honolulu, and Hilo, which have undergone significant urbanization during the study period. Data were obtained from the National Climatic Data Center and the Western Regional Climate Center. For the 88-yr (1919–2006) study period, length of record averages 52 years for the selected stations. The number of stations with data in any given year varies between 6 and 20, with the greatest number of stations available during 1944–1980. For each station, years or seasons with more than one missing month were not included. Up to one missing month per year was filled with the monthly mean. For each station, annual anomalies were calculated as departures from the respective 1944–1980 mean. Stations span an elevation range of 3–3400 m, although relatively few stations are situated at the higher elevations. Indices were computed separately for stations below and above 800 m (N = 17 and 4 stations, respectively) as the means of the anomalies for all available stations in each elevation range, for each year. A Hawai‘i Temperature Index (HTI) was computed as the weighted mean of low- and high-elevation indices with weights of 0.575 and 0.425, corresponding to the relative proportion of land area below and above 800 m elevation, respectively. Secular trends were determined using linear regression and tested for significance, with attention to the effects of autocorrelation, using the method of *Santer et al.* [2000].

3. Results and Discussion

[5] The changes in surface temperature are summarized in Table S2 (in the auxiliary material) and illustrated in Figure 1. Two features are of particular interest; one is the

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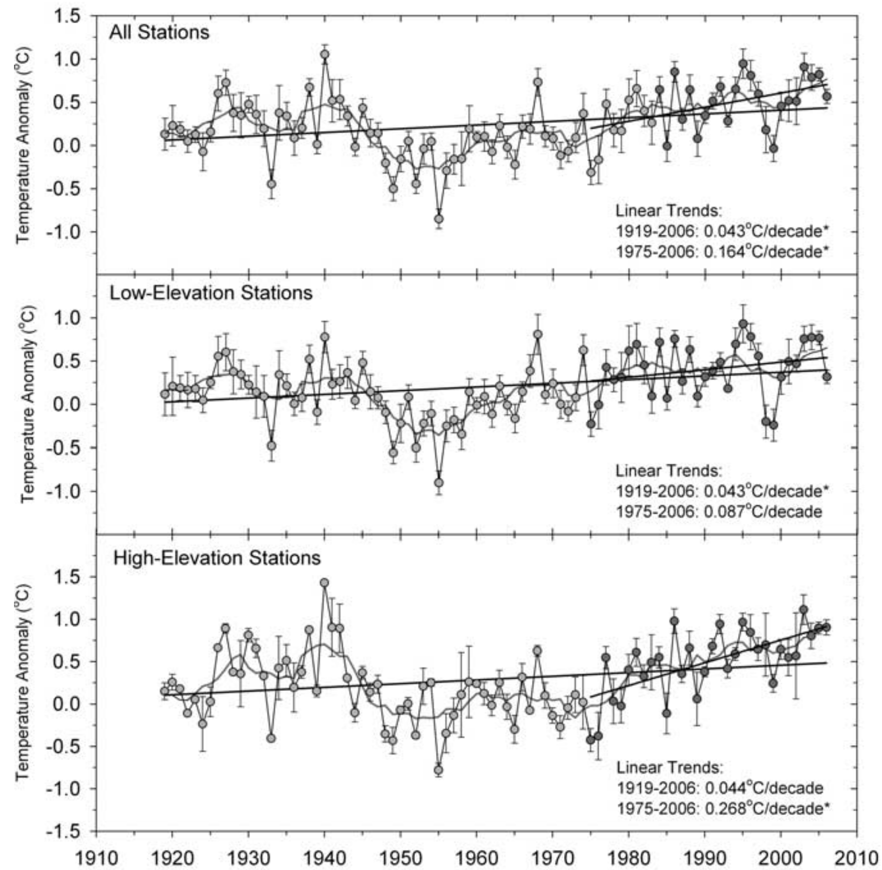

Figure 1. Average surface temperature anomalies in Hawaii. Time series calculated from monthly station data after removing the calendar month means and averaging into calendar years. Smoothed curve is the annual data filtered with a 7-yr running mean. Linear trends computed for two periods, 1919–2006 and 1975–2006. The latter period emphasizes the enhanced level of global warming documented by *IPCC* [2007]. (top) All stations (N = 21), with area weightings of 0.575 and 0.425 for low- and high-elevation stations, respectively. Middle panel: Time series plot from observing stations located at the lower elevations (<800 meters). (bottom) Time series plot from observing stations located at the higher elevations (> 800 meters). Error bars show +0.5 standard deviation. Thick lines show 7-yr running means. Asterisks indicate slopes significant at p = 0.05.

long-term increase in temperature and the accelerated rate of increase in the last few decades (0.04°C/decade for the full record versus about 0.2°C/decade since 1975). The recent trend for Hawai'i is within the range of warming rates found by *Folland et al.* [2003] for South Pacific islands during 1954–1998, where island stations with statistically significant trends had warming rates ranging from 0.11°C/decade (Apia, Samoa; Alofi, Niue; and Aitutaki, Cook Islands) to 0.31°C/decade (Papeete, French Polynesia). The higher elevation stations (Figure 1, bottom plot) warmed by about a factor of three (0.27°C/decade) compared to the lower sites (0.09°C/decade, not significant at p = 0.05), during the period since 1975. The second feature of interest is the strong tuning of the temperature curves to the PDO. This is clearly illustrated in Figure 2 (top plot), where the Hawaii temperature index (HTI) is plotted along with the annual PDO values. For much of the record, the HTI varies in close concert with changes in the PDO, but in recent decades, temperatures in Hawaii warm relative to the variation in the PDO (Figure 2, top plot inset).

[6] Linkage between air temperature fluctuations in Hawai'i and the PDO is likely to involve changes in regional SST. In general, the positive phase of the PDO is associated with warm SST anomalies in the tropical eastern North Pacific and along the west coast of North America [*Mantua et al.*, 1997]. Recent warming of coastal waters has been sufficient to cause large-scale coral bleaching around Hawai'i [*Jokiel and Brown*, 2004]. Comparing the HTI time series with SST anomalies for 22°N, 156°W (a point approximately 200 km upwind [NNE] of O'ahu), as expected, shows that air temperature in the islands is strongly influenced by the surrounding ocean (Figure 2, bottom plot). Note that air temperature (HTI) decreased relative to SST between 1920 and the mid-1950s. Since that time, however, the upward HTI trend significantly exceeds the SST trend (Figure 2, bottom plot inset).

[7] We examined trends for two six-month seasons, summer (May–October) and winter (November–April), roughly corresponding to the dry and wet seasons throughout much of Hawai'i. In general, warming trends are lower for summer and higher for winter, compared with the annual trends (Table S2). As with the annual trends, warming in both seasons has been greater for high elevation stations and for the most recent period.

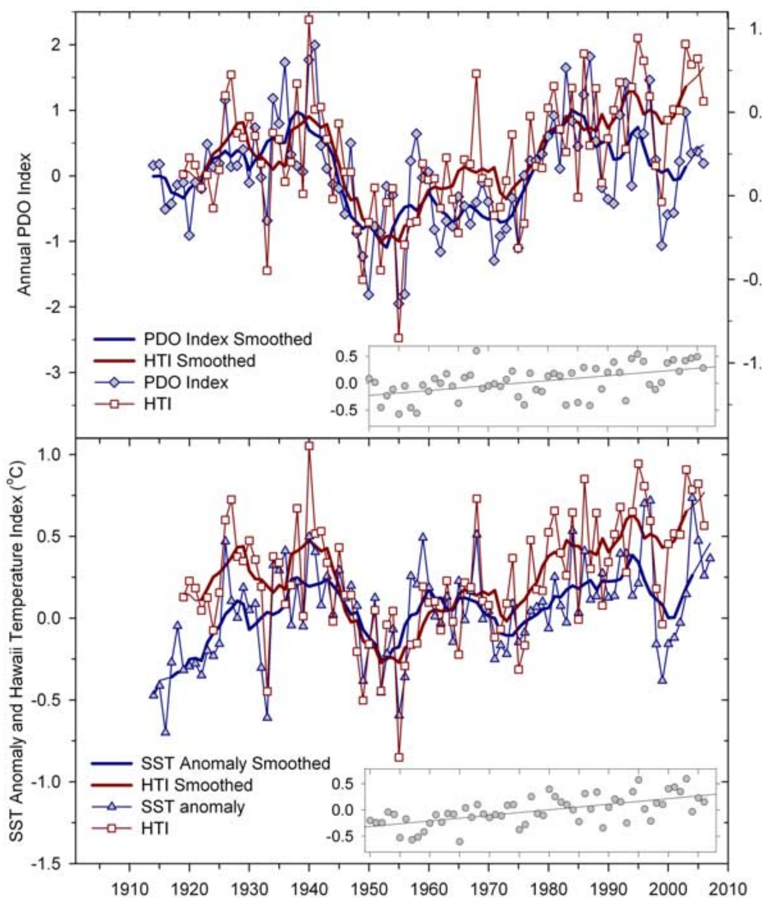

Figure 2. (top) Annual and smoothed (with a 7-yr running mean) HTI and PDO for the period of study. Note the separation of the two curves in recent decades. (bottom) Sea surface temperature anomaly (°C) time series for 22°N, 156°W based on the Extended Reconstructed Sea Surface Temperatures (ERSST) data set [*Smith and Reynolds*, 2004], shown in comparison with the HTI. Thick lines show 7-yr running means. Plotted in the lower right hand corner of the plots are the 1950–2006 residuals derived from linear regression of HTI against the PDO index and SST anomaly.

[8] We also examined trends in mean daily maximum (T_{max}) and minimum (T_{min}) temperatures, and the associated change in the diurnal range. T_{max} was found to have no significant long-term (1919–2006) warming or cooling trends for annual, summer, or winter periods, except for high-elevation and non-urban stations during winter, which had moderate warming trends (Table S2). Since 1975, significant increases have occurred in T_{max} only for non-urban stations. T_{min}, on the other hand, has seen significant long-term and recent increases for both elevation ranges and both seasons, with the exception of low-elevation stations during summer (Table S2). Remarkably steep increases in T_{min}, approaching 0.5°C/decade, are evident since 1975 at high elevations. These changes imply a decrease in the daily temperature range (DTR). *Vose et al.* [2005] found a global trend in DTR over land areas of −0.066°C/decade due to more rapid T_{min} increases during 1950–2004, but no trend in DTR for the 1979–2004 period. Figure 3 shows the difference between the T_{max} and T_{min} anomalies for Hawai'i, illustrating the decline in DTR found consistently over the whole record, including the period since 1979.

[9] As noted above, we examined temperature trends separately for stations below and above 800 m. It is evident that higher elevation areas of Hawaii have warmed more rapidly in the past ~30 years, with changes on the order of 0.27°C/decade for annual mean temperature at high elevations compared to 0.09°C/decade for the lower elevation sites (Table S2). The amplification of warming trends with elevation implies a change in the vertical temperature lapse rate in the Islands during the past few decades. The inferred changes in the lapse rate, while perhaps partly an artifact of higher variability in the small high-elevation sample, appear to be quasi-periodic, loosely following fluctuations in the PDO (Figure 4). With this in mind, we note that extremes in the annual mean lapse rate index (not shown) tend to be associated with El Niño (when greater warming aloft results in smaller lapse rates) and La Niña (when less warming aloft results in higher lapse rates). The apparent recent increase in atmospheric stability inferred by the more rapid high-elevation warming is consistent with the observed upward trend in the frequency of occurrence of the trade-wind inversion (TWI) over Hawai'i since the late 1970s [*Cao et al.*, 2007].

[10] To consider the possible impact of urbanization on the 5 stations with the highest population in our station network, we calculated the linear trends as above with and without those stations. We found that the differences in mean temperature trends, if anything, were in the opposite direction—that is, the non-urban sites exhibited slightly higher temperature increases than with the urban stations included (Table S2). However, trends in Tmax and Tmin were higher

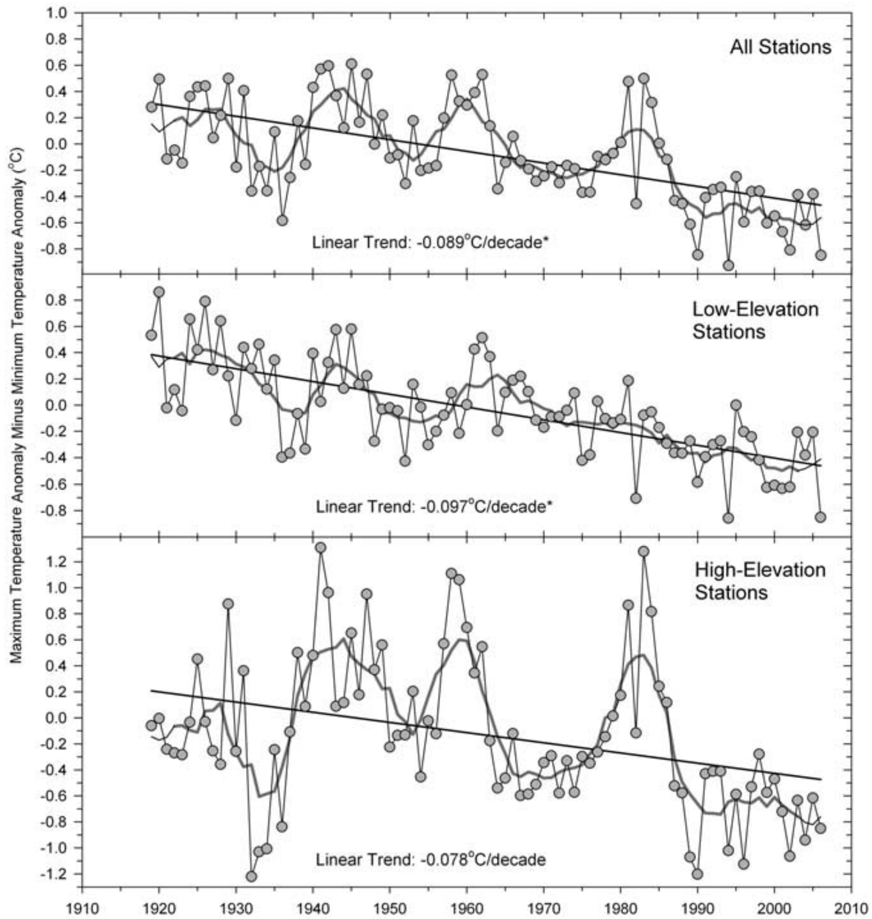

Figure 3. Time series of T_{max} anomaly minus T_{min} anomaly for (top) all stations, (middle) low elevation stations, and (bottom) high elevation stations. Thick lines show 7-yr running means. Asterisks indicate slopes significant at p = 0.05.

and lower, respectively, when urban stations were excluded (Table S2), suggesting that urbanization has countered daytime warming and enhanced nighttime warming.

4. Conclusions

[11] Despite its tropical oceanic location, Hawai'i has experienced rapid warming, especially since the mid-1970s. The long-term trend temperature trend is substantial and the recent trend is only slightly lower than the global trend: 0.043°C/decade (Hawai'i, 1919–2006) vs. 0.074°C/decade (global, 1906–2005 [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007, p. 253]) and 0.163°C/decade (Hawai'i, 1975–2006) vs. 0.177°C/decade (global, 1981–2005 [*IPCC*, 2007, p. 253]). Temperature variation in

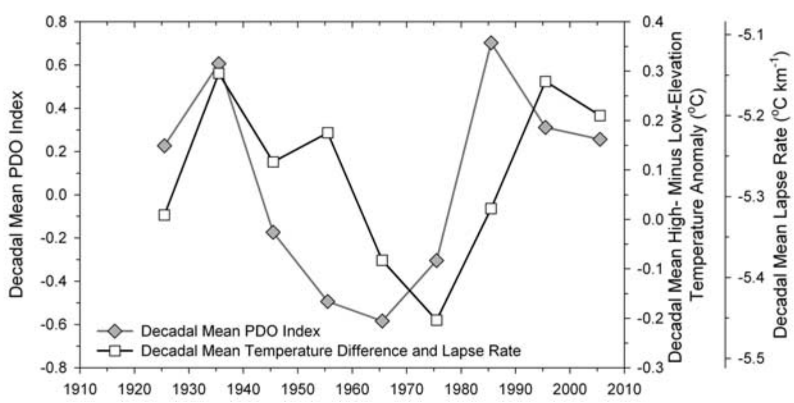

Figure 4. Changes in temperature differences between high elevation and low elevation stations in Hawaii in comparison with the PDO. Left axis: Decadal averages of the PDO index (blue curve). Right axis: Decadal averages of high-elevation minus low-elevation temperature anomalies and the estimated lapse rate (red curve); larger negative values indicate a steeper temperature lapse rate (less stable atmosphere) and vice versa.

Hawai'i appears to have been tightly coupled to the PDO, perhaps through regional SST variation. However, in recent decades Hawai'i's air temperature trend has diverged from PDO and local SST trends, perhaps signaling increasing influence of global warming.

[12] The rapid increase in T_{min} consistent with global trends prior to 1979 appears to have continued through recent years in Hawai'i. Globally, greater nighttime warming may have resulted from cloud cover increases [*Braganza et al.*, 2004]. *Nullet and Ekern* [1988] found an inverse relationship between temperature variations and changes in solar radiation in Hawai'i, suggesting that changes in cloudiness play a role in temperature change here. In the subtropics, however, strengthening of Hadley-cell subsidence in recent decades [*Quan et al.*, 2004] has resulted in reduced cloud cover [*Chen et al.*, 2002]. At the summit of Haleakalā, Maui, solar radiation and net radiation have changed at rates of 0.52 and 0.77 W m^{-2} yr^{-1}, respectively, during 1990–2007, suggesting decreasing cloudiness (http://webdata.soc.hawaii.edu/climate/HaleNet/Index.htm, Station 153). While the reasons for enhanced T_{min} trends in Hawai'i are unknown, the effects of the pronounced and persistent nighttime warming on carbon exchange, because of increased nighttime respiration [cf. *Alward et al.*, 1999], may have significant negative impacts on Hawai'i's vulnerable terrestrial ecosystems, where native plants may be in competition with alien species better adapted to higher nighttime temperatures.

[13] The enhanced warming at high elevations in Hawai'i is consistent with changes found in other regions [*Huber et al.*, 2005]. Future temperature increases at high elevations along the American Cordillera are likely to cause further melting of alpine glaciers, with potentially severe hydrological and ecological consequences [*Bradley et al.*, 2004]. The alpine tundra climatic type decreased in coverage by 73% during the past 20 years in the mountains of the western United States [*Diaz and Eischeid*, 2007]. In Hawai'i, where upper mountain slopes harbor most of the remaining intact native ecosystems, rapid warming is likely to have severe impacts. Endangered Hawaiian honeycreepers (*Drepanidae*) currently find refuge in high-elevation forests, where low temperatures limit disease-carrying mosquitoes [*Benning et al.*, 2002]. If rapid warming continues at high elevations in Hawai'i, it will likely hasten the extinction of these birds.

[14] The implied recent changes in the vertical lapse rate in Hawai'i mean a shift toward a more stable atmosphere. This finding is consistent with observations of greater persistence of the TWI [*Cao et al.*, 2007] and a downward trend in precipitation [*Chu and Chen*, 2005]. Should the diminishing vertical lapse rate trend continue, Hawai'i's climate is likely to continue to become drier as warming continues. Reduced precipitation in combination with a possible increase in potential evapotranspiration due to increased temperature would result in significant reductions in ground-water recharge and stream discharge, and would severely impact vulnerable high-elevation ecosystems.

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