Climatic Changes in Mountain Regions of the American Cordillera and the Tropics: Historical Changes and Future Outlook

Authors: Diaz, Henry F., Bradley, Raymond S., and Ning, Liang

Source: Arctic, Antarctic, and Alpine Research, 46(4) : 735-743

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1938-4246-46.4.735

Arctic, Antarctic, and Alpine Research, Vol. 46, No. 4, 2014, pp. 735-743

Climatic changes in mountain regions of the American Cordillera and the tropics: historical changes and future outlook

*Henry F. Diaz**
Raymond S. Bradley† and
Liang Ning†

*Corresponding author: NOAA/Cooperative Institute for Research in Environmental Sciences, University of Colorado, 325 Broadway, Boulder, Colorado 80305, U.S.A., henry.f.diaz@noaa.gov
†Department of Geosciences, University of Massachusetts, 611 North Pleasant Street, Amherst, Massachusetts 01003, U.S.A.

Abstract

We review some recent work regarding climatic changes in selected mountain regions, with particular attention to the tropics and the American Cordillera. Key aspects of climatic variability and trends in these regions are the amplification of surface warming trends with height, and the strong modulation of temperature trends by tropical sea surface temperature, largely controlled by changes in El Niño–Southern Oscillation on multiple time scales. Corollary aspects of these climate trends include the increase in a critical plant growth temperature threshold, a rise in the freezing level surface, and the possibility of enhanced subtropical drying. Anthropogenic global warming projections indicate a strong likelihood for enhancement of these observed changes.

DOI: http://dx.doi.org/10.1657/1938-4246-46.4.735

Introduction

Mountain regions cover about one-fifth of the earth's continental areas, providing basic life support directly for close to 10% of the world's population, and indirectly to over half. They play a crucial role in supplying freshwater resources to many regions, both within the mountains themselves, and in the broader regions downslope. Ecosystems along mountain slopes are closely stacked because of sharp vertical temperature and precipitation gradients and are particularly sensitive to anthropogenic climatic change (Beniston, 1994; Diaz and Graham, 1996; Messerli and Ives, 1997; Beniston et al., 1997; Decker and Bugmann, 1999; Diaz et al., 2003a; Huber et al., 2005; Bradley et al., 2006, 2009; Nogués-Bravo et al., 2006; Sorg et al., 2012). Highland tropical forests support a remarkable level of biodiversity and are rich in endemic species (Messserli and Ives, 1997; Myers et al., 2000). With the additional pressures of land-use change and habitat fragmentation, such regions are especially vulnerable. While these issues are of general concern throughout the tropics, they are particularly problematical on tropical and subtropical islands, as well as on isolated mountains on the continents, where the opportunities for species migration are obviously severely constrained. In addition to the exceptional loss of habitat due to deforestation, encroaching urbanization and the introduction of invasive species in recent decades have only exacerbated the situation.

Temperatures have been rising throughout the world, but there are many studies of station records from different regions that indicate the magnitude of temperature changes has been greater at higher elevations (Wang et al., 2014; see also Diaz and Graham, 1996; Diaz and Bradley, 1997; Diaz et al., 2003b; Vuille et al., 2003; Pepin and Norris, 2005; Pepin and Lundquist, 2008; Liu et al., 2009; Rangwalla and Miller, 2012). Recent work provides a theoretical basis for this amplification of warming with elevation (Ohmura, 2012; O'Gorman and Singh, 2013).

In the following we provide a context for some of the recent studies by focusing on climatic changes in mountain regions of the American Cordillera, in the tropics in general, and Hawai'i in particular that have occurred over recent decades. We use the historical perspective of the observed changes to compare with potential changes in future climate, as indicated by regional atmospheric circulation models. We update some previous latitudinal-altitudinal transects with more recent observations and climate model simulations (Diaz et al., 2003b, 2011; Bradley et al., 2009; Karmalkar et al., 2008, 2011; see also Pepin and Lundquist, 2008), present climate trend maps for critical indicators of upper montane climatic variability, such as the freezing level surface (FLS), and a plant growth threshold surface (taken here as the height of the 6.5 °C surface; Koerner and Paulsen, 2004), and discuss some of the hydrological and ecological implications of such changes.

Large-Scale Context of Climatic Changes in the Past 60 Years

In this section we examine changes in selected climate variables that are considered major drivers of hydrological and ecological changes in mountain regions. Figure 1 shows the time-latitude diagram (or Hovmöller diagram) based on the "Microwave Sounding Unit Temperature of the Lower Troposphere" (MSU TLT) data set (which provides a weighted average temperature for the troposphere below ~400 mb level or ~7000 m) (data available from Remote Sensing Systems, Inc.: http://www.ssmi.com/msu/msu_data_description.html; see Mears and Wentz, 2009). The data cover the period from January 1979 to February 2012, and they were averaged by latitude band for each month of record. This temperature record exhibits variability on several time scales, which in the tropics is principally associated with El Niño–Southern Oscillation (ENSO), and sustained cooling after the Pinatubo volcanic eruption in 1991. Also evident is a secular warming trend that is particularly pronounced in extra-tropical latitudes.

The freezing level height (FLH) in the atmosphere is an important geophysical threshold, potentially affecting a range of hydrological and ecological processes. Figure 2 shows the distribution of mean free air temperature in the atmosphere (1973–2002) based on NCEP reanalysis data. The freezing level height occurs at ~4500 m throughout the tropical belt. A study

1523-0430/4 $7.00

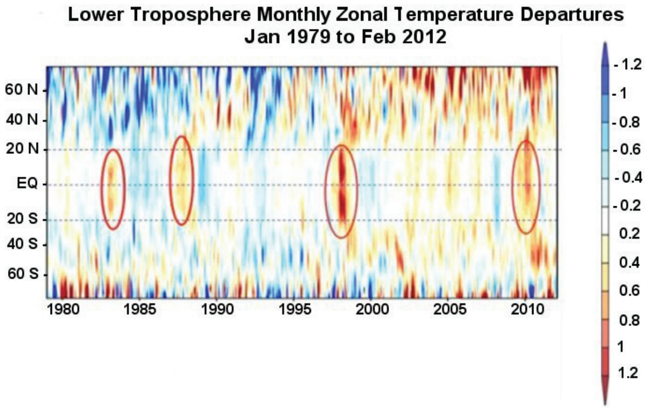

FIGURE 1. Time versus latitude monthly mean temperature for the lower troposphere (below ~7 km) from MSU data, expressed as deviations from the (1979–2012) mean (in °C). Tropical temperatures are strongly modulated by the El Niño–Southern Oscillation (ENSO). Also evident is a secular warming trend and sustained cooling after the Pinatubo volcanic eruption in 1991.

of FLH changes along the American Cordillera by Diaz et al. (2003b; cf. their fig. 2), examined upper air data from 1948 to 2000. In this region of the tropics, FLH increased by ~73 m (1.43 m yr^{-1}), over the period, with a slightly lower rate of increase from 1958 to 2000 (~53 m, 1.17 m yr^{-1}), the difference due possibly to a prolonged period of cool tropical Pacific sea surface temperature (SST), or perhaps due to biases in the early years of the Reanalysis product, or both. Interestingly, in a recently published paper that looked at millennial-scale changes in upper treeline in high mountain ridges in the Great Basin of the western United States, changes in the mean position of the treeline scaled to ~60 m shifts per degree Celsius change in mean annual temperature (Salzer et al., 2013).

Bradley et al. (2009) expanded the earlier analysis of Diaz et al. (2003b) to cover the tropics as a whole (28.75°N–28.75°S, for 1977–2007) finding a general increase in the elevation of the FLH surface across the region, but with the largest zonally averaged increases poleward of the equatorial zone (Fig. 3). FLH increases across the entire tropics were closely related to the pattern of tropical SST changes (*r* = 0.83) (see also Diaz et al., 2003). In the American Tropics, FLH is strongly modulated by the phase of ENSO, with FLH (averaged over 20°N–20°S) rising by 73 m for a 1 °C increase in SSTs in the Niño 3 region of the eastern Equatorial Pacific (90°W–150°W and 5°S–5°N). As SSTs continue to increase in the future, FLH will certainly rise further, but there is as yet no consensus in model simulations on the future nature of ENSO variability.

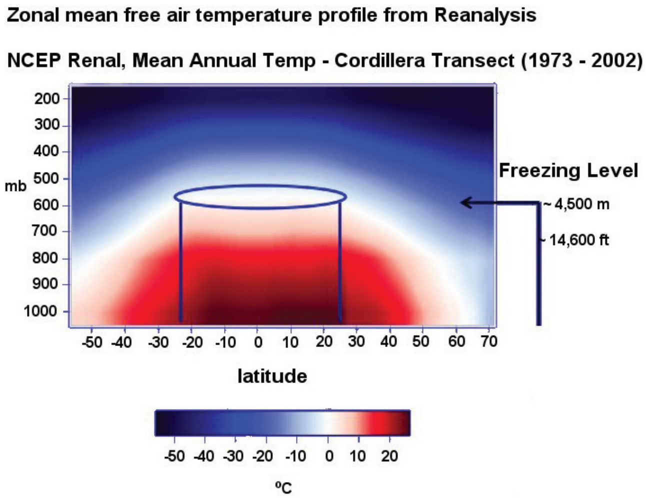

FIGURE 2. The distribution of mean free air temperature (°C) in the atmosphere (1973–2002) based on NCEP reanalysis. Freezing level height occurs at ~4500 m in the tropical belt.

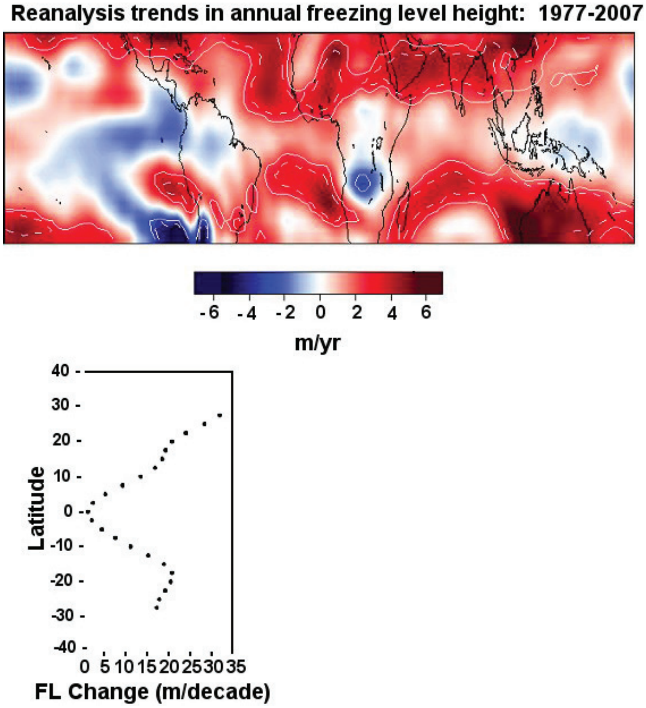

FIGURE 3. Changes in tropical freezing level heights for the period 1977–2007 (top panel) and profile of zonally averaged values (bottom panel). After Bradley et al. (2009).

Over the past 100 years, global surface temperature has increased by ~0.8 °C, more than half of it occurring in the past 40 years (Hansen et al., 2010). Based on NCEP reanalysis data (Kistler et al., 2001) the tropical free air temperature has increased by ~0.5 °C over the past four decades at both the 700 mb level (~10,000 ft 3 km^{-1}) and at the 400 mb level (~23,000ft 7 km^{-1}). In both instances, there is considerable spatial variability, with some regions in the vicinity of the tropical warm pools exhibiting warming that exceeds 0.8 °C.

Koerner and Paulsen (2004) and Koerner et al. (2011) have argued for a thermally controlled upper treeline boundary associated with a surface mean annual temperature of about 6.5 °C. Figure 4 shows zonally averaged changes in the elevation of this surface in the free air, displayed in a manner analogous to Figure 1. A rise of ~200 m in the past 60 years is evident, equivalent to a warming of ~1.3 °C at the elevation of this surface in the tropics (~3500–3600 m). Much of the evidence regarding elevational changes in temperature has been drawn from free air radiosonde measurements, which do not provide a direct measure of changes at the ground surface. Nevertheless, in our studies of isolated mountain peaks that extend far above the surrounding topography, we have found that surface

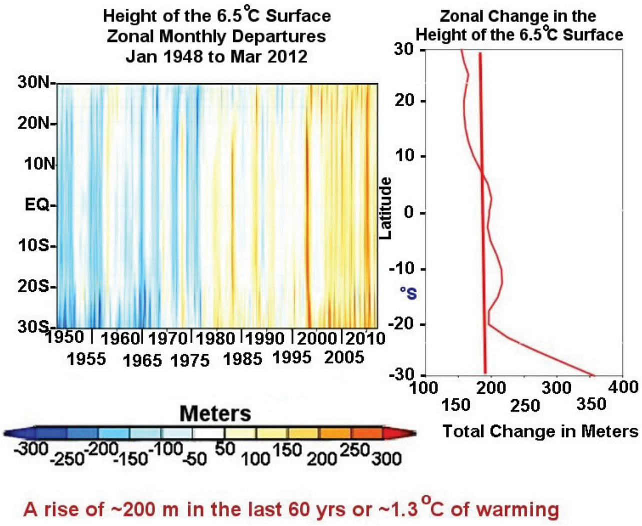

FIGURE 4. Time longitude changes in the height (m) of the mean annual 6.5 °C surface (left panel) and the zonal profile of the total change over the 1950 to 2011 period (right panel).

temperatures do closely track those in the free air (cf. Bradley et al., 2009, their fig. 3). We therefore argue that trends in FLH and for other temperature levels are applicable to conditions experienced on the highest mountain peaks, especially in remote island locations. Furthermore, with a rise in FLH, additional factors such as a decrease in the fraction of precipitation falling as snow (and more as rain) and associated decreases in albedo and increases in absorbed solar radiation will reinforce the ecological effects of higher free air temperatures.

Regional Climate Changes

THE AMERICAN CORDILLERA

The western cordillera of the Americas forms a unique transect that intersects the major features of the global atmospheric circulation and flanks the world's largest ocean. The climate of the Americas—and the western Cordillera in particular—is changing, and the impacts of those changes are rapidly emerging in the form of modified streamflow patterns, plant phenology, terrestrial and aquatic ecosystem structure, wildfire regimes, and many other phenomena (IPCC, 2007a, 2007b). The mountain regions that stretch from Alaska to southern Argentina and Chile, home to nearly 200 million people, are especially vulnerable to changes in climate and to the ensuing changes in snowpack, streamflow, and ecosystem functioning that support these societies (Bradley et al., 2009; Diaz et al., 2003b; Vuille et al., 2003, 2008).

Temperatures have been rising in all of the world's mountain zones over recent decades (Fig. 5). Accelerated warming at higher elevations of the western United States, and mountain regions farther south, has been documented by a number of investigators. Temperature changes for the past few decades in the Rocky Mountain region are greater than for the rest of the contiguous United States, and the warming has been greatest at high elevations (Figs. 6 and 7) (Hoerling et al., 2007). In the tropical Andes, warming has also accelerated in the past 30 years (Fig. 8). Subsidiary effects include changes in phenology (Inouye et al., 2000; Cayan et al., 2001;

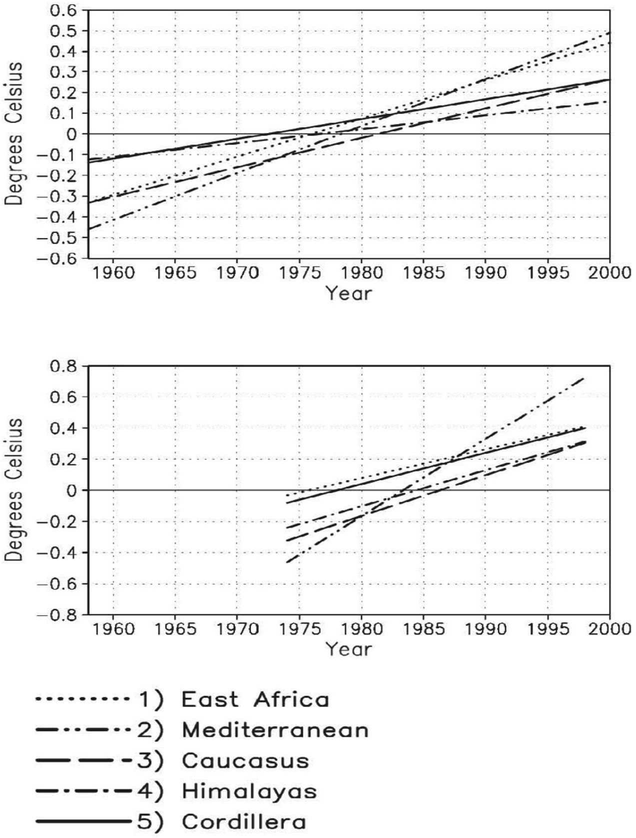

FIGURE 5. Linear trends in near-surface air temperature (°C) for five different mountainous regions, based on the NCEP/NCAR reanalysis data set. Top panel is for 1958–2000, lower panel for the period 1974–1998. Source: Diaz et al. (2003b).

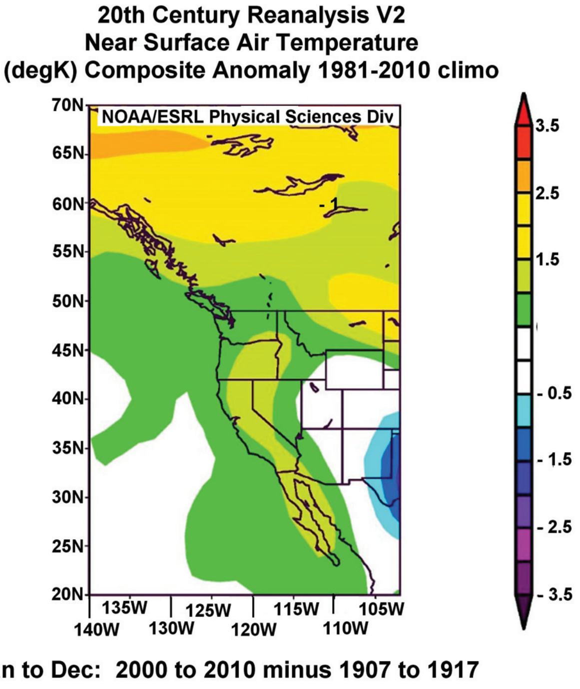

FIGURE 6. Near-surface mean annual temperature change (°C). Map shows 2000–2010 minus 1907–1917. Notice much greater warming in the mountainous western U.S.A. Source: NOAA Earth System Research Laboratory, 20th century reanalysis.

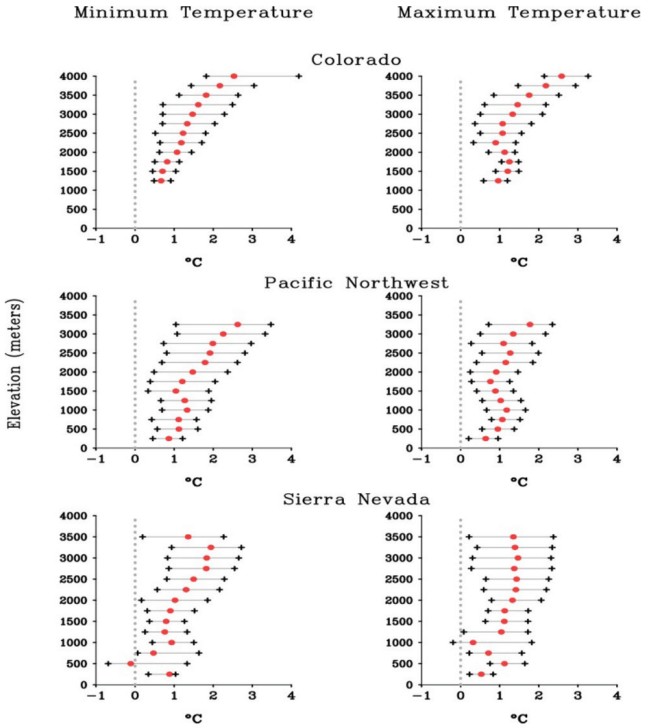

FIGURE 7. Distribution of annual mean minimum and maximum temperature trends in °C, expressed as total trend for the period 1979–2006, calculated and plotted in successive 250-meter intervals. The median of the distribution of linear trends is plotted along with the approximate 5 and 95% cumulative distribution values (small crosses). From Diaz and Eischeid (2007).

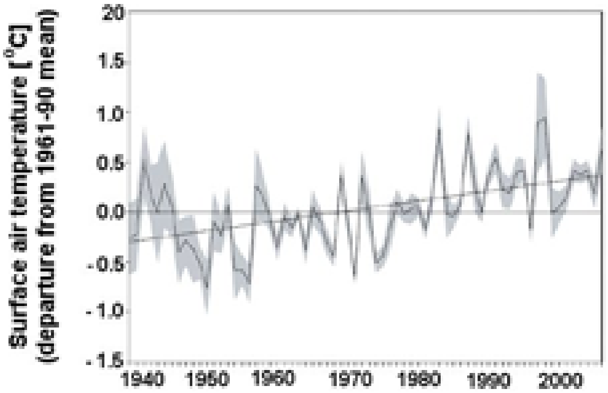

FIGURE 8. Annual temperature anomalies 1939–2006, relative to 1961–1990 averages in the tropical Andes (1°N–23°S) with ±2 S.E. Time series based on records from 279 stations. The increase in temperature in the Cordillera is ~0.1 °C/decade. Source: Vuille et al. 2008.

Westerling et al., 2006; Salzer et al., 2009), glaciology and hydrology (Barnett et al., 2004, 2008; Kaser et al., 2004; Coudrain et al., 2005; Juen et al., 2007; Knowles et al., 2006; Mote et al., 2005; Regonda et al., 2005; Stewart et al., 2005; Pierce et al., 2008), and ecosystem changes (Pounds et al., 2006; Breshears et al., 2005, 2008; Diaz and Eischeid, 2007; Buytaert et al., 2011).

Figure 9 shows projected 100-year temperature changes from the surface to ~9 km height along a meridional transect along the American Cordillera with doubled levels of CO_2, based on 10 general circulation model simulations of future climate from the IPCC Fifth Assessment Report. Projections are shown for annual, winter, and summer temperature in the respective hemispheres under the RCP4.5 concentration trajectory scenario. The results are consistent with previous results reported by Bradley et al. (2004, 2006) using an earlier suite of general circulation models (GCMs)—namely a future with greater total warming with increasing elevation. Figure 10 presents a comparison of the latitudinal profile of annual and respective winter and summer FLH change from the historical and RCP4.5 climate model simulations. A significant rise in the FLS is evident, particularly in tropical latitudes.

Other studies using higher resolution regional climate simulations for the northern Andes and the Central America portion of the Cordillera (see Urrutia and Vuille, 2009; Karmalkar et al., 2011; Rauscher et al., 2008) all indicate that warming will be amplified with height, reaching up to +4 °C at the highest mountain elevations, by the end of this century. Such a large warming will have tremendous impacts on natural and human systems, as discussed in a number of studies (inter alia, Inouye et al., 2000; Cayan et al., 2001; Barnett et al., 2005, 2008; Coudrain et al., 2005; Mote et al., 2005; Stewart et al., 2005; Regonda et al., 2005; Bradley et al., 2006, 2009; Diaz et al., 2006; Pounds et al., 2006; Westerling et al., 2006; Baker and Mosely, 2007; IPCC, 2007b; Diaz and Eischeid, 2007; Giambelluca et al., 2008).

Figure 11 illustrates how restraining the future growth of greenhouse gases in the atmosphere will have a significant impact on the total future temperature changes as indicated by the different rises of the FLH in the two simulations, with RCP4.5 and RCP8.5 scenarios (van Vuuren et al., 2011)—a difference on the order of ~400 m between the high and low GHG concentration scenarios. This large difference indicates that the higher concentration pathway would have a much greater impact on water resources and ecosystem health in the Americas.

MOUNTAINS IN TROPICAL ISLANDS

ENSO variability occurring on a time scale of ~3–7 years, and its low frequency tropical mode (with ~10–30 year time scale, nominally referred to as the Pacific Decadal Oscillation, PDO), dominates climatic variability in the tropics and in large parts of the temperate regions as well. Decadal climate variability will modulate and at times may interfere with the secular warming trend associated with anthropogenic climate change (Bonfils and Santer, 2011). As illustrated in Figure 1, the amplitude of warming in the middle troposphere associated with extreme ENSO phases is of the order of ~4 °C, and longer-term changes in the background SST field in the tropical Pacific also have significant impacts on FLH throughout the tropics, affecting mountainous tropical islands such as those in the Hawaiian archipelago (Giambelluca et al., 2008; Diaz et al., 2011).

Observed changes in the climate of Hawai‘i are generally consistent with expectations from climate change projections (IPCC, 2007a). Results from these studies indicate a significant warming trend over the past 80 years, but they also point to an amplification of the warming signal at higher elevations. Indicators of enhanced upper elevation warming include a reduction in the frequency of occurrence of freezing temperatures on the upper slopes of the higher terrain (which exceeds 13,000 ft per 4000 m in Maui and the Big Island) and

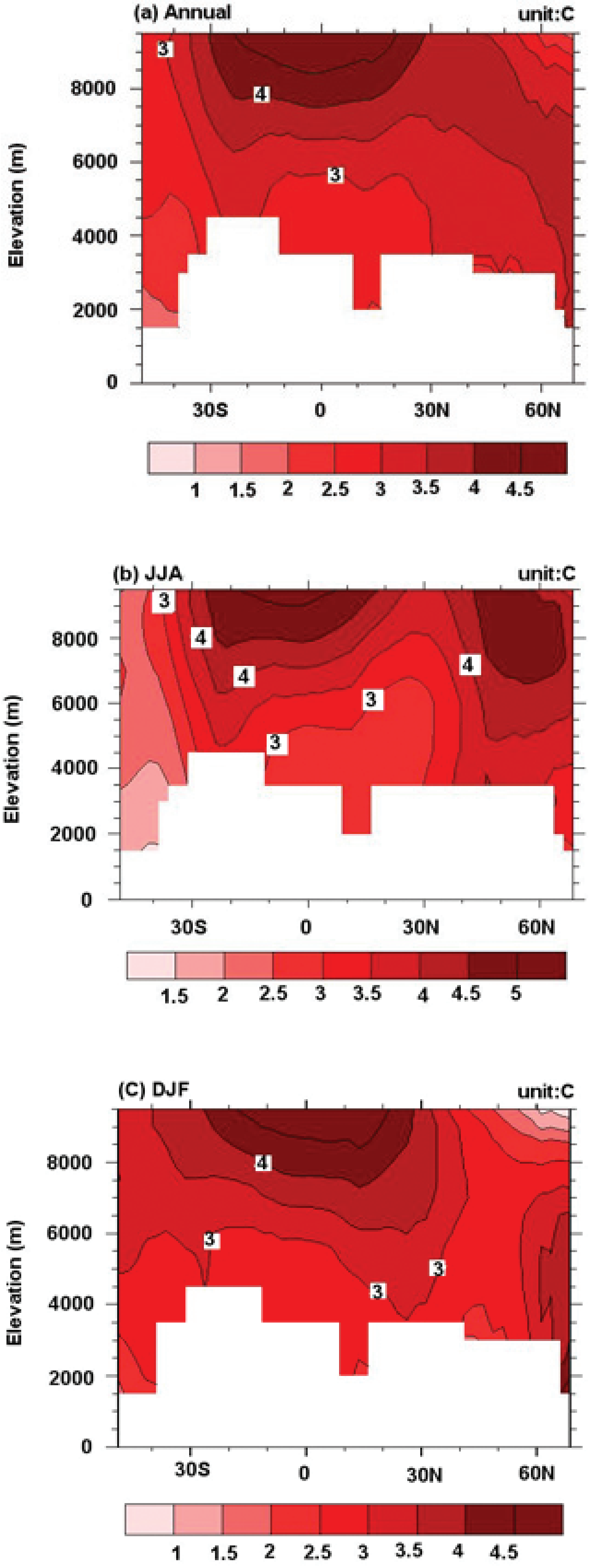

FIGURE 9. **The mean change in temperature for the 10 GCMs for (a) annual, (b) boreal summer, and (c) boreal winter under the RCP4.5 scenario. Differences are calculated for the period 2081–2100 minus 1981–2000.**

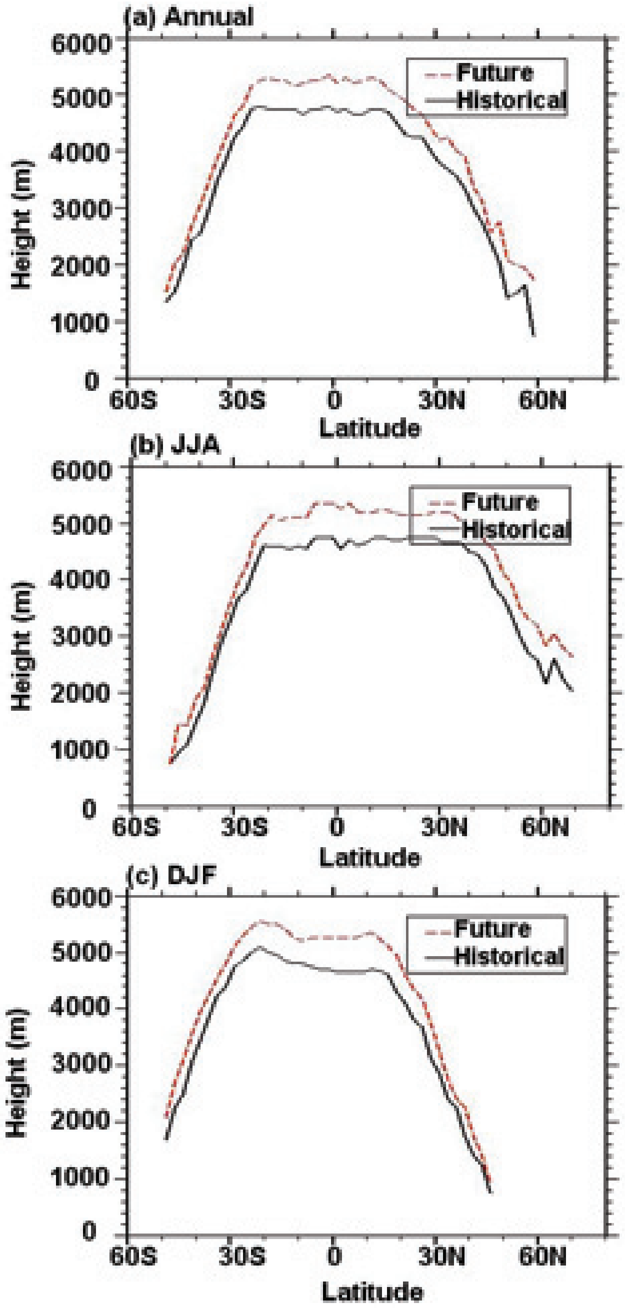

FIGURE 10. **The historical (solid curve) and future (dashed curve) freezing elevations on (a) annual, (b) boreal summer, and (c) boreal winter. Differences are calculated for the period 2081–2100 minus 1981–2000.**

a concomitant rise in the FLS in the region. These findings are in good agreement with analogous studies done for other mountainous areas of the world.

The foregoing discussion illustrates that these altitudinal-dependent climate changes comprise a broad geographical context, as can be seen from Figure 12, which compares changes in the FLH above Hawai‘i to changes in free air temperature at 500 mb along the northern Andes. The warming in the middle troposphere amounts to ~1.6 °C decade^{-1} in both cases. A vertical profile of temperature and humidity changes is presented in Figure 13 (Diaz et al., 2011) and shows both warming and drying for the past

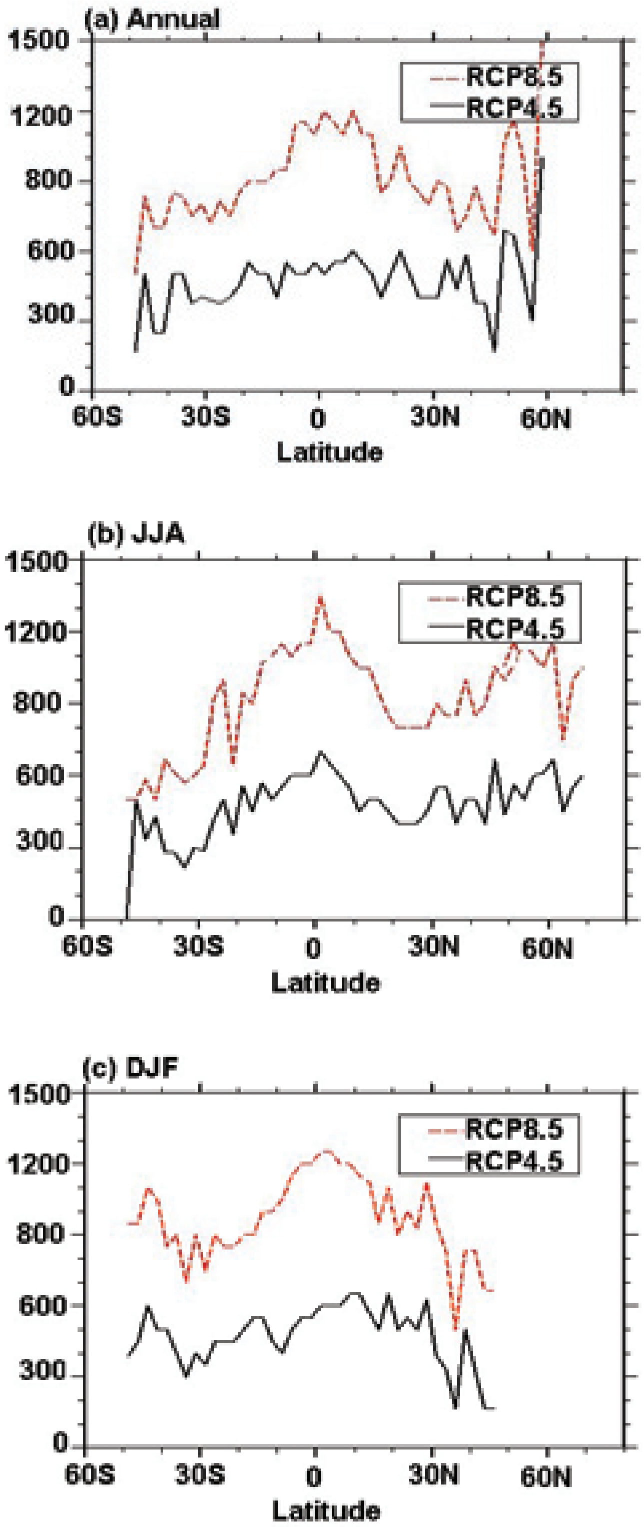

FIGURE 11. The differences between historical and future freezing elevations on (a) annual, (b) boreal summer, and (c) boreal winter under the RCP4.5 (solid curves) and RCP8.5 (dashed curves) scenarios. Differences are calculated for the period 2081–2100 minus 1981–2000.

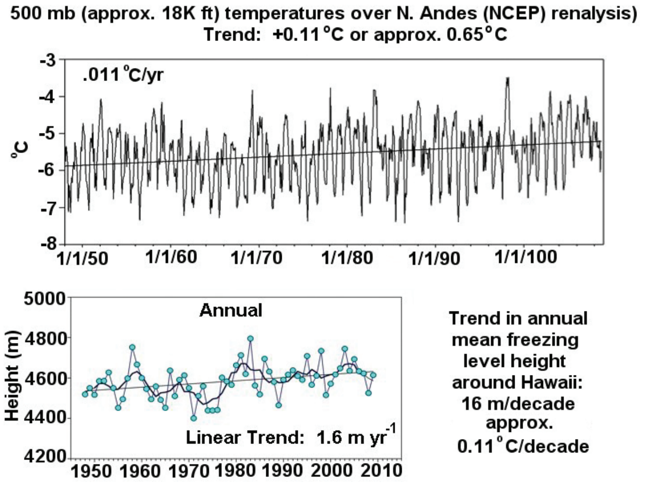

FIGURE 12. Comparison of (top panel) 500 mb air temperature for the northern Andes (cf. Fig. 8), and (bottom panel) the rise in freezing level height in Hawai‘i. Temperature changes in both regions at approximately equal altitudes are very similar. Bottom panel is taken from Diaz et al. (2011).

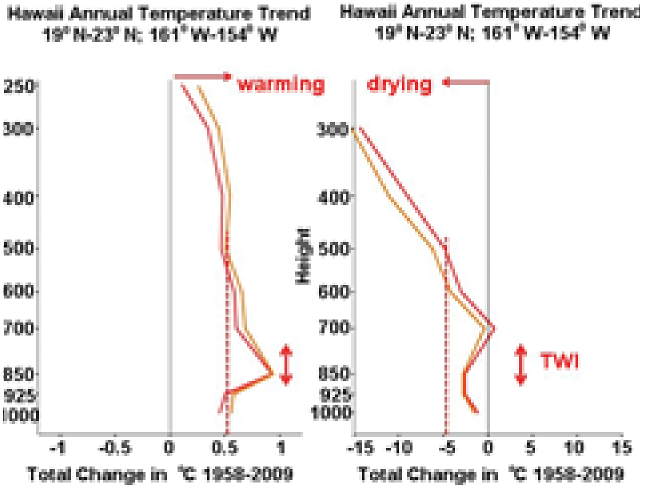

FIGURE 13. Vertical profile of mean annual temperature and relative humidity changes in Hawai‘i for selected pressure levels. Shown is the 1958–2009 total linear trend in (left panel) mean annual temperature and (right panel) relative humidity. TWI = trade wind inversion. Values were calculated in two ways: one using the time series of annual values at each level (red curves), and the other using pentad averages to smooth the variability and extract a more robust estimate (orange curves). Data from NCEP reanalysis. Source: Diaz et al. (2011).

few decades, with maximum warming in the region of the local trade wind inversion layer (TWI). Table 1 gives warming rates for Hawai‘i and individual islands for different time periods and elevation ranges. Warming is greatest in the most recent decades and for the highest elevations in the islands.

Discussion and Concluding Remarks

Global climate models used in the latest IPCC Assessments project a late 21st-century global surface temperature increase of ~3.5 °C. Warmer oceans will lead to an enhanced hydrologic cycle, an increase of latent heat input to the atmosphere, and hence

TABLE 1

Linear air temperature trends for elevation ranges in the Hawaiian islands, by individual island and for the whole state, for periods of 88 (1920–2007), 50 (1958–2007), and 30 years (1978–2007).

		Statewide by Elevation Range			Statewide by Island				
Trends (°C decade^{-1})	Period	Low (<350m)	Middle (350–1500m)	High (>1500m)	Ha	Ma	Oa	Ka	State
88-year	1920–2007	0.073	0.093	0.078	0.034	0.049	0.043	0.058	0.046
50-year	1958–2007	0.148	0.135	0.329	0.114	0.091	0.078	0.056	0.085
30-year	1978–2007	0.046	0.048	0.339	–0.014	0.056	0.113	0.018	0.043

greater warming with elevation (Ohmura, 2012). The study by Ohmura (2012) evaluated long-term surface temperature records for multiple sets of station records using high and low elevation pairs to assess differences in trends. The author found that in about 60% of the areas analyzed there was a significant amplification of recent warming trends at the higher elevations. A similar large-scale comparison of surface temperature trends for stations at different elevations around the globe (Wang et al., 2013) also indicates greater warming trends at higher elevations compared to lower elevation sites.

Some important atmospheric surfaces, such as the freezing level height and an approximate minimum growth temperature threshold for tree growth, exhibit large upward shifts in the past half-century. A rise of ~200 m in the 6.5 °C surface, assuming a typical vertical temperature lapse rate of ~6.5 °C km^{-1} translates to an approximate warming at the nominal altitude of this surface of ~1.3 °C. Ecosystem changes are already occurring in many regions and are having a significant impact on tree stand mortality, and fire occurrence and intensity (Westerling et al., 2006; Allen et al., 2010; Williams et al., 2013).

Global warming and other anthropogenic effects will have far-reaching consequences for the mountain environments of the Americas (e.g., Barnett et al., 2005; Bradley et al., 2006; Urrutia and Vuille, 2009). There are many daunting challenges that confront mountainous regions, many of which have been reported in a number of studies over the past few decades. Among the greatest of these is maintaining a sustainable water supply in the face of a growing population, during a period of increasingly variable and changing climate (Huber et al., 2005; Diffenbaugh et al., 2013). In the western American Cordillera, a consensus has been reached among a diverse group of researchers and resource managers that climate change will seriously alter the mountain snowpack—the principal source of precious water—and with it, ecosystem function, landscape integrity, and concomitant socioeconomic activity in the region (Diaz et al., 2006; Bradley et al., 2006; Rosenzweig et al., 2007). Other studies have found similar impacts emerging in other countries of the Western Hemisphere (Coudrain et al., 2005; Juen et al., 2007; Vuille et al., 2008; Ruiz et al., 2012).

The high spatial heterogeneity of mountain climates and environments, and the sparsity of on-the-ground measurements, challenges our ability to document current rates of change, and to model the specific changes that can be expected under future climate scenarios. As societal pressures on mountain ecosystems increase, planning for sustainable development in these regions, as well as downstream areas, which depend on them, requires more detailed scenarios of future climate changes (with high spatial resolution) in order to make realistic assessments of their environmental consequences. Changes in the alpine cryosphere are already clearly visible and represent some of the earliest signs of large-scale climate change. A reduction in the area covered by snow and ice not only serves as an indicator of change but also provides powerful feedbacks through changes in albedo. In addition, melting of permafrost destabilizes slopes in areas of high relief, leading to landslides, rockfalls and other climate-related geomorphic hazards, such as the formation of unstable proglacial lakes, which may lead to potentially catastrophic flooding (Milly et al., 2002) and other significant hazards in many places (Allamano et al., 2009), as has already occurred in the tropical Andes (Bradley et al., 2006; Vuille et al., 2008).

Changes in hydrological variability, precipitation, and snow cover impact a broad range of socioeconomic sectors, including hydropower generation (Barnett et al., 2004), ecosystem health (Breshears et al., 2005, 2008; Williams et al., 2013), water resources for irrigation and civil supply (Messerli et al., 2004; Coudrain et al., 2005; Knowles et al., 2006; Milly et al., 2008; Wi et al., 2012), and tourism-related industries (Bradley et al., 2006; Rosenzweig et al., 2007; Orlove et al., 2008). Decision-makers in these different sectors need more accurate data on current and future conditions in the high mountains for effective resource management planning. This requires more investment in environmental monitoring within high mountain regions, and further research on future climate scenarios using regional climate models that can be linked to glaciological, hydrological, and ecological models (Diaz et al., 2006).

References Cited

Allamano, P., Claps, P., and Laio, F., 2009: Global warming increases flood risk in mountainous areas. *Geophysical Research Letters*, 36: L24404, doi: http://dx.doi.org/10.1029/2009GL041395.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., and Cobb, N., 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259: 660–684.

Baker, B. B., and Mosely, R. K. 2007: Advancing treeline and retreating glaciers: implications for conservation in Yunnan, P.R. China. *Arctic, Antarctic, and Alpine Research,* 39: 200–209.

Barnett, T. Malone, R., Pennell, W., Stammer, D., Semtner, B., and Washington, W., 2004: The effects of climate change on water resources in the West: Introduction and overview. *Climatic Change* 62: 1–11.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P., 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438: 303–309.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., Bala, G., Wood, A. W., Nozawa, T., Mirin, A. A., Cayan, D. R., and Dettinger, M. D., 2008: Human-induced changes in the hydrology of the western United States. *Science*, 319: 1080–1083, doi: http://dx.doi.org/10.1126/science.1152538.

Beniston, M. (ed.), 1994: *Mountain Environments in Changing Climates*. London: Routledge, 461 pp.

Beniston, M., Diaz, H. F., and Bradley, R. S., 1997: Climatic change at high elevation sites: an overview. *Climatic Change*, 36: 233–251.

Bonfils, C., Santer, B. D., 2011: Investigating the possibility of a human component in various Pacific decadal oscillation indices. *Climate Dynamics*, 37: 1457–1468.

Bradley, R. S., Keimig, F. T., and Diaz, H. F., 2004: Projected temperature changes along the American Cordillera and the planned GCOS Network. *Geophysical Research Letters,* 31: doi: http://dx.doi.org/10.1029/2004GL020229.

Bradley, R. S., Vuille, M., Diaz, H. F., and Vergara, W., 2006: Threats to water supply in the tropical Andes. *Science*, 312: 1755–1756.

Bradley, R. S., Keimig, F. T., Diaz, H. F., and Hardy, D. R., 2009: Recent changes in freezing level heights in the tropics with implications for the deglacierization of high mountain regions. *Geophysical Research Letters,* 36: L17701, doi: http://dx.doi.org/10.1029/2009GL037712.

Breshears, D. D., Cobb, N. S., Rich, P. M., Price, K. P., Allen, C. D., Balice, R. G., Romme, W. H., Kastens, J. H., Floyd, M. L., Belnap, J., Anderson, J. J., Myers, O. B., and Meyer, C. W., 2005: Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the USA,* 102: 15144–15148.

Breshears, D. D., Huxman, T. E., Adams, H. D., Zou, C. B., and Davison, J. E., 2008: Vegetation synchronously leans upslope as climate warms. *Proceedings of the National Academy of Sciences of the USA,* 105: 11591–11592.

Buytaert, W., Cuesta-Camacho, F., and Tobón, C., 2011: Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Global Ecology and Biogeography*, 20: 19–33.

Cayan, D. R., Kammerdiener, S., Dettinger, M. D., Caprio, J. M., and Peterson, D. H., 2001: Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society,* 82: 399–415.

Coudrain, A., Francou, B., and Kundewicz, Z. W., 2005: Glacier shrinkage in the Andes and consequences for water resources. *Hydrological Sciences Journal*, 50: 925–932.

Decker, A., and Bugmann, H. K. (eds.), 1999: *Global Change and Mountain Regions.* Stockholm: International Geosphere-Biosphere Program, Report 49, 85 pp.

Diaz, H. F., and Bradley, R. S., 1997: Temperature variations during the last century at high elevation sites. *Climatic Change*, 36: 253–279.

Diaz, H. F., and Graham, N. E., 1996: Recent changes in tropical freezing heights and the role of sea surface temperature. *Nature*, 383: 152–155.

Diaz, H. F., and Eischeid, J. K., 2007: Disappearing "Alpine Tundra" Köppen climatic type in the western United States. *Geophysical Research Letters*, 34: L18707, doi: http://dx.doi.org/10.1029/2007GL031253.

Diaz, H. F., Grosjean, M., and Graumlich, L., 2003a: Climate variability and change in high elevation regions: past, present and future. *Climatic Change*, 59: 1–4.

Diaz, H. F., Eischeid, J. K., Duncan, C., and Bradley, R. S., 2003b: Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years. *Climatic Change*, 59: 33–52.

Diaz, H. F., Villalba, R., Greenwood, G., and Bradley, R. S., 2006: The impact of climate change in the American Cordillera. *Eos*, 87(32): 315.

Diaz, H. F., Giambelluca, T. W., and Eischeid, J. K., 2011: Changes in the vertical profiles of mean temperature and humidity in the Hawaiian Islands. *Global & Planetary Change*, 77: 21–25.

Diffenbaugh, N. S., Scherer, M., and Ashfaq, M., 2013: Response of snow-dependent hydrologic extremes to continued global warming. *Nature Climate Change*, 3: 379–384.

Giambelluca, T. W., Diaz, H. F., and Luke, M. S. A., 2008: Secular temperature changes in Hawai'i. *Geophysical Research Letters*, 35: L12702, doi: http://dx.doi.org/10.1029/2008GL034377.

Hansen, J., Ruedy, R., Sato, M., and Lo, K., 2010: Global surface temperature change. *Reviews of Geophysics*, 48: RG4004, doi: http://dx.doi.org/10.1029/2010RG000345.

Hoerling, M., Eischeid, J., Quan, X., and Xu, T., 2007: Explaining the record US warmth of 2006. *Geophysical Research Letters*, 34: L17704, doi: http://dx.doi.org/10.1029/2007GL030643.

Huber, U., Reasoner, M., and Bugmann, H. (eds.), 2005: *Global Change and Mountain Regions, A State of Knowledge Overview*. Dordrecht: Kluwer Academic Publishers, 652 pp.

Inouye, D. W., Barr, B., Armitage, K. B., and Inouye, B. D., 2000: Climate change is affecting altitudinal migrants and hibernating species. Proceedings of the National Academy of Sciences, 97: 1630–1633.

IPCC, 2007a: *Climate Change 2007—The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*. Cambridge, U.K: Cambridge University Press, 996 pp.

IPCC, 2007b: North America. *In Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the IPCC.* Cambridge, UK: Cambridge University Press, 976 pp.

Juen, I., Kaser, G., and Georges, C., 2007: Modeling, observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú). *Global and Planetary Change,* 59: 37–48.

Karmalkar, A. V., Bradley, R. S., and Diaz, H. F., 2008: Climate change scenario for Costa Rican montane forests. *Geophysical Research Letters*, 35: L11702, http://dx.doi.org/doi:10.1029/2008GL033940.

Karmalkar, A. V., Bradley, R. S., and Diaz, H. F., 2011: Climate change in Central America and Mexico: regional climate model validation and climate change projections. *Climate Dynamics*, 37: 605–629, doi: http://dx.doi.org/10.1007/s00382-011-1099-9.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., van den Dool, H., Jenne, R., and Fiorino, M., 2001: The NCEP/NCAR 50-year reanalysis: monthly means, CD-ROM and documentation. *Bulletin of the American Meteorological Society,* 82: 152–168.

Knowles, N., Dettinger, M., and Cayan D. 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, 19: 4545–4559.

Koerner, C., and Paulsen, J., 2004: A world-wide study of high altitude treeline temperatures. *Journal of Biogeography*, 31: 713–732.

Koerner, C., Paulsen, J., and Spehn, E. M., 2011: A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. *Alpine Botany*, 121: 73–78.

Liu, X., Cheng, Z., Yan, L., and Yin, Z., 2009: Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. *Global and Planetary Change*, 68: 164–174.

Mears, C. A., and Wentz, F. J., 2009: Construction of the RSS V3.2 lower-tropospheric temperature dataset from the MSU and AMSU microwave sounders. *Journal of Atmospheric and Oceanic Technology*, 26: 1493–1509, doi: http://dx.doi.org/10.1175/2009JTECHA1237.1.

Messerli, B., and Ives, J. D. (eds.), 1997: *Mountains of the World: A Global Priority*. New York: Parthenon Publishing Group, 495 pp.

Messerli, B., Viviroli, D., and Weingartner, R., 2004: Mountains of the world: vulnerable water towers for the 21st century. *Ambio*, Special Report No. 13: 29–34, http://www.jstor.org/stable/25094585.

Milly, P., Wetherald, R., Dunne, K., and Delworth, T., 2002: Increasing risk of great floods in a changing climate. *Nature*, 415: 514–517.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., Lettenmaier, D., and Stouffer, R., 2008: Stationarity is dead—whither water management? *Science*, 319: 573–574, doi: http://dx.doi.org/10.1126/science.1151915.

Mote, P. W., Hamlet, A. F., Clark, M. P., and Lettenmaier, D. P., 2005: Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society*, 86: 39–49.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J., 2000: Biodiversity hotspots for conservation priorities. *Nature,* 403: 853–858.

Nogués-Bravo, D., Araújo, M. B., Errea, M. P., and Martínez-Rica, J. P., 2007: Exposure of global mountain systems to climate warming during the 21st Century. *Global Environmental Change*, 17: 420–428.

O'Gorman, P. A., and Singh, M. S., 2013: Vertical structure of warming consistent with an upward shift in the middle and upper troposphere. *Geophysical Research Letters*, 40: 1838–1842, doi: http://dx.doi.org/10.1002/grl.50328.

Ohmura, A., 2012: Enhanced temperature variability in high-altitude climate change. *Theoretical and Applied Climatology*, 110: 499–508.

Orlove, B., Wiegandt, E., and Luckman, B. H., (eds.), 2008: *Darkening Peaks: Glacial Retreat, Science and Society.* Berkeley: University of California Press, 282 pp.

Pepin, N. C., and Lundquist, J. D., 2008: Temperature trends at high elevations: Patterns across the globe. *Geophysical Research Letters*, 35: L14701, doi: http://dx.doi.org/10.1029/2008GL034026.

Pepin, N. C., and Norris, J. R., 2005: An examination of the differences between surface and free-air temperature trend at high-elevation sites: Relationships with cloud cover, snow cover, and wind. *Journal of Geophysical Research*, 110: D24112, doi: http://dx.doi.org/10.1029/2005JD006150.

Pierce, D. W., Barnett, T. P., Hidalgo, H. G., Das, T., Bonfils, C., Santer, B. D., Bala, G., Dettinger, M. D., Cayan, D. R., Mirin, A., Wood, A. W., and Nozawa, T., 2008: Attribution of declining western U.S. snowpack to human effects. *Journal of Climate*, 21: 6425–6444.

Pounds, J. A., Bustamante, M. R., Coloma, L. A., Consuegra, J. A., Fogden, M. P. L., Foster, P. N., La Marca, E., Masters, K. L., Merino-Viteri, A., Puschendorf, R., Ron, S. R., Sanchez-Azofeifa, G. A., Still, C. J., and Young, B. E., 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, 439: 161–167.

Rangwalla, I., and Miller, J. R., 2012: Climate change in mountains: a review of elevation-dependent warming and its possible causes. *Climate Change*, 114: 527–547.

Rauscher, S. A., Giorgi, F., Diffenbaugh, N. S., and Seth, A., 2008: Extension and intensification of the Meso-American mid-summer drought in the twenty-first century. *Climate Dynamics*, 31: 551–571.

Regonda, S., Rajagopalan, B., Clark, M., and Pitlick, J., 2005: Seasonal climate shifts in hydroclimatology over the western United States. *Journal of Climate*, 18: 377–384.

Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T. L., Seguin, B., and Tryjanowski, P., 2007: Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, U.K.: Cambridge University Press, 79–131.

Ruiz, D., Martinson, D. G., and Vergara, W., 2012: Trends, stability and stress in the Colombian Central Andes. *Climatic Change*, 112: 717–732.

Salzer, M. W., Hughes, M. K., Bunn, A. G., and Kipfmueller, K. F., 2009: Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proceedings of the National Academy of Sciences*, 106: 20348–20353.

Salzer, M. W., Bunn, A. G., Graham, N. E., and Hughes, M. K., 2013: Five millennia of paleotemperature from tree-rings in the Great Basin, USA. *Climate Dynamics*, doi: http://dx.doi.org/10.1007/s00382-013-1911-9.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., and Beniston, M., 2012: Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, 2: 725–731.

Stewart, I. T., Cayan, D. R., and Dettinger, M. D., 2005: Changes towards earlier streamflow timing across western North America. *Journal of Climate*, 18: 1136–1155.

Urrutia, R., and Vuille, M., 2009: Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century. *Journal of Geophysical Research,* 114: D02108, doi: http://dx.doi.org/10.1029/2008JD011021.

Van Vuuren, D. P., Edmonds, J., Kaimnuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K., 2011: The representative concentration pathways: an overview. *Climate Change*, 109: 5–31.

Vuille, M., Bradley, R. S., Werner, M., and Keimig, F. T., 2003: 20th century trends in climate in the tropical Andes. *Climatic Change*, 59: 137–155.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., and Bradley, R. S., 2008: Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, 89: 79–96.

Wang, Q., Fan, X., and Wang, M., 2014: Recent warming amplification over high elevation regions across the globe. *Climate Dynamics*, 43: 87–101, doi: http://dx.doi.org/10.1007/s00382-013-1889-3.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W., 2006: Warming and earlier spring increase in U.S. forest wildfire activity. *Science*, 313: 940–943.

Wi, S., Dominguez, F., Durcik, M., Valdes, J., Diaz, H. F., and Castro, C. L., 2012: Climate change projections of snowfall in the Colorado River Basin using dynamical downscaling. *Water Resources Research.,* 48: W05504, doi: http://dx.doi.org/10.1029/2011WR010674.

Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., Swetnam, T. W., Rauscher, S. A., Seager, R., Grissino-Mayer, H. D., Dean, J. S., Cook, E. R., Gangodagamage, C., Cai, M., and McDowell, N. G., 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3: 292–297.

MS accepted February 2014