Recent warming at the tropical treeline of North America

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Tropical treelines are critical zones for observing and understanding regional responses to climatic change (Diaz *et al*. 2003), especially because the low latitudes play a prominent role in the global climate system (Hoerling and Kumar 2003), and mountain areas regulate downstream availability of water resources (Bradley *et al*. 2004). In North America, tropical treelines are also part of the North American Monsoon System (NAMS); this system's control over summer precipitation, thunderstorm activity, and lightning patterns in the southwestern US extends to other regions via atmospheric connections (Vera *et al*. 2006; Dominguez *et al*. 2009). Few weather stations with uninterrupted data series exist above 3000 m in rural areas throughout the entire American Cordillera, from Alaska to Tierra del Fuego (Bradley *et al*. 2004), making it difficult to test hypotheses, calibrate models, and detect landscape feedbacks to human activities.

To evaluate the response of high-altitude, low-latitude environments to climatic changes, we analyzed hydroclimatic processes at the tropical treeline in the NAMS region, using half-hour data automatically collected between May 2001 and July 2009, at Nevado de Colima, Mexico (19°35' N, 103°37' W, 3760 m above sea level). This unique dataset has been generated by scientific-quality, commercially available sensors, specifically assembled (WebFigure 1) and configured to operate in this environment (see Biondi *et al*. 2005). A total of 142 201 records on 14 variables were recorded over a period of 2962 full days. Missing half-hour values caused by either equipment failures or post-processing corrections were minimal, accounting for 0–23% of measurements, with air temperature having the second most complete time series (WebTable 1). Daily summaries were computed only for days that had less than eight missing half-hour observations. Seasonal differences were studied in terms of monsoonal patterns by comparing the summer (wet) (June–October) with the winter (dry) (November–May) periods (Barlow *et al*. 1998; Mitchell *et al*. 2002).

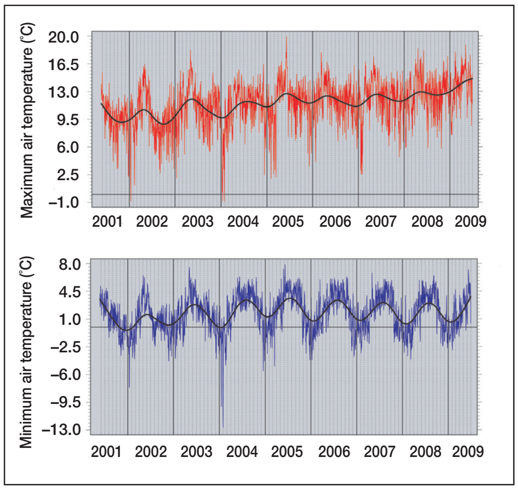

Figure 1. *Daily maximum (red) and minimum (blue) temperatures over the period of record (2962 days; dotted vertical lines mark the beginning of each month, and solid lines show the start of each year). Spring is the warmest season because clouds decrease shortwave radiation reaching the ground during the summer monsoon, which usually starts between the end of May and the beginning of June. Maximum values have increased more than the minima, thereby widening the daily temperature range (Figure 2). A cubic smoothing spline (black curve) with a 50% frequency response of 365 days (Cook and Peters 1981) was used to represent long-term trends.*

Maximum temperature has increased more in recent times than the minimum temperature (Figure 1), causing an expansion in the daily range of air temperatures (Figure 2). Since incoming shortwave radiation has remained stable over this period (WebFigure 2), and precipitation has fluctuated from year to year without any visible trend (WebFigure 3), the observed temperature increase appears to be unrelated to changes in downwelling solar energy or in monsoonal patterns. In addition, most of the warming occurred in maximum values during the winter (dry) season, while maximum and minimum temperatures followed parallel trajectories during the summer (wet) season. At this elevation, with an average daily barometric pressure of 655 hectopascals, maximum temperatures reflect the annual and daily energy cycle because of the dominant role of ground heating caused by incoming shortwave radiation. Indeed, spring is the warmest season in this area, because it is followed by pronounced cooling during the summer monsoon, due to increased cloudiness (Biondi *et al*. 2005).

Previous observations made primarily at lower elevations and higher latitudes have uncovered an increase in minimum (nighttime) temperatures (Alward *et al*. 1999), causing a reduction in the daily temperature range (Easterling *et al*. 1997). Similarly, water vapor feedbacks that drive regional responses to anthropogenic forcing (Huntington 2006), and variability of shortwave radiation reaching land surfaces (Long *et al*. 2009), have mostly been investi-

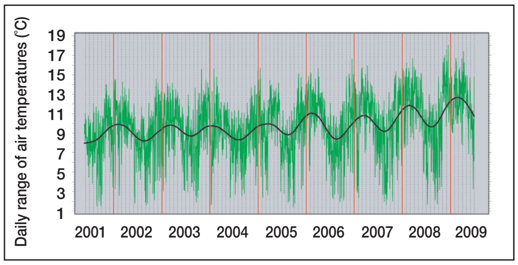

Figure 2. *Daily temperature range calculated as the difference between the daily maximum and minimum temperatures, showing greater values during the winter (dry) season, which have also progressively increased over time. A cubic smoothing spline (black curve) with a 50% frequency response of 365 days (Cook and Peters 1981) was used to represent long-term trends. Dotted vertical lines mark the beginning of each month, and red solid lines show the start of each year.*

gated in environments that are different from high-elevation tropical sites, where interactions with global climatic changes are still a subject of debate (Wu *et al.* 2007; Buytaert *et al.* 2009). The recent increase in maximum daily temperatures we uncovered at our study site is most likely related to a decrease in wind speed over time (WebFigure 4), especially during the winter (dry) season and around noon time (WebFigure 5). However, these observations should be regarded with due caution, being based on only one station and one temperature sensor. Further measurements, both on the surface and throughout the free atmosphere, together with remote-sensing data and regional modeling experiments, are needed to determine if these North American ecosystems, and the coupled atmospheric and oceanic circulation that affects them, are changing in unexpected ways, given the consequences this could have for resource managers and policy makers concerned with transboundary (Mexico–US) terrestrial, coastal, and marine environments.

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