

# A 400-year Tree-ring Chronology from the Tropical Treeline of North America

High-elevation sites in the tropics may be particularly sensitive to rapid climate change. By sampling treeline populations, I have developed the first extensive (> 300 years) tree-ring chronology in tropical North America. The site is Nevado de Colima, at the western end of the Mexican Neovolcanic Belt, and the species studied is Mexican mountain pine (*Pinus hartwegii*). Despite past logging in the area, 300 to 500-year old pines were found at 3600–3700 m elevation, about 300 m below the present treeline. The Nevado de Colima tree-ring chronology is well replicated from 1600 to 1997. Calibration with Colima climatic records points to summer monsoon precipitation as the strongest dendroclimatic signal. Most trees also exhibit extremely low growth in 1913 and 1914, following the January 1913 Plinian eruption of the Volcan de Colima. Because *P. hartwegii* is found on top of high mountains from Mexico to Guatemala, there is potential for developing a network of tropical treeline chronologies.

## INTRODUCTION

The North American tropics are a heavily populated area that is highly vulnerable to natural disasters. This was particularly evident in October 1998, when Hurricane Mitch left Honduras and other Central American countries with > 5000 people dead, > 8000 missing, > 10 000 wounded, and more than 1 million displaced (1). Droughts, as well as floods, impact the region. For instance, it is well established that Mexico experiences frequent and severe droughts (2), and that the effects on society can be dramatic (3), to the point that a number of major political upheavals in Mexican history have been directly linked to drought-related social instability (4). Despite its social relevance, scientific investigation of interdecadal climate dynamics in tropical North America has been hindered by a lack of data, as reliable meteorological records are limited to the last century, are continuous only at a few urban locations, and therefore do not provide extensive temporal and spatial coverage.

Forecasting the low-frequency likelihood of hydrological extremes benefits from a knowledge of climate variability at global and regional scales. World averages indicate that recent years have been the warmest since the beginning of instrumental records, about two centuries ago (5), and since the start of the millennium as reconstructed using proxy climate data (6). Several lines of evidence suggest that temperatures are rising in tropical regions, which occupy a critical role in the hydrological cycle (7). Freezing-level height, or the elevation of the 0°C isotherm, has increased more than 100 m in areas between 30°S and 30°N from 1970 to 1990 (8). Evidence from ice-core records indicates anomalous warming of tropical glaciers over the past few decades (9), which is consistent with the temperature increase observed in instrumental and proxy records from high elevations worldwide (10). Higher tropical air temperatures have been linked to an increase in tropical sea surface temperatures (8), which are intimately related to the frequency and intensity of El Niño/Southern Oscillation (ENSO) episodes (11), and interact in complex ways with the decadal Pacific oscillation (12,

13). Furthermore, tropical sea surface temperatures are a component of the North American monsoon system (14), which controls warm season precipitation not only in tropical North America, but also over much of the United States (15). As sea surface temperature changes, the consequences for summertime precipitation, and for the agricultural crops that depend on precipitation, may be better understood by obtaining long-term records of the eastern tropical Pacific climate system.

Tropical climate varies on several temporal scales (16). Because tropical mountains may be particularly sensitive to rapid climate change (17), multi-century long, annually resolved, proxy records from those environments are ideal tools for reconstructing the modes of climate variability in the tropics. Such records would also contribute to understanding the interaction between regional and basin-wide phenomena, such as the North American Monsoon and ENSO, respectively. At higher latitudes, annually resolved climate records for the past few centuries have been provided by dendrochronological studies of long-lived tree species (18).

Dendrochronological records from the tropics are rare, mostly because tropical tree species often form either unclear or undatable growth rings. Progress has recently been made in the development of tree-ring chronologies for tropical areas (19). In the North American tropics, tree species from low elevations have been heavily impacted by human activities, and their ring patterns are usually difficult to analyze (20). On the other hand, trees growing at the highest elevations experience strong seasonality, and form distinct growth layers (21), but their dendrochronological potential has remained largely untested. By sampling treeline populations, I have developed the first long (> 300 years) tree-ring chronology in the region of North America between 20°N and the Equator (22; Table 1). The site, Nevado de Colima, is at the western end of the Mexican Neovolcanic Belt, and the species, *Pinus hartwegii*, is present throughout Mexico and Central America (23). This report presents a detailed analysis of that timberline, multi-century long, tree-ring chronology.

## MATERIALS AND METHODS

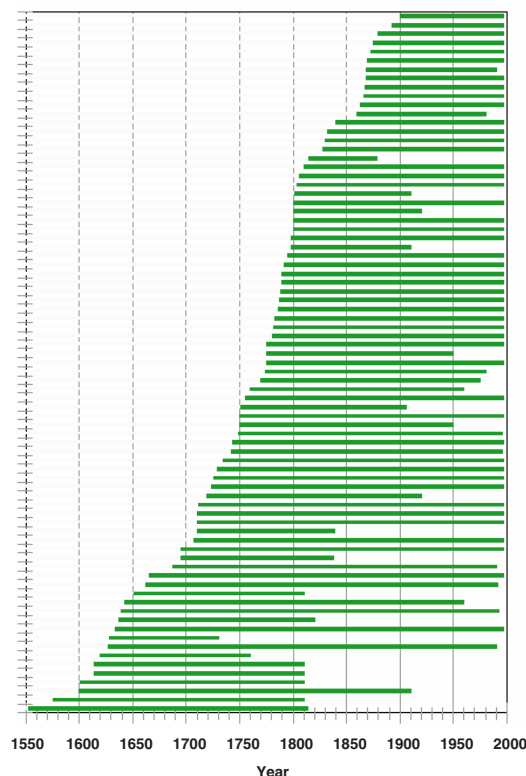
Sampled pines were selected according to criteria that favor steep, rocky sites, sparsely occupied by trees with large branches and flat crown top (24). An effort was made to avoid locations and trees affected by nonclimatic factors, e.g. human disturbance, grazing, fire, insect outbreaks, fungi, mistletoe. Evidence of recurring low-intensity fires, ax marks, and nearby selective logging was noted on most dominant pines. Two or more increment cores, 5 mm thick and 50 to 70 cm long, were extracted from each tree about 1.0 m above ground level, in a direction parallel to the topographic contour, and at 90°–180° from each other. Detailed information on sampled trees was recorded in the field and entered into a computer database. All wood samples were transported to the laboratory, surfaced, visually crossdated (25), and measured to the nearest micron. After numerical verification of dating accuracy (26), the standard tree-ring chronology was computed as follows:

$$\varpi_t = n_t^{-1} \sum_i [ \log (w_{it} + k) - y_{it} ]$$

with  $\varpi_t$  = chronology value at year  $t$ ;  $\Sigma_i$  = summation of the  $i$ -



**Figure 1.** *Pinus hartwegii* on Nevado de Colima, 3660 m elevation. The tree being sampled was 110.5 cm in diameter and about 300-years old. Remnant wood, such as the log in the foreground, has not yet been sampled. Photo: F. Biondi.



**Figure 2.** Length of the 79 tree-ring segments (from 30 trees) included in the Nevado de Colima chronology, which currently extends back to A.D. 1553 and is well replicated over the past four centuries.

values,  $i = 1, \dots, n$ ;  $w$  = cross-dated ring width (mm);  $k$  = constant added to avoid taking the logarithm (log) of zero;  $y$  = modified negative exponential or straight line with slope  $\leq 0$ . This computational method is based on an exponential model, and is well suited for estimating the most recent portion of historical trends (27). Climatic signals in tree-ring records were identified by means of response functions (28) and correlation analyses with monthly temperature and precipitation data. The standard chronology was high-pass filtered using an autoregressive AR(3) model (29), and low-pass filtered using a 30-year cubic smoothing spline (30).

Climate was quantified by comparing monthly precipitation and temperature records for 1949–1997 from 6 low-elevation stations (31; Table 1) to 4 years (1994–1997) of weather monitoring at 3500 m elevation on the Colima Volcano (32). Precipitation and temperature records from Colima stations were quality-controlled by cross-correlating them among themselves and with the high-elevation station. Annual rainfall averages 800–

1000 mm at all elevations, and is concentrated in the summer monsoon season (June–October). Temperature decreases with elevation, and the annual average is 23°–26°C in the lowlands and about 7°C at the summit. Temperature at treeline has decreased slightly from 1994 to 1997. On the mountaintop, May is the warmest month, and December the coldest, while June and January are the corresponding extremes at the base of the mountain. Even at treeline, monthly mean temperature never falls below zero; monthly minimum temperature may fall below zero in December and January (32).

## RESULTS AND DISCUSSION

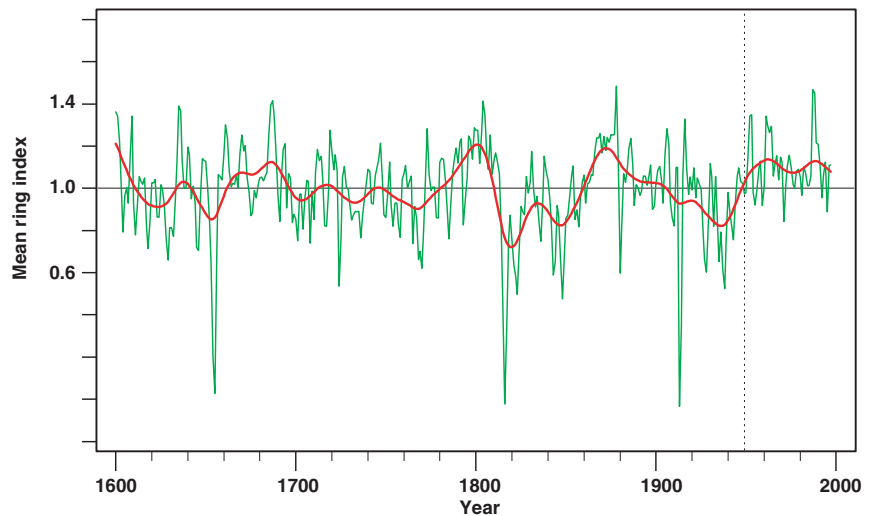
Despite past logging in the area, it was possible to locate pines up to 500-years old on top of the mountain. The size of sampled trees (total 49) ranged from 47 to 128 cm, with a mean of 91 cm and a standard deviation of 16 cm. The oldest trees were found at 3600–3700 m elevation (Fig. 1), about 300 m below

**Table 1.** Summary of information on Colima meteorological stations, high-altitude weather station, and timberline tree-ring site.

Name	Latitude (°N)	Longitude (°W)	Elevation (m)	Distance* (km)	Length of Record	
					Precipitation	Temperature
Ixtlahuacan	19.00	103.73	300	65	01/41 – 11/97	09/57 – 11/97
Buenavista	19.20	103.60	580	35	10/48 – 05/98	01/70 – 05/98
Coquimatlan	19.21	103.80	420	46	08/47 – 05/98	01/62 – 05/98
Costeno (Colima)	19.22	103.72	433	39	03/49 – 05/98	03/49 – 05/98
Peñitas	19.27	103.82	450	36	09/57 – 12/97	01/62 – 12/97
Cuahtemoc	19.33	103.60	950	20	07/47 – 05/98	06/80 – 05/98
Volcancito	19.52	103.61	3500	7	05/94 – 12/97	04/94 – 12/97
Nevado de Colima	19.58	103.62	3700	0	1600–1997	

\* Approximate horizontal distance from the Nevado de Colima tree-ring site.

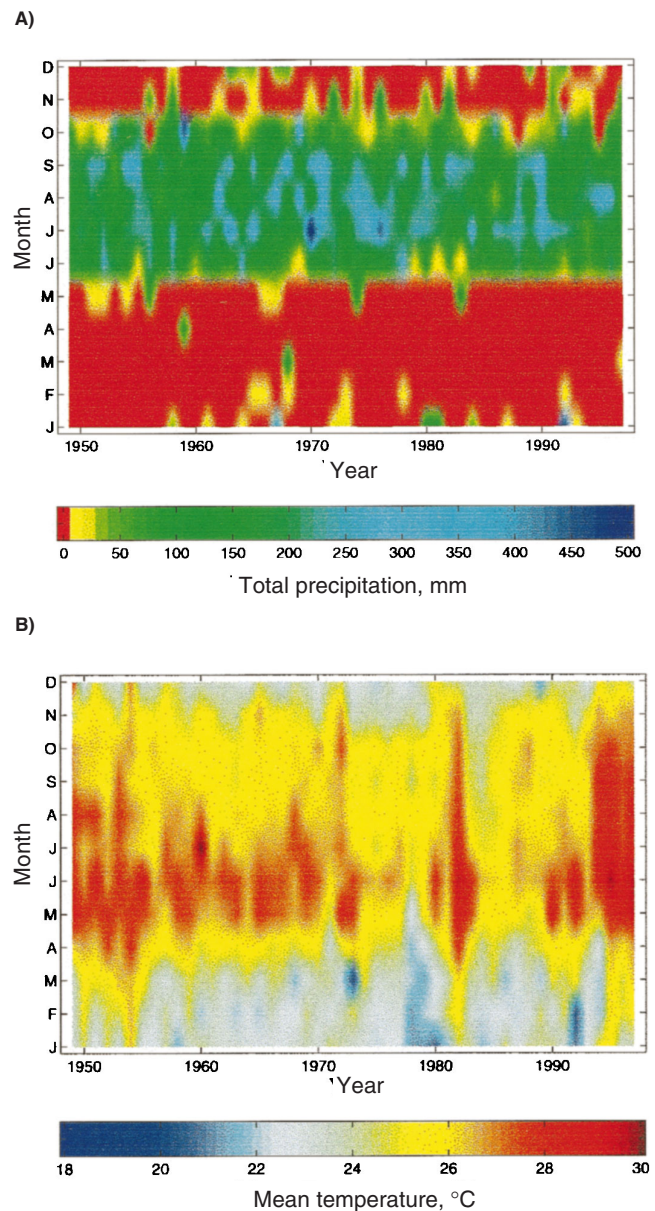
**Figure 3.** Annual (thin line) and decadal (30-yr cubic smoothing spline; thick line) patterns in the Nevado de Colima tree-ring chronology. The period after 1949 (dashed vertical line) was compared to instrumental records of climate. The extremely low values in 1913, 1816, and 1655 are probably related to volcanic eruptions.



the present treeline. Sampled pines at the uppermost altitudinal edge were less than 100-years old, and much smaller than the oldest trees. Xylem rings in most samples were clearly defined, and interannual variability was high enough to allow for matching growth patterns across samples (crossdating). Out of 128 specimens from 49 dominant pines collected in 1997, 79 segments from 30 trees have been visually and numerically crossdated. Most of the remaining samples were either too short or complacent for inclusion in the chronology, others were simply undatable. Mean segment length from 1600 to 1997 is 204 years, allowing the retrieval of interannual-to-interdecadal patterns (33). Sample depth ( $n_t$ ) ranges from 67 to 10 cores back to 1634, and remains  $\geq 3$  cores back to 1600 (Fig. 2).

Besides interannual and interdecadal patterns, a few abrupt changes are visible in the chronology (Fig. 3). Most trees show extremely low growth in 1913 and 1914, following the January 1913 Plinian eruption of the Volcan de Colima and the 1912 eruption of Novarupta in Alaska (34). Of 63 measured segments, 22 had no visible ring in 1913, and 8 were missing the 1914 ring as well. Another negative peak occurs in 1816, the 'year without a summer' (35) that followed the 1815 eruption of Tambora in Indonesia. Of 55 measured segments, 11 had no visible ring in 1816, and 7 were missing the 1817 ring as well. Frost damage in the 1813 latewood was also common in many samples. The 1655 extremely low value (Fig. 3) may be related to the eruption of Long Island in Papua New Guinea, whose date has been placed in the mid-1600s (36). The connection with volcanic eruptions is promising, albeit that it requires additional studies to separate climatic from volcanic signals, and to distinguish the effects of local eruptions from those of distant events. Relevant information should be provided by two parallel, ongoing research efforts. First, a network of tropical treeline chronologies is being developed for testing the regional coherence of tree-ring patterns. Second, intensive monitoring of weather and tree growth at Nevado de Colima is being arranged to uncover growing season length and wood formation response to intra-annual climatic patterns.

Although individual years may be affected by volcanic eruptions, either nearby or far away, reliable crossdating among annual tree-ring series implies that average variability in the *P. hartwegii* chronology is related to climate. Interestingly, the tree-ring chronology (Fig. 3) indicates higher than normal growth during the period of instrumental weather records, i.e. the second half of the 20<sup>th</sup> century. Dendroclimatic calibration relied on the Colima station, which has the longest record (Fig. 4). Monsoon precipitation is the strongest signal in the tree-ring chronology, as shown by a significant positive response to June rainfall in the bootstrapped response function. Linear correlation



**Figure 4.** Pseudocolor plot (46) of climatic variables, by month and year, at Colima from 1949 to 1997. A) Total precipitation. Notice the scarce ( $< 10 \text{ mm month}^{-1}$ ) precipitation outside the intense summer monsoon wet season ( $> 100 \text{ mm month}^{-1}$ ), which begins in June. B) Mean temperature. Higher values in the last few years are consistent with reports of widespread warming in the Tropics (8, 9).

( $r$ ) from 1949 to 1997 between the standard chronology and June precipitation is 0.4 ( $p$ -value  $< 0.01$ ). Even though this correlation is not high in absolute terms, it is among the best correlations obtained in tropical regions (37). Since June marks the passage from the dry to the wet season, it may also coincide with the beginning of cambial growth. Reconstructing the long-term variability of June precipitation would provide an index for the North American summer monsoon which, on a regional scale, heavily influences agricultural crops in Mexico, and, on a global scale, has a fundamental role in tropical climate change prediction.

The large-scale significance of the Nevado de Colima tree-ring record was investigated by drawing spatial correlation maps. Point correlations were objectively interpolated (38) to obtain contour intervals. Figure 5 depicts the statistical relationship with tree-ring chronologies for western North America (39), computed using the standard version of the *P. hartwegii* chronology. The relationship between this tropical record and tree-ring chronologies in the mid-latitudes suggests the presence of a spatial dipole, with inverse associations prevailing in Southern California, and direct ones being predominant in the interior Northwest. A similar synoptic pattern is commonly found when correlating western American tree-ring chronologies with large-scale indices of Pacific climate, such as the Pacific Decadal Oscillation (40). With regard to seasonal climatic variables over the conterminous USA, spatial correlations were computed using the prewhitened version of the *P. hartwegii* chronology. There is a positive connection with summer Palmer Drought Severity Index (PDSI; 41) over the Midwest (Fig. 6), an area where the North American monsoon influences summer rainfall (15). PDSI integrates temperature, precipitation, insolation, and soil properties to represent drought intensity as departure from average moisture conditions (42). The direct association between the Nevado de Colima tree-ring record and summer

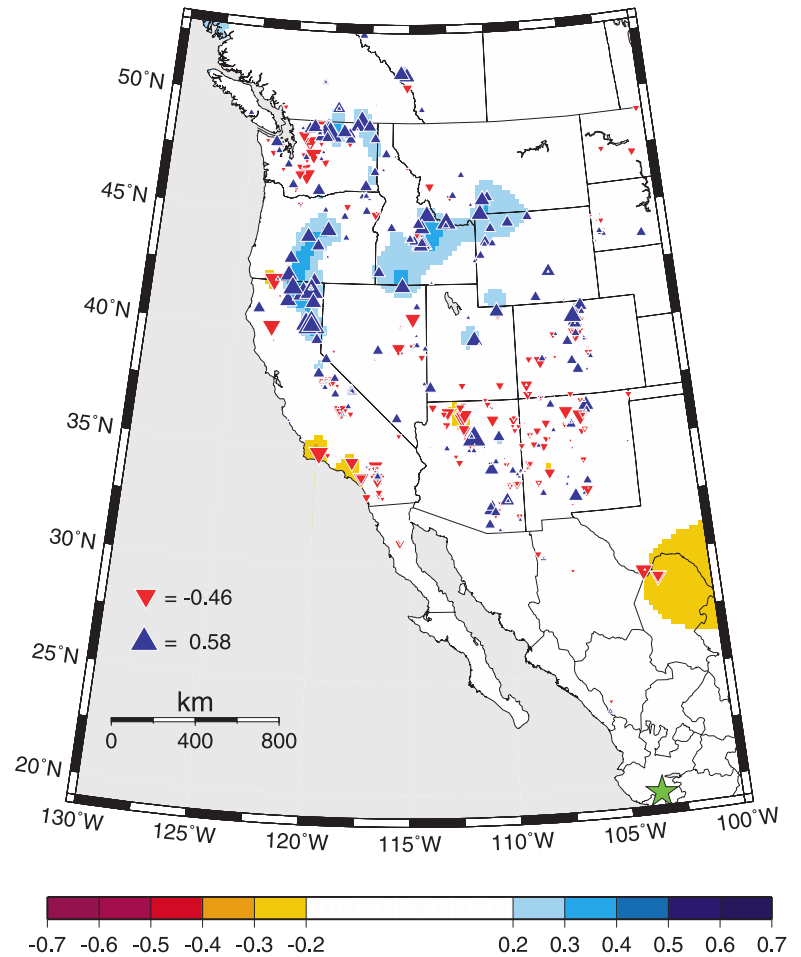
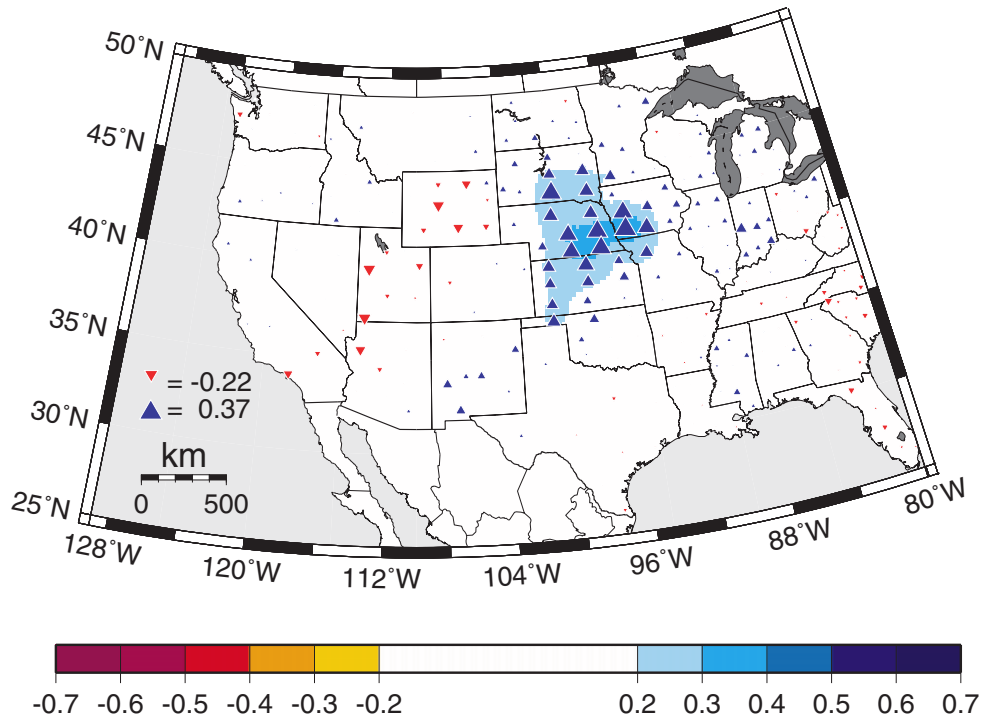


Figure 5. Correlation from 1915 to 1997 between the Nevado de Colima chronology and all other tree-ring chronologies for western North America. Symbol size for point correlations ( $\blacktriangle$  positive,  $\blacktriangledown$  negative) is directly proportional to absolute  $r$  value. Symbol size and corresponding  $r$  value are shown for the highest positive and lowest negative point correlations. Contour intervals were objectively determined (38). Spatial patterns below  $30^{\circ}$  N are unreliable because of the sudden drop in data coverage.

Figure 6. Correlation from 1915 to 1997 between the Nevado de Colima chronology and summer (June through August) Palmer Drought Severity Index over US climate divisions. (Symbols and contours as in Fig. 5.)



PDSI indicates that greater tree growth occurs in years when drier conditions characterize the central USA.

The ecology and geography of treeline *Pinus* species in the tropics has not been investigated in detail. Little scientific information, if any, exists on the present and past location of the tree limit, defined as the maximum elevation (m a.s.l.) reached by woody plants taller than 2 m (43). Regeneration, growth, mortality, and disturbance processes are also in need of careful study. Presumably, *P. hartwegii* communities are as sensitive to climate change as their higher latitude counterparts, such as *P. cembra* in the European Alps (44) or *P. balfouriana*, *P. aristata* and *P. longaeva* in the American Rockies (21). However, geocological paradigms developed from treeline studies of the Old and New World are unlikely to be of any value for understanding the tropi-

cal pine timberline. Given the length of the Nevado de Colima tree-ring chronology, its sensitivity to climate, and the species distribution on mountaintops (> 3000 m) from Mexico to Honduras (23), there is potential for developing a network of multi-century tropical chronologies. That dendrochronological database would be extremely helpful to local managers and researchers for understanding ecological processes, climatic variability, and forest-climate relationships linked to the eastern tropical Pacific and to major volcanic eruptions. From a global perspective, the data may shed light on the role of tropical mountain ranges for regulating the interaction between ENSO events, onset and strength of the summer monsoon, and location of the Inter-Tropical Convergence Zone, which in turn are the factors that control precipitation regimes in the tropics of North America (45).

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