



## Climate change scenario for Costa Rican montane forests

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[1] Tropical montane cloud forests are characterized by persistent immersion in clouds, an important source of moisture during the dry season. Future changes in temperature and precipitation could alter cloud cover at the vegetation level and seriously affect mountain ecosystems. A regional climate modeling study that focuses on changes in the distributions of temperature and precipitation in Costa Rica shows, in general, an increase in temperature and a decrease in precipitation under the A2 scenario. At high elevations, warming is amplified and future temperature distribution lies outside the range of present-day distribution. Compared to the Caribbean side, temperature changes are greater at high elevations on the Pacific side. Model results also show significant changes in precipitation amounts and variability and an increase in the altitude of cloud formation on the Pacific side that may have serious implications for mountain ecosystems in and around Costa Rica. **Citation:** Karmalkar, A. V., R. S. Bradley, and H. F. Diaz (2008), Climate change scenario for Costa Rican montane forests, *Geophys. Res. Lett.*, 35, L11702, doi:10.1029/2008GL033940.

### 1. Introduction

[2] Highland tropical forests are rich in endemic species and crucial in maintaining freshwater resources in many regions. Much of their remarkable biodiversity is due to the steep climate gradients found on tropical mountains. The ecosystems along the mountain slopes are closely stacked due to sharp vertical temperature and precipitation gradients and are particularly vulnerable to climatic changes. Future warming is expected to be amplified with elevation in the lower troposphere and this has significant implications for the mountainous regions of the world [Bradley *et al.*, 2004, 2006]. In fact, mountain regions throughout the world have experienced large upward shifts in freezing levels in recent decades [Diaz *et al.*, 2003; Vuille and Bradley, 2000]. One of the key objectives of this research is to understand the nature of climatic changes in Central America along the mountain slopes and their implications for ecosystem dynamics. Giorgi [2006] showed that Central America is a major emerging “Hot-Spot” in the Tropics, for which potential climate change impacts on the environment are likely to be particularly pronounced due to a decrease in precipitation and an increase in precipitation variability as projected by global climate model simulations. Future

drying in Central America is one of the most consistent results among models [Rauscher *et al.*, 2008; Giorgi, 2006; Neelin *et al.*, 2006; Aguilar *et al.*, 2005]. Reduction in precipitation may have detrimental impacts on the region’s unique biodiversity. Indeed, biological changes associated with changes in climate have already been identified in the Monteverde Cloud Forest Reserve (MCFR) [Pounds *et al.*, 1999, 2006] in Costa Rica. In this study, changes in the distribution of monthly mean surface temperature and monthly precipitation totals in Costa Rica are investigated using observations, and climate simulations of contemporary as well as the A2 emissions scenario.

### 2. Data and Methods

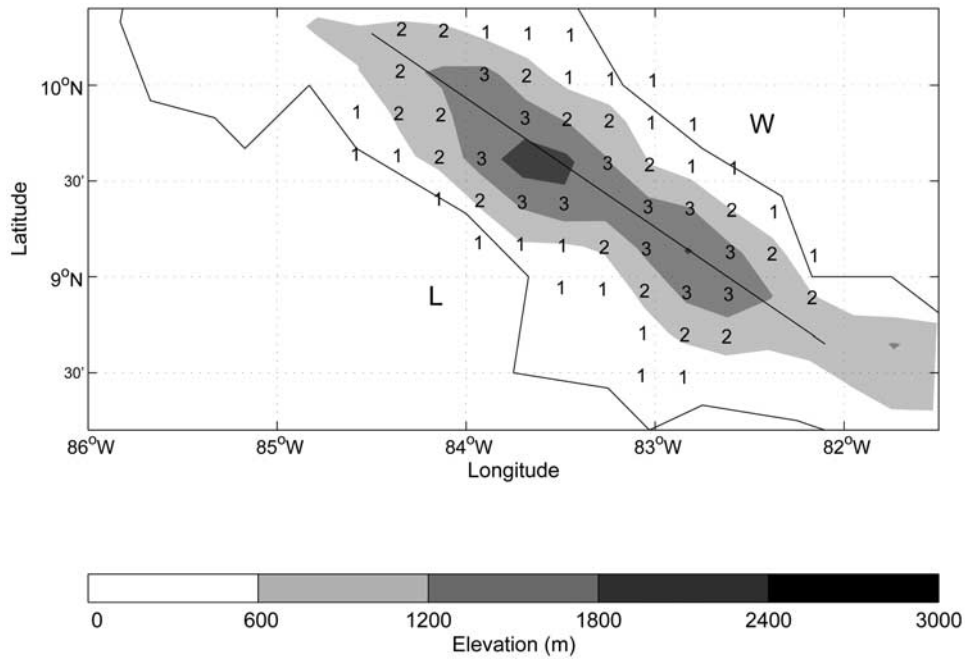
[3] To study climate change in Central America, a topographically complex region, we performed regional climate simulations using the UK Hadley Center PRECIS (Providing Regional Climates for Impact Studies) modeling system [Jones *et al.*, 2004]. We carried out a control run (1961–1990) and a doubled CO<sub>2</sub> run (SRES A2, 2071–2100) at a resolution of 25 km (0.22° lat-long) over the region of Central America (supplementary Figure S1<sup>1</sup>) that includes several biodiversity hotspots. However, this study focuses on a sub-region within our model domain covering Costa Rica (Figure 1). The observed data sets used here, to validate present day model simulation (the control run), are the Climate Research Unit (CRU) [Mitchell *et al.*, 2004] data for temperature and the CRU and Global Precipitation Climatology Centre (GPCC) data for precipitation. Both data sets are monthly data, gridded to a 0.5° latitude-longitude grid, and include only land points.

[4] We present regional changes in the distribution of surface air temperature and precipitation in Costa Rica (Figure 1) using probability density functions (PDFs). To describe monthly mean temperature distribution, we use the normal (Gaussian) distribution. The gamma distribution is used to describe total monthly precipitation distribution. The gamma distribution is the most appropriate choice for describing precipitation because it is bounded on the left by zero, is positively skewed and also offers a tremendous amount of flexibility in the shape of the distribution function [Groisman *et al.*, 1999; Wilks, 1995]. The gamma distribution is computed using two parameters: shape ( $\alpha$ ) and scale ( $\beta$ ) parameter. Parameter estimation is given as  $\mu = \alpha\beta$ ,  $\sigma^2 = \alpha\beta^2$ , where  $\mu$  denotes the mean and  $\sigma$  the standard deviation of the distribution.

[5] We present analysis for DJF (Dec–Feb), a dry season in Costa Rica. The vegetation in tropical montane cloud forests intercepts cloud water from orographic, advected

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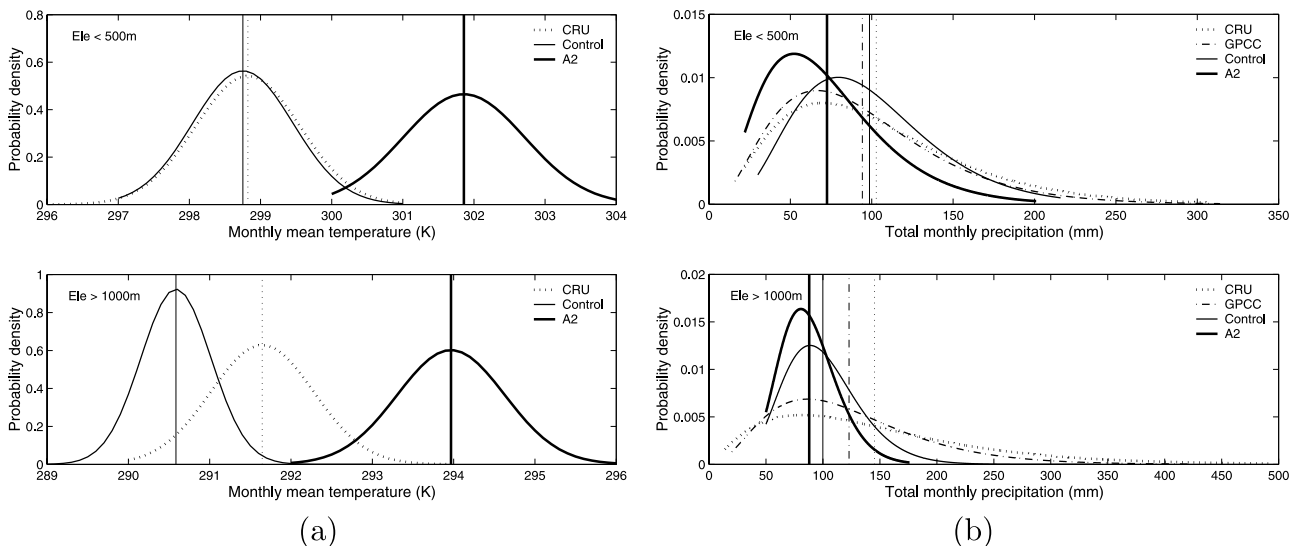
**Figure 1.** Model region covering Costa Rica used in this study. PDFs are calculated for land points with ‘low’ (<500 m) and ‘high’ (>1000 m) elevations and also for three elevation zones (1:10–600 m, 2:600–1200 m, 3:1200–1800 m) on both the windward (W) and leeward (L) sides each. Numbers show the locations of grid points in each zone overlaid on model topography (shaded contours).

clouds and wind blown mist and so the height at which clouds develop is a critical factor for these ecosystems. This “horizontal precipitation” accounts for a significant amount of the total precipitation in these regions in the dry season [Bruijnzeel and Proctor, 1993; Clark et al., 1999] and changes in this amount in future may significantly affect the vegetation and species living on the mountains. In fact, Pounds et al. [2006] have shown that biological changes in the MCFR could be associated with a dramatic decline in dry season mist frequency. The biological and climatic patterns may also suggest that atmospheric warming has

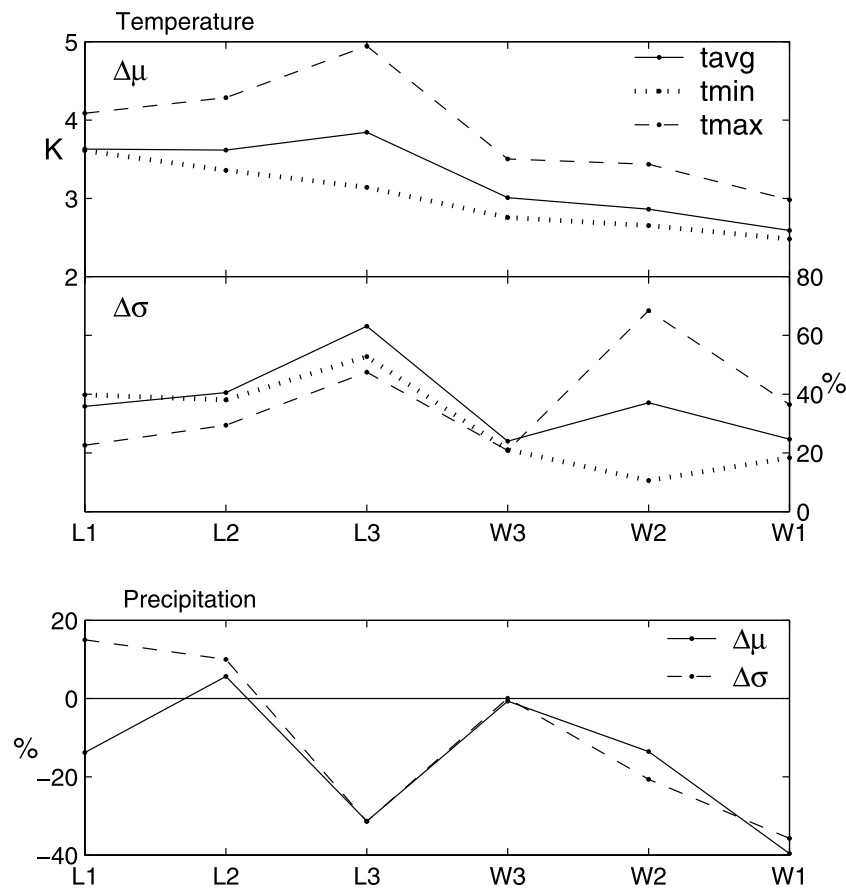
raised the average altitude of the base of the orographic cloud bank during the dry season.

**3. Results**

[6] Figure 2 shows temperature and precipitation PDFs for the observed and model (control and A2) data sets. The distributions as a function of elevation are studied by estimating separate PDFs for ‘low’ (<500 m) and ‘high’ (>1000 m) elevations for land points in Figure 1. For low elevations, model temperature distribution (Figure 2a)



**Figure 2.** Probability distributions of (a) mean monthly temperatures and (b) monthly precipitation for DJF in Costa Rica for ‘low’ (top panels) and ‘high’ (bottom panels) elevations. Vertical lines mark the means.



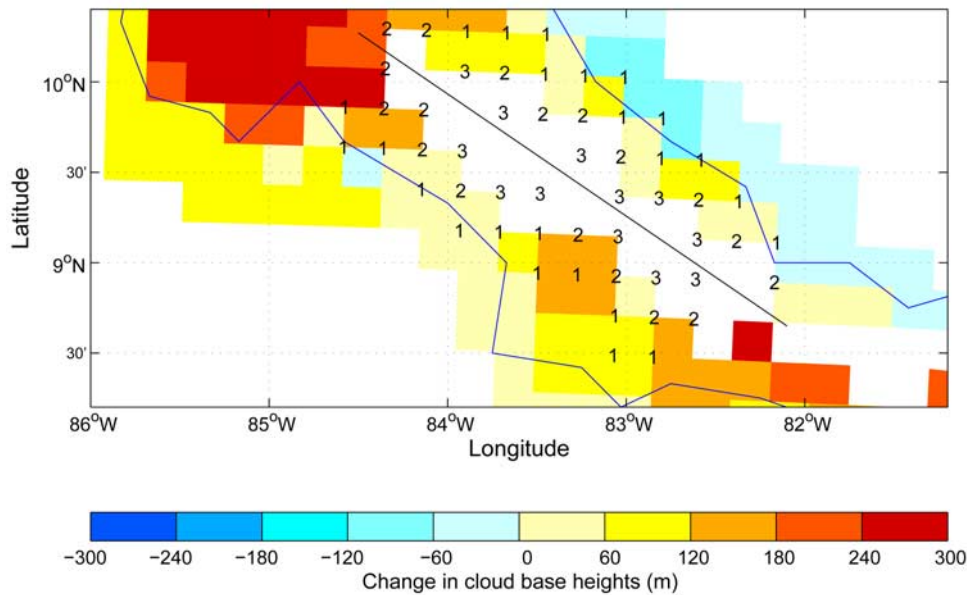
**Figure 3.** Changes (A2 - Control) in the mean ( $\Delta\mu$ ) and standard deviation ( $\Delta\sigma$ ) of PDFs along a transect across Costa Rica for elevation zones described in Figure 1. The top panel is for mean (tavg), minimum (tmin) and maximum (tmax) temperature and the bottom panel is for precipitation.

agrees well with the observed (CRU) data in terms of mean and shape of the distribution. However, for high elevations, the model temperatures average is  $\sim 1.1$  K less than CRU (mean for points above 1000 m). In general, the model shows a cold bias when compared to the CRU data with differences increasing with elevation, and for individual grid-points may be as large as 2 to 3 K. However, given the sparsity of high elevation observations that are available for use in the CRU data set, the significance of this difference is difficult to assess. Under the A2 scenario, the mean of the distribution increases by 3.1 K and 3.38 K at low and high elevations respectively suggesting slightly amplified warming at higher altitudes. The standard deviation increases by 21% at lower elevations and by 53% at higher elevations relative to the control run; thus the model indicates that high altitude temperatures will not only experience a greater increase in temperature relative to lowlands but will also be more variable. It is important to note that the future temperature PDF for high elevations lie completely outside the range of present day temperature PDF.

[7] As seen in the case of temperature, at low elevations, model precipitation distribution (Figure 2b) agrees well with the CRU and GPCC distributions in terms of mean and standard deviation. However, at high elevations, model precipitation is less than observations where the model mean is 31% lower than the CRU and 19% lower than

the GPCC data. There is also much lower variability in the model precipitation distribution than in the observed PDFs at high elevations. The width ( $2\sigma$ ) of the model precipitation is 65% narrower than the CRU and 50% narrower than the GPCC data. This shows that the model is not very successful in capturing the precipitation variability in this topographically complex region. With the reduction in mean in the A2 future scenarios, the width of the distribution also decreases by 12% at low elevations and by 24% at high elevations, so high elevation regions will become drier with less variability. In general, the model indicates that high elevation regions will receive less precipitation in DJF, and there will be a decrease in the frequency of high precipitation amounts and an increase in the frequency of low precipitation amounts.

[8] These results highlight the fact that highlands of Costa Rica are projected to experience greater changes in temperature and precipitation distribution relative to the lowlands. Also, the Caribbean and Pacific mountain slopes have different climate regimes and could have varied impacts. For this reason, we computed temperature and precipitation PDFs along a transect across Costa Rica by dividing the windward (Caribbean) and the leeward (Pacific) slopes into three elevation zones (Figure 1) each. The change (A2 - Control) in PDFs for each of these zones is shown schematically in Figure 3 (tabulated in supplementary Table S1).



**Figure 4.** Change (A2 - Control) in cloud base heights in meters in Costa Rica for land points below 800 m during DJF.

[9] The maximum change in mean temperature along a transect across Costa Rica is at high elevations on the leeward side (Figure 3, zone L3); the same is true for maximum temperatures. However, mean minimum temperatures increase steadily from the windward to the leeward side. This increase may be associated with enhanced cloud cover on the leeward side, resulting in nocturnal warming and thereby increasing minimum temperatures in future. In general, the warming is greater on the leeward slopes than on the windward slopes for the mean as well as maximum and minimum temperatures. The change in the width of the distribution mimics the changes seen in the mean of the distribution.

[10] During the DJF dry season, cloud formation at high elevations is a primary source of moisture to this area. In particular, the model shows highest precipitation totals in Costa Rica at mid-elevations along the windward slopes (supplementary Figure S3). The high elevation leeward slopes, in contrast, are very dry and have a narrow precipitation distribution. Under the A2 scenario, a decrease in precipitation is experienced along both slopes in Costa Rica as seen in Figure 3, except for a slight increase seen on the leeward side at middle elevations (600–1200 m). The maximum percentage decrease in precipitation is seen at low elevations on the windward side (Figure 3, zone W1). But the high-elevation leeward slopes also show considerable drying (~31%). Under the A2 scenario, precipitation PDFs on the windward side get narrower, indicating a decrease in precipitation variability in winter. The Pacific lowlands (Figure 3, zone L1, zone L2), however show an increase in the variability under the A2 simulation.

[11] The climatic changes seen in our simulation, particularly the warming trend, may lead to an increase in the altitude of cloud formation in the region and seriously affect the moisture supply to the montane forests during the dry season. *Nair et al.* [2003] and *Ray et al.* [2006] demonstrated that orographic cloud formation is sensitive to the

land use change and deforestation in Costa Rican lowland, and these changes have resulted in increasing cloud base heights. However, *Still et al.* [1999] used the relative humidity (RH) surface as a cloud formation proxy and showed that the cloud base consistently shifted upwards in DJF in their  $2 \times \text{CO}_2$  GCM simulation as a result of increasing surface temperatures. We determined a change in cloud base heights (A2-Control) in our simulations for land-points in Costa Rica (Figure 1) with elevations less than 800 m using model surface values for temperature, RH and pressure (see supplementary material). We see an overall increase in the cloud base height (Figure 4) up to 300 m during DJF. These values should be treated as theoretical estimates as they are based on assumptions of adiabatic cooling and no change in the moisture content of the air as it's been uplifted. However, this exercise illustrates the fact that while atmospheric moisture content might increase (and does increase in the model) as a result of intensified hydrological cycle in future, rising temperatures might drive cloud bases to higher altitudes. These changes can be attributed to warming alone, as the model does not incorporate a land use change.

#### 4. Conclusions

[12] This analysis suggests that climate change effects in Central America, and more specifically around Costa Rica will be more pronounced at high elevations than in the lowlands, particularly on the Pacific side, during the DJF dry season. The region will not only experience a greater increase in temperature of over 3 K, but is likely to experience higher variance, such that future temperature PDFs are likely to lie completely outside the range of present day temperature PDFs. The model simulation indicates that high elevation Pacific slopes and the Caribbean lowlands will receive less precipitation up to 30%. There will also be, in general, a decrease in the frequency of high precipitation amounts and an increase in the frequency of



low precipitation amounts in DJF. In addition, simulations indicate an overall increase in the height of the orographic cloud base. These changes have important implications for tropical montane forest ecosystems in Costa Rica, pointing to a future with significantly more moisture stress due to higher temperatures and a reduction in precipitation from both horizontal and vertical processes.

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## References

- Aguilar, E., et al. (2005), Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003, *J. Geophys. Res.*, *110*, D23107, doi:10.1029/2005JD006119.
- Bradley, R. S., F. T. Keimig, and H. F. Diaz (2004), Projected temperature changes along the American cordillera and the planned GCOS network, *Geophys. Res. Lett.*, *31*, L16210, doi:10.1029/2004GL020229.
- Bradley, R. S., M. Vuille, H. F. Diaz, and W. Vergara (2006), Threats to water supplies in the tropical Andes, *Science*, *312*(5781), 1755–1756.
- Bruijnzeel, L. A., and J. Proctor (1993), Hydrology and biogeochemistry of tropical montane cloud forests: What do we really know?, in *Tropical Montane Cloud Forests: Proceedings of an International Symposium*, edited by L. S. Hamilton, J. O. Juvik, and F. N. Scatena, pp. 25–46, East-West Cent., Honolulu, Hawaii.
- Clark, K. L., R. O. Lawton, and P. Butler (1999), *The Physical Environment of Monteverde*, Oxford Univ. Press, New York.
- Diaz, H. F., J. K. Eischeid, C. Duncan, and R. S. Bradley (2003), Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years, *Clim. Change*, *59*(1–2), 33–52.
- Giorgi, F. (2006), Climate change hot-spots, *Geophys. Res. Lett.*, *33*, L08707, doi:10.1029/2006GL025734.
- Groisman, P. Y., et al. (1999), Changes in the probability of heavy precipitation: Important indicators of climatic change, *Clim. Change*, *42*(1), 243–283.
- Jones, R. G., M. Noguer, D. C. Hassel, D. Hudson, S. S. Wilson, G. J. Jenkins, and J. F. B. Mitchell (2004), Generating high resolution climate change scenarios using PRECIS, 40 pp., Met Off., Hadley Cent., Exeter, UK.
- Mitchell, T. D., T. R. Carter, P. D. Jones, M. Hulme, and M. New (2004), A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100), *Working Pap. 55*, Tyndall Cent., Univ. of East Anglia, Norwich, UK.
- Nair, U. S., R. O. Lawton, R. M. Welch, and R. A. Pielke Sr. (2003), Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of cumulus cloud field characteristics to lowland deforestation, *J. Geophys. Res.*, *108*(D7), 4206, doi:10.1029/2001JD001135.
- Neelin, J. D., M. Munnich, H. Su, J. E. Meyerson, and C. E. Holloway (2006), Tropical drying trends in global warming models and observations, *Proc. Natl. Acad. Sci. U. S. A.*, *103*(16), 6110–6115.
- Pounds, J. A., M. P. L. Fogden, and J. H. Campbell (1999), Biological response to climate change on a tropical mountain, *Nature*, *398*(6728), 611–615.
- Pounds, J. A., et al. (2006), Widespread amphibian extinctions from epidemic disease driven by global warming, *Nature*, *439*(7073), 161–167.
- Ray, D. K., U. S. Nair, R. O. Lawton, R. M. Welch, and R. A. Pielke Sr. (2006), Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of orographic cloud formation to deforestation in the plains, *J. Geophys. Res.*, *111*, D02108, doi:10.1029/2005JD006096.
- Rauscher, S. A., F. Giorgi, N. S. Diffenbaugh, and A. Seth (2008), Extension and intensification of the Meso-American mid-summer drought in the twenty-first century, *Clim. Dyn.*, doi:10.1007/s00382-007-0359-1.
- Still, C. J., P. N. Foster, and S. H. Schneider (1999), Simulating the effects of climate change on tropical montane cloud forests, *Nature*, *398*(6728), 608–610.
- Vuille, M., and R. S. Bradley (2000), Mean annual temperature trends and their vertical structure in the tropical andes, *Geophys. Res. Lett.*, *27*(23), 3885–3888.
- Wilks, D. S. (1995), *Statistical Methods in the Atmospheric Sciences: An Introduction*, Academic, San Diego, Calif.

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