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Projected temperature changes along the American cordillera and the planned GCOS network

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[1] Analysis of 7 GCM simulations with 2x CO_2 levels shows large and statistically significant free air temperature changes (compared to controls) along the axis of the American Cordillera (from Alaska to southern Chile). At all latitudes, the modeled change in temperature increases with elevation. Temperature increases are especially large in boreal summer months from ∼35–50°N, and year-round in the high mountains of Peru, Bolivia and northern Chile. If these models are correct, mountain ranges that extend high into the lower troposphere are likely to experience significant warming, with implications for glacier mass balance and water resources, montane ecosystems and high elevation agricultural activities. There are few high elevation meteorological stations to validate the model projections, or to monitor future changes. The planned GCOS (Global Climate Observing System) network is not adequate to address the critical issues raised by these model simulations; additional high elevation observing stations are needed.

INDEX TERMS: 1610 Global Change: Atmosphere (0315, 0325); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 9350 Information Related to Geographic Region: North America; 9360 Information Related to Geographic Region: South America. **Citation:** 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*, LXXXXX, doi:10.1029/2004GL020229.

1. Introduction

[2] It is well documented that large temperature changes are likely in polar regions (where temperatures are close to, or below the freezing point) with enhanced levels of greenhouse gases [*IPCC*, 2001]. What have received less attention are temperature changes in mountain regions of the world, where similarly low temperatures are also recorded. In both regions, warming affects the mass balance of glaciers, the stability of permafrost, the extent and duration of lake ice cover, the growth of trees at their polar or montane limits and the extent and productivity of tundra and other marginal ecosystems [*Gottfried et al.*, 2002]. Furthermore, in many mountain regions in the inter-tropical zone, population density is quite high and upland agriculture is practiced (to over 4000 m in some areas). Glaciers and melting snow are critical water resources for hydroelectric power generation as well as consumptive use in many mountain regions and adjacent lowlands downstream [*Liniger et al.*, 1998; *Mote*, 2003; *Barnett et al.*, 2004]. Thus, potential climatic changes in mountain regions are of particular interest.

[3] Models used in the IPCC climate change assessment indicate that, on a zonally averaged basis, the axis of largest mean annual temperature change with doubled CO_2 levels extends from near the surface in the Arctic to the mid-troposphere in the inter-tropical zone. Here, we re-examine these model simulations, focusing on temperature changes in the lower troposphere along the axis of the American Cordillera that extends high into the atmosphere from southern Chile (∼50°S) to Alaska (∼70°N). We note that these computed temperature changes are in the free air. Surface temperatures are not identical to equivalent free air temperatures (recorded by radiosondes) and the differences may vary diurnally, seasonally and geographically (notwithstanding the fact that radiosonde data are rarely obtained from sites in mountainous regions, so direct comparisons are subject to considerable spatial discrepancies) [*Seidel and Free*, 2003]. Nevertheless, in the Americas, at least, trends in free air temperatures (such as the height of the freezing level) and trends in surface temperatures over recent decades are generally similar [*Diaz and Graham*, 1996; *Vuille and Bradley*, 2000; *Diaz et al.*, 2003; *Vuille et al.*, 2003]. We therefore consider model-derived, projected free air temperature changes as indicative of the changes that are likely to affect surface temperatures along the American Cordillera. This in turn points to those locations where it would be prudent to undertake climate monitoring both for model validation and climate change detection.

2. Analysis

[4] We analysed mean monthly temperatures and geopotential heights from seven coupled atmosphere-ocean general circulation models (Table 1) from the CMIP2+ phase of the Coupled Model Intercomparison Project (CMIP) [*Covey et al.*, 2003]. The CMIP2+ model runs include control runs and simulations with 1% per year compound CO_2 increase (over 80 years) in which CO_2 doubles at around year 70.

[5] The spatial domain was a series of 49 (2.5° × 2.5°) grid boxes which run in a transect along the North America/South America Cordillera. Using the ETOPO5 five minute gridded earth topography data (available from NOAA's National Geophysical Data Center) mean elevations were calculated for grid boxes in an area encompassing the Cordillera. Then, for each row of grid boxes, the grid box with maximum mean elevation was chosen. As seen in Figure 1, the chosen boxes form a nearly continuous transect.

[6] For a given model, bilinear interpolation was used to determine the temperature at each grid box for each model

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Table 1. CMIP2+ Models Used in the Analysis[a]

Model	Atmospheric Resolution	Number of Vertical Levels	Control Run CO_2 (ppmv)
CGCM2	T32 (3.8° × 3.8°)	17	330
CSM 1.0	T42 (2.8° × 2.8°)	18	355
ECHAM4/OPYC3	T42 (2.8° × 2.8°)	17	353
ECHO-G[b]	T32 (3.8° × 3.8°)	17	353
HadCM2	2.5° × 3.75°	15	322.6
MRI1	T42 (2.8° × 2.8°)	21	345
DOE PCM	T42 (2.8° × 2.8°)	18	355

[a] Atmospheric resolution is expressed either as latitude × longitude or as a spectral truncation with a rough translation to latitude × longitude.

[b] For the ECHO-G increased CO_2 run, there were data for only 78 years, and thus data from years 63 through 78 were used to calculate the means from both ECHO-G runs.

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level. Then, using bilinear interpolation with the geopotential heights at each level, the temperature at each grid box was determined for each of the levels from 500 m to 9500 m by 1000 m increments (i.e., 500 m, 1500 m, . . ., 9500 m). Seasonal and annual mean temperatures at those levels were determined for the 61st through the 80th years of both the control runs and the increased CO_2 runs, and then differences between the increased CO_2 run means and the control run means were calculated.

3. Results

[7] Figure 2 shows modeled mean annual and seasonal changes in temperature along the America Cordillera transect based on the difference between 2x CO_2 simulations and control runs, averaged for the 7 models (for results from individual models, see auxiliary material[1]). The solid white line shows the maximum 5′ × 5′ elevation in each grid box. The black triangles show some of the highest mountains in each country along the transect. Thus the area between the white line and the black triangles indicates the highest montane regions that may be impacted by the projected temperature changes. Several models use either sigma (or hybrid sigma) levels, which follow terrain near the surface. For those models there are no data in the lower levels at many grid boxes in the transect. In Figure 2, data are displayed only for those latitudes and levels where data were available from all seven models (missing data are blocked out in white).

[8] At all latitudes, the expected temperature changes increase with elevation. Maximum temperature changes are expected in the mid-upper troposphere (8–10,000+m) in the inter-tropical zone and at the poleward boundary of the Hadley circulation in each hemisphere during summer months in the respective hemisphere. Thus, in boreal summer, warming >3°C is simulated for the high mountains of the Rockies at ~42°N, as well as in the mid-troposphere of the inter-tropical region. In boreal winter months, maximum warming switches to a similar latitude in the southern hemisphere. We interpret this pattern as related to an increase in tropical convection (with associated release of latent heat) and an increase in subsidence at the poleward margins of the Hadley cells [*Quan et al.*, 2004]. As noted in *IPCC* [2001] models indicate a general increase in precipitation in the intertropical zone and a reduction in sub-tropical regions, consistent with this interpretation. There is also strong warming in the Arctic in winter, in the lower troposphere, possibly related to a breakdown of near-surface temperature inversions, which would lead to mixing with relatively warm air above the surface boundary layer [cf. *Bradley et al.*, 1992]. We assessed the statistical significance of the changes by conducting a t-test at each grid point in each model. For both annual and boreal summer, the projected changes are statistically significant at the 0.01 level, in all models. In boreal winter, points poleward of ~50N, from the surface to the highest elevations examined, were not as significant in ~50% of the models. This is related to the higher variance in winter at these latitudes, and the smaller projected temperature changes, particularly at the highest elevations (middle panel, Figure 2).

[9] Of particular interest are those areas where the highest mountain regions intersect those regions where large temperature changes are simulated. In the southern hemisphere, temperature increases of >2.5°C are projected for the mountain zone from ~10°S (in Peru) through Bolivia to ~40°S (in Chile/Argentina). Many towns and large cities (such as La Paz and Lima) rely on runoff from glaciers in nearby high mountains for both water supplies and hydroelectric power. Meteorological data from these mountain regions are sparse, but indicate strong warming trends [*Vuille et al.*, 2003]. Moreover, glaciological evi-

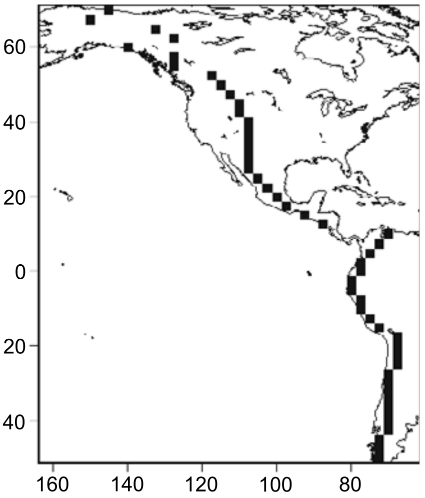

Figure 1. The transect of grid boxes along the North America/South America cordillera. Using the ETOPO5 five minute gridded earth topography data (available from NOAA's National Geophysical Data Center) mean elevations were calculated for grid boxes in an area encompassing the Cordillera. Then, for each row of grid boxes, the grid box with maximum mean elevation was chosen.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020229.

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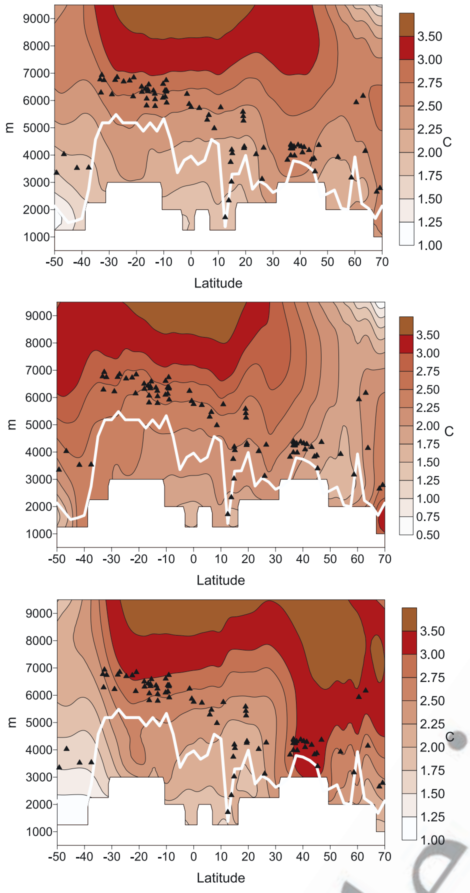

Figure 2. Mean change in temperature (2x CO_2 minus control runs) for the 7 models listed in Table 1. Data are displayed only for those latitudes and levels where data are available from all seven models. The solid white line connects elevations of the highest regions in each grid box; those elevations are the maximum of all the 5′ x 5′ ETOPO5 elevations in the grid box. The black triangles show some of the highest mountain peaks in each country along the transect. The white line crosses the missing data region in a few places due to some rounding in interpolation by the imaging software and to the topography files used by the models, which use sigma (or hybrid sigma) levels. *Upper panel*: mean annual temperature change; *Middle panel*: Dec–Feb mean temperature change; *Lower panel*: June–Aug mean temperature change.

dence is unequivocal in indicating that dramatic glacier retreat is underway already [*Thompson et al.*, 1993; *Brecher and Thompson*, 1993]. Ice core evidence from some locations also show that the heaviest oxygen isotope values of the last millennium were in recent decades, which has been interpreted as indicating the unusual nature of recent warming [*Thompson et al.*, 2003].

[10] Changes in temperature of the magnitude indicated in Figure 2 would likely result in the complete disappearance of glaciers from many regions due to an increase in the height of the equilibrium line altitude as freezing levels in the atmosphere rise in elevation [*Diaz and Graham*, 1996; *Diaz et al.*, 2003]. In the tropics, this may affect the lower margins of some glaciers, but a possible scenario is that increased humidity will reduce the vapor pressure gradient over the ice, leading to reduced sublimation and more melting (i.e., less energy being used in latent heat flux and more in sensible heat transfer). This would effectively lead to an increase in ice melting where solar radiation receipts are high (as in the inter-tropical zone) even in zones which remain below freezing [cf. *Wagnon et al.*, 1999]. Although the mechanisms may vary latitudinally, the overall effect will be for glaciers and ice caps to lose mass, with associated consequences for long-term water resources and hydropower production. Ecosystems downslope will also be affected, with the largest changes taking place in the alpine tundra and treeline zones. This could lead to treeline migration upslope in some areas, with associated reduction in the area of tundra ecosystems, though the exact response will also depend on precipitation changes. In those areas where temperatures rise and precipitation declines, ecosystem responses may be complex. In sub-tropical zones where mountains are forested to the summits, temperature changes may eliminate some ecosystems as they are forced to higher elevations that are more restricted in area [*Still et al.*, 1999]. Plant and animal populations may also become isolated in separate zones along particular mountain ranges. Such changes have important implications for planning of national parks and biosphere reserves that are designed for species conservation.

4. Implications for GCOS

[11] The Global Climate Observing System (GCOS) of the World Meteorological Organisation is a plan for long-term measurements at rural locations where very high

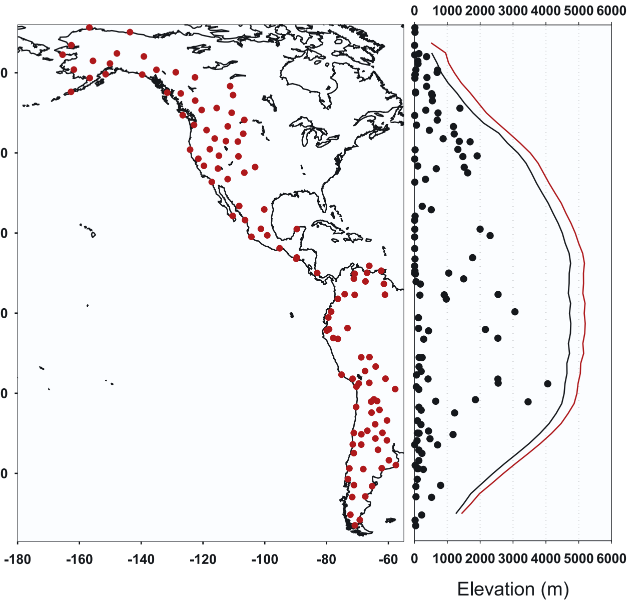

Figure 3. Distribution of planned GCOS station network in the western Americas and (on the right, black dots) the elevations of those stations with respect to latitude. Only 3 stations are planned for sites above 3000 m. Thus, the network fails to monitor those regions that model simulations indicate will have the greatest changes in temperature. Mean annual freezing level heights for control runs and 2x CO_2 simulations are shown at right, in relation to planned GCOS network.

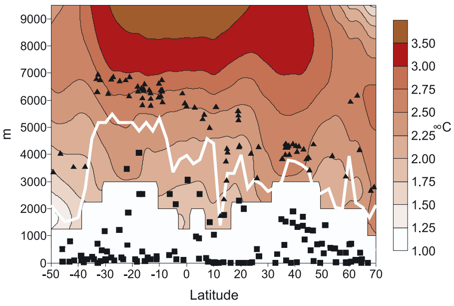

Figure 4. Mean annual change in temperature (2x CO_2 minus control runs) for the 7 models listed in Table 1 compared to the planned GCOS network (squares) shown in Figure 3. More stations at higher elevations are needed to properly assess the model projections and monitor the large changes that the models indicate will affect high montane regions. The small black triangles represent the highest elevation mountains in countries along the transect.

quality observations will be maintained indefinitely into the future [*Karl et al.*, 1995]. The goal is to establish for posterity a global climate monitoring network that will provide unequivocal data to assess climate changes. Figure 3 shows the planned GCOS network for the western part of the Americas with the distribution of those stations by latitude and elevation. Also shown are the mean annual freezing level heights averaged for the 7 model control and 2x CO_2 simulations. All GCOS stations are well below the freezing levels and only 3 stations are currently planned for elevations above 3000 m in the entire transect. Given that the model simulations indicate the largest changes in the future will be at high elevations, the GCOS network will not adequately sample the higher elevation zones of the American Cordillera where the impact of changes in climate may be greatest (Figure 4). The GCOS network should include a subset of stations at high elevation sites along the mountain chain, from southern Chile to Alaska [*Bradley and Hardy*, 2003]. Such a network will contribute to climate change detection and attribution, and to model verification studies. Furthermore, because the projected changes will inevitably affect the lower altitude range of the present snow zone, there is also a need for a range of stations, from altitudes at the current snow zone upwards through the altitude of projected (future) freezing levels. These could be established along selected transects across the main axis of the Cordillera. It is feasible to establish such a network, taking advantage of (for example) high elevation astronomical observatories, ski areas and mountain passes to facilitate access to the stations and instrument maintenance, without compromising station quality. Without such revisions to the current GCOS plan, areas that will be significantly affected by temperature change (and where changes already appear to be large) will not be adequately observed.

[12] These results are based on large-scale GCMs that provide a broad view of projected temperature changes in the future. They point to very significant changes that are consistent across many models. However, detailed regional climate modeling should be undertaken to refine this assessment of potential anthropogenic climate changes at the local level in areas with mountainous topography.

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References

Barnett, T., R. Malone, W. Pennell et al. (2004), The effects of climate change on water resources in the West: Introduction and overview, *Clim. Change*, *62*, 1–11.

Bradley, R. S., and D. R. Hardy (2003), A high elevation climate reference network for the Americas, in *Report of the GCOS Regional Workshop for South America on Improving Observing Systems for Climate*, *WMO/TD No 1183*, pp. 77–82, World Meteorol. Organ., Geneva, Switzerland.

Bradley, R. S., F. T. Keimig, and H. F. Diaz (1992), Climatology of surface-based inversions in the North American Arctic, *J. Geophys. Res.*, *97*, 15,699–15,712.

Brecher, H. H., and L. G. Thompson (1993), Measurement of the retreat of Qori Kalis in the tropical Andes of Peru by terrestrial photogrammetry, *Photogramm. Eng. Remote Sens.*, *59*, 1017–1022.

Covey, C., K. M. AchutaRao, U. Cubasch et al. (2003), An overview of results from the Coupled Model Intercomparison Project (CMIP), *Global Planet. Change*, *37*, 103–133.

Diaz, H. F., and N. E. Graham (1996), Recent changes in tropical freezing heights and the role of sea surface temperature, *Nature*, *384*, 152–155.

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

Gottfried, M., H. Pauli, K. Reiter, and G. Grabherr (2002), Potential effects of climate change on alpine and nival plants in the Alps, in *Mountain Biodiversity—A Global Assessment*, edited by C. Körner and E. M. Spehn, pp. 213–223, Parthenon, London.

Intergovernment Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.

Karl, T. R., F. Bretherton, W. Easterling, and K. Trenberth (1995), Long-term climate monitoring of the Global Climate Observing Systems (GCOS), *Clim. Change*, *31*, 135–147.

Liniger, H. P., R. Weingartner, and M. Grosjean (1998), Mountains of the world: Water towers for the 21st century—A contribution to global freshwater management, report, 32 pp., Mt. Agenda Inst. of Geogr. Univ. of Berne, Switzerland.

Mote, P. W. (2003), Trends in snow water equivalent in the Pacific Northwest and their climatic causes, *Geophys. Res. Lett.*, *30*(12), 1601, doi:10.1029/2003GL017258.

Quan, X., H. F. Diaz, and M. P. Hoerling (2004), Changes in the Hadley Circulation since 1950, in *The Hadley Circulation: Present, Past and Future*, edited by H. F. Diaz and R. S. Bradley, Springer-Verlag, New York, in press.

Seidel, D. J., and M. Free (2003), Comparison of lower-tropospheric temperature climatologies and trends at low and high elevation radiosonde sites, *Clim. Change*, *59*, 53–74.

Still, C. J., P. N. Foster, and S. H. Schneider (1999), Simulating the effects of climate change on tropical montane cloud forests, *Nature*, *398*, 608–610.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis et al. (1993), "Recent warming": Ice core evidence from tropical ice cores, with emphasis on central Asia, *Global Planet. Change*, *7*, 145–156.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis et al. (2003), Tropical glacier and ice core evidence of climate change on annual to millennial time scales, *Clim. Change*, *59*, 137–155.

Vuille, M., and R. S. Bradley (2000), Mean annual temperature trends and their vertical structure in the tropical Andes, *Geophys. Res. Lett.*, *27*, 3885–3888.

Vuille, M., R. S. Bradley, M. Werner, and F. T. Keimig (2003), 20th century trends in climate in the tropical Andes, *Clim. Change*, *59*, 75–99.

Wagnon, P., P. Ribstein, G. Kaser, and P. Berton (1999), Energy balance and runoff seasonality of a Bolivian glacier, *Global Planet. Change*, *22*, 49–58.

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