FINAL REPORT

Regional-Scale Climate Change: Observations and Model Simulations

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SUMMARY

This collaborative proposal addressed key issues in understanding the Earth's climate system, as highlighted by the U.S. Climate Science Program. The research focused on documenting past climatic changes and on assessing future climatic changes based on suites of global and regional climate models. Geographically, our emphasis was on the mountainous regions of the world, with a particular focus on the Neotropics of Central America and the Hawaiian Islands. Mountain regions are zones where large variations in ecosystems occur due to the strong climate zonation forced by the topography. These areas are particularly susceptible to changes in critical ecological thresholds, and we conducted studies of changes in phonological indicators based on various climatic thresholds.

1. Climatic changes at regional scales: the mountainous regions of the Americas

One of the key objectives of our research is to understand the nature of climatic changes in regions of the world that are likely to be most sensitive to future climate change. We have shown that, in addition to the well-known amplification of warming at high latitudes, future warming is also amplified with elevation within the lower troposphere and this has significant consequences for mountainous regions of the world (**Figure 1**; Bradley et al. 2009 and references therein). Mountain regions throughout the world have already experienced significant warming in the past 50 years (0.7–0.8ºC) with particularly large upward shifts in freezing levels in recent decades. Analysis of temperature data for the western U.S. reveals a similar pattern of change (Diaz and Eischeid, 2007).

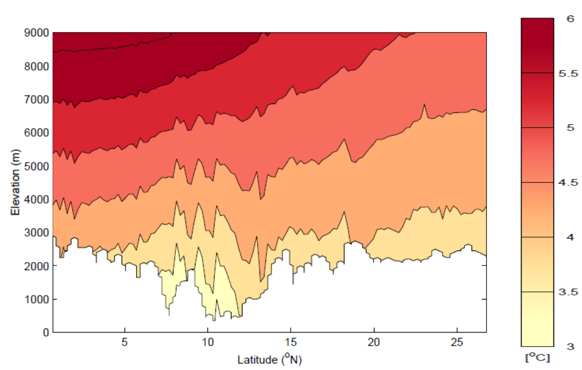

Figure 1. Changes in free air (mean annual) temperatures with height, from the Equator to 27N, in a

transect along the American Cordillera. Temperature changes are for scenario A2 versus baseline (1961-90), using the Hadley Center PRECIS RCM (discussed further below). Warming increases with elevation and thus the highest mountains near the Equator (4000-6500m) will experience more warming than areas at lower elevations.

We have extended previous investigations into changes in the height of the freezing level in the tropical atmosphere (Bradley et al. 2009). The free air 0-degC isotherm has increased across most of the region, particularly in the outer Tropics. In the tropical Andes, south of the Equator, surface temperatures and upper air data show a similar trend in temperature, of about 0.1-degC per decade over the last 50 years. Meteorological observations at 5680 m on the summit of the Quelccaya Ice Cap, the largest ice mass in the Tropics, indicate that daily maximum temperatures often exceed 0-degC from October-May, and rise well above freezing for much of the year around the ice cap margin at 5200 m. Consequently, the ice cap is rapidly losing mass. Similar conditions are affecting other high elevation ice caps and glaciers from Venezuela and Colombia to northern Chile, with important implications for water supplies across the region. Over the Tropics as a whole, freezing level height (FLH) is closely related to mean SSTs, with inter-annual variations in FLH controlled by the phase of ENSO variability (**Figure 2**). More extensive monitoring of climatic conditions at high elevations in the mountains of the Tropics is urgently needed to keep track on these changes.

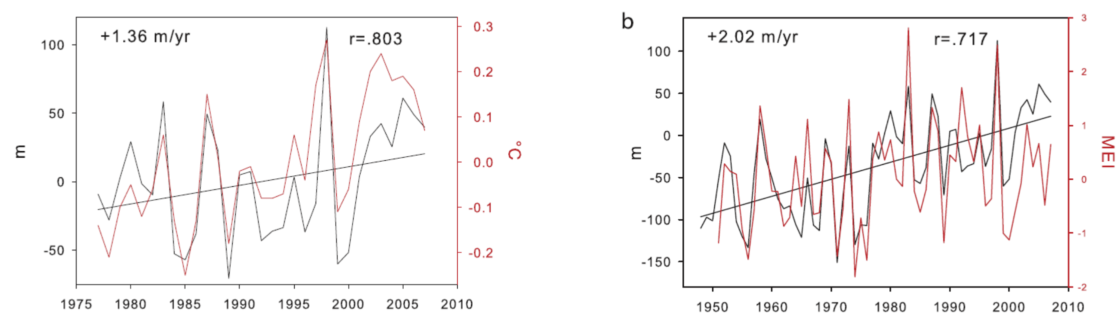

Figure 2a (left). Mean annual freezing level heights (relative to 1977-2007 average) from 28.75°N to 28.75°S, compared to SSTs averaged across the same region.
Figure 2b (right). Mean freezing level height departures from the 1977–2007 mean across the entire Tropics (28.75°N–28.75°S) compared to the November–March multivariate ENSO index (MEI). (Bradley et al., 2009).

We find that over the last approximately 30 years, freezing level heights across the Tropics have risen by about 45 m, on average. If this same relationship prevailed during glacial times, a mean SST cooling of 2-3-degC (as most paleo-oceanographic proxies now suggest) would have led to a fall in the zero degree isotherm across the Tropics of about 500-750 m, with obvious effects on glacierization throughout the mountains of the region. Additional factors such as an increase in snowfall and associated changes in albedo and net radiation accompanying the change in FLH would have reinforced the effects of lower temperatures, leading to more positive mass balance regimes, and increased glacierization of the high mountains.

Our research shows that in addition to the well-known amplification of warming at high latitudes, warming is also amplified with elevation within the lower tropical troposphere. We have analyzed changes in temperature and precipitation in Hawaii and also find a significant amplification of the warming signal with elevation, as well as a continuing disparity between trends in maximum and minimum daily temperatures (Giambelluca et al., 2008). In Hawaii, mean minimum temperatures have continued to rise at a higher rate than mean maximum temperature. At the same time, some areas in the Hawaiian Islands have received less rainfall with a tendency for smaller large-intensity events in the past 25 years. This work is aimed at identifying critical ecological and water resources systems and regions at risk from ongoing and predicted global climate change, with emphasis on understanding the nature of particular ecosystem thresholds in relation to changes in climate. Despite its tropical oceanic location, Hawaii has experienced rapid warming, especially since the mid-1970s. Both the long-term and recent temperature trends have been only slightly lower than the global trends: 0.05C per decade (Hawaii, 1919-2006) vs. 0.074C per decade (global, 1906-2005; IPCC, 2007, p. 253) and 0.163C per decade (Hawaii, 1975-2006) vs. 0.177C per decade (global, 1981-2005; IPCC, 2007, p. 253). Temperature variation in Hawaii appears to have been tightly coupled to the PDO, perhaps through regional SST variation. However, in recent decades air temperature trends in the Hawaii region have diverged from PDO and SST trends, perhaps signaling increasing influence of global warming.

The implied recent changes in the vertical lapse rate in Hawaii imply a shift toward a more stable atmosphere. This finding is consistent with observations of greater persistence of the Trade Wind Inversion and a downward trend in precipitation in recent decades. Should the vertical lapse rate trend continue, Hawaii's climate is likely to continue to become drier as warming continues. Reduced precipitation in combination with increased temperature would also result in significant impacts to water resources and vulnerable high-elevation ecosystems. The enhanced warming at high elevations in Hawaii is consistent with changes found in other tropical regions. In Hawaii, where upper mountain slopes harbor most of the remaining intact native ecosystems, rapid warming is likely to have severe impacts. Endangered Hawaiian honeycreepers (*Drepanidae*) currently find refuge in high-elevation forests, where low temperatures limit the activity of disease-carrying mosquitoes. If rapid warming continues at high elevations in Hawai'i, it will likely hasten the extinction of these birds.

We have collaborated on two studies, with colleagues in the People's Republic of China. The first examines trends in temperature across the Tibetan-Qinghai Plateau over the last 50 years. This shows exceptional warming over the last decade, especially in summer, with important consequences for glacier ablation at high elevations, and consequent impacts on runoff and regional hydrology. The second study examines future climate change impacts on ecosystems, using a couple of alternative methods to classify ecoregions for modern climate conditions from observations. The analysis was repeated using the IPCC AR4 GCM simulations from the Hadley Center HadCM3 coupled model for the second half of this century (Baker et al., 2010). In the last two decades of the 20th century the rate of warming (0.3C per decade) over China has been considerably greater than the global trend value of 0.19C per decade. Current fully-coupled general circulation models project that this trend will continue into the future with mean annual temperatures increasing 1.8 to 3.5C by 2050 and 2 to 7C by 2100. Our analysis shows that changes in climate by 2050, from projected anthropogenic forcings are likely to result in novel combinations of climate and topo-edaphic factors that will have substantial impacts on the distribution and persistence of natural vegetation and animal species. Moreover, these changes are sufficient to create environmental conditions that are not present anywhere in China today.

The Koeppen-Trewartha classification provided an additional method for visualizing and interpreting how climate space and consequently vegetation space shifted under a future scenario. Using this method we were able to document that the spatial patterns of climate change resulted in a northern migration of warmer climate types and an increase in the elevational limits of forests as well as a slight expansion in the high latitude desert and arid shrubland regions in northwestern China (**Figure 3**). These shifts were consistent with observations of impacts on vegetation from recent climate change and future predictions from more process-based vegetation models (Baker et al., 2010).

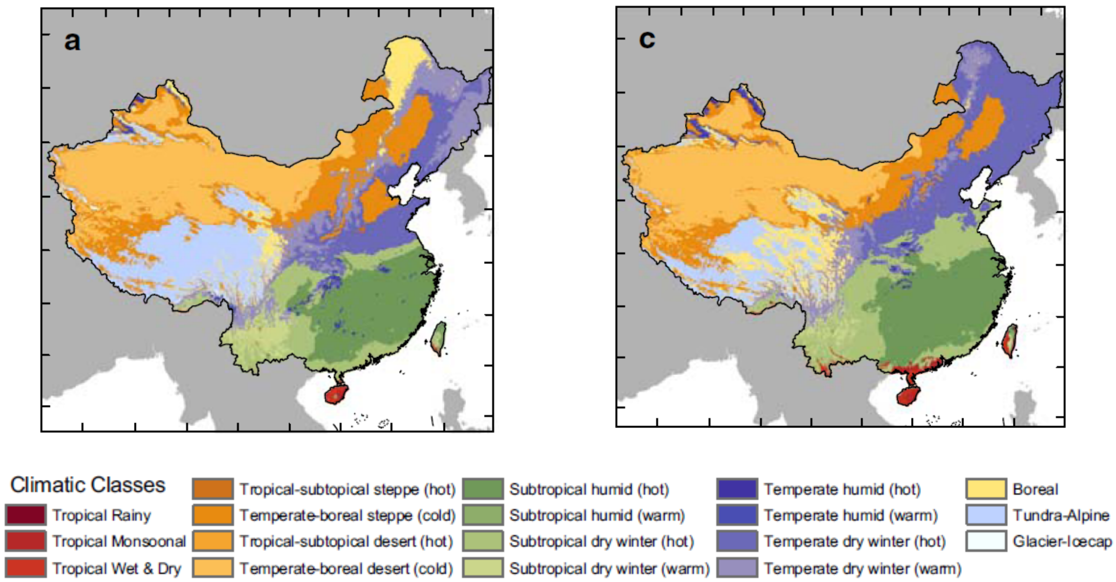

Figure 3. Spatial representation of Köppen–Trewartha climate classification for the People's Republic of China. **(left)** Climate classification of the historical climate for the individual cells of the PRISM climatology (30-year average 1961–1990). **(right)**Climate classification of the individual cells of the climate data for the 2050s time period (30-year average 2041–2070) under the HadCM3 A1FI scenario (Baker et al., 2009)

As noted, mountain regions (particularly in the Tropics) are centers of biodiversity and rising temperatures may lead to extinctions as ecosystems become isolated and reduced below the critical size needed to maintain particular species. In many parts of the Neotropics, upland forests are under threat from a burgeoning population, but tremendous efforts are nevertheless underway to preserve ecosystems as biosphere reserves and national parks. It is important to ensure that these efforts take into account possible changes in climate resulting from anthropogenic greenhouse gases. Mountain biosphere reserves—regions of high relative relief, where the sharp vertical gradients in temperature lead to the establishment of closely stacked ecosystems—are particularly vulnerable to climate changes, as small changes can have large impacts on ecosystem functions and biodiversity. Amplification of temperature changes with elevation would have particularly serious consequences for the mountain biosphere reserves of Costa Rica and adjacent regions, which have been set aside to preserve biodiversity. Indeed, biological changes associated with changes in climate have already been identified in the Monteverde Cloud Forest Preserve in Costa Rica.

Since our goal is to understand climate change in areas of high relief in the tropics and the potential impacts on ecosystem dynamics, higher resolution simulations were undertaken. For the Central America study we used the UK Hadley Center PRECIS ("***P***roviding ***RE***gional ***C***limates for ***I***mpact ***S***tudies") regional climate model. The model is based on an improved version of the atmospheric component of the latest Hadley Center coupled climate model, used in the AR4 IPCC assessment. We carried out a control run (1961-1990, with observed SSTs and sea-ice.) and a doubled CO_2 run (SRES A2, and A1B 2071-2100) at a resolution of 25 km (0.22^o) over the region of Central America (**Figure 4**) that includes several biodiversity hotspots. Model verification was performed by comparing control run results with observations and reanalysis data.

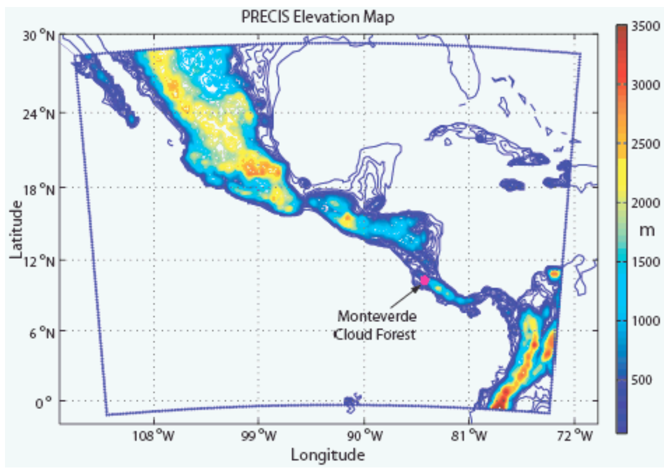

Figure 4. Model domain and topography of the region studied. The model grid is of size 136 x 179. The maximum elevation is 3286m. A buffer zone of eight grid cells along the boundaries, used to relax RCM values to the GCM integration, is omitted from the analysis.

The temperature comparison used data from the Global Historical Climate Network (GHCN), the Climate Research Unit (CRU), the National Centers for Environmental Prediction (NCEP**)**, and the North American Regional Reanalysis (NARR); for precipitation we used CRU and Global Precipitation Climatology Center (GPCC) data. Our analysis shows that PRECIS successfully captures present-day observed spatial and temporal climate variability. In general, the model does a reasonable job of simulating interannual variability compared to the observations (**Figure 5**; Karmalkar 2010; Karmalkar et al**.**, 2011).

The overall model performance (spatio-temporal variability) is presented in the form of a Taylor diagram for the main climatic regimes in the region (**Figure 5**). Temperature at 1.5 m (circles) is particularly well simulated, with the model closely matching the observed magnitude of variance and exhibiting a pattern correlation with the modern datasets >0.95. Precipitation (triangles) is simulated less well, but the simulated variance is still within ±25% of observed values and the correlation with observations is about 0.6.

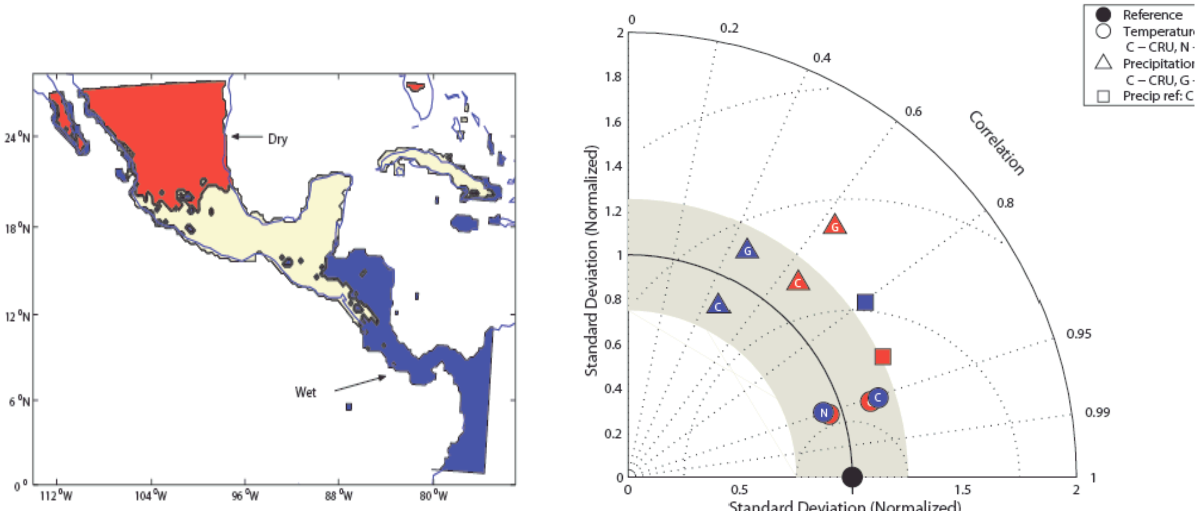

Figure 5. (**left**): Principal regional climate regimes (based on cluster analysis of temperature and precipitation data);
(**right**): "Taylor diagram" showing second-order statistics of model 1.5m temperature (circles) and precipitation (triangles) for the regions shown on left. The radial co-ordinate gives the magnitude of total standard deviation, normalized by the observed value, and the angular co-ordinate gives the correlation with observations. It follows that the distance between the reference (observed/reanalysis) point and model statistics points is proportional to the r.m.s model error. Symbols denote different comparison datasets (C=CRU temperature & precipitation; N=NARR precipitation, G=GPCC precipitation).

Compared to the present-day climate, SRES A2 simulations show 4K warming over land areas and about 3K increase in sea surface temperatures. A comparison between the baseline and a doubled CO_2 experiment also shows elevation dependency, resulting in more pronounced warming at high elevations (**Figure 6**).

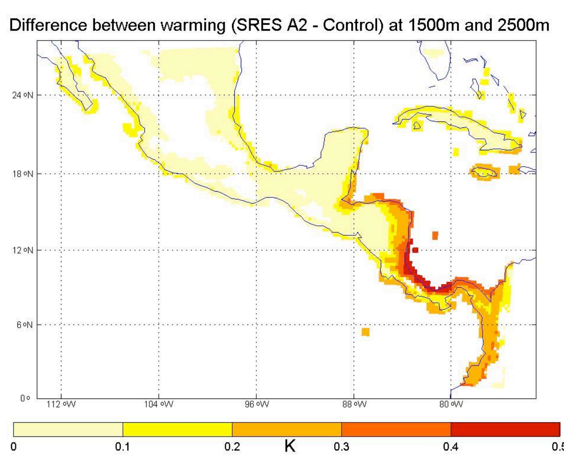

Figure 6. Warming is expected to increase with elevation. This figure shows the difference between warming (SRES A2–Control Run) at 1500m and 2500m. Warming at 2500m is up to 0.5K greater in some regions than that at 1500m.

During the dry season the moisture input from horizontal precipitation processes is critical for cloud forests that are already stressed from reduced rainfall. Studies have shown reductions in mist frequency or moisture input from horizontal precipitation processes in the Montverde cloud forest region since the mid-1970s. Relative humidity, used as a proxy for cloud base heights (**Figure 7**) and precipitation and soil moisture show drier conditions south of ~20ºN, in 2xCO_2 world. Additional studies are needed to identify critical ecological thresholds and to extract these parameters (or proxies thereof) from the model simulations.

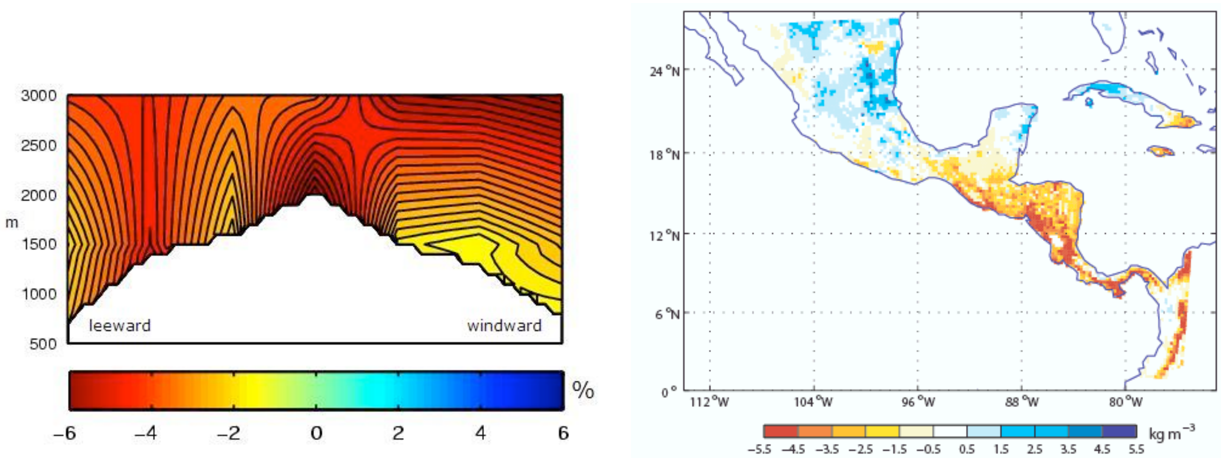

Figure 7. (left) Relative humidity difference (in %) between doubled CO_2 and control run along a transect (NW-SE) across Costa Rica. Leeward slopes will be considerably drier in future compared to present-day conditions.
(Right): Simulated change in soil moisture (kg m^{-3}) for April under 2xCO_2 conditions.

A number of different methods were used to demonstrate the model's success in simulating spatial and temporal variability of temperature and precipitation (Karmalkar et al. 2010a). The temperature bias has modest values across the model domain, and is higher in the wet season than the dry season. Uncertainties in the driving data and also in the comparison data sets could explain a part of the temperature bias. The bimodal annual cycle of precipitation in the region is well simulated by the regional model. PRECIS shows a dry precipitation bias in the wet season and a wet bias in the dry season suggesting that it does not fully capture the precipitation variability in the region. Since the model uses observed sea surface temperatures as the surface boundary conditions for the baseline run, the temperature and precipitation variability related to ENSO is well captured by the model. The Caribbean low-level jet, which is a major source of moisture to Central America, is well simulated in terms of its position, magnitude and the spatial extent. Overall, the model demonstrates its skill in simulating large-scale and regional temperature and precipitation variations in Central America and Mexico giving us some confidence in its use for assessing future climate projections.

A combination of the EOF analysis and cluster analysis on simulated temperature and precipitation data produced clusters that resemble the large-scale climate regimes observed in Central America and these clusters were used to quantify model biases for different regions within the model domain. In the case of surface air temperature, PRECIS shows a cold bias with respect to CRU and a warm bias with respect to the NARR data. Lapse rate calculations for a variety of data sets including the GHCN and WorldClim station data suggest that although CRU has a warm bias at high elevations, it does not fully explain the cold bias seen in PRECIS. The model lapse rate for high elevations is indeed steeper than all the comparison data sets suggesting that the model indeed has a cold bias. The cold bias is higher in the wet season than that in the dry season and also increases with elevation when compared to the CRU data. In study by Karmalkar et al. (2010) we considered the following questions: (1) why does the model show a cold bias? (2) why does the bias increase with elevation?, and (3) is temperature bias related to precipitation bias? One of the candidates for the systematic cold bias in PRECIS could be the driving GCM. The third generation Hadley Centre atmospheric model (HadAM3), which provides boundary conditions for PRECIS has been tested thoroughly for its performance. HadAM3 results compare well with the observed mean climate and also with other climate models in the Atmospheric Model Intercomparison Project. In the tropics, HadAM3 performs better than the AMIP ensemble mean throughout the troposphere. Overall, HadAM3 has been shown to produce a good simulation of the present-day climate when forced with observed sea surface temperatures, which is how it is employed in the validation phase of this study. Nevertheless, a cold bias at all tropospheric levels in the tropics is detected in HadAM3 simulations. There is also a dry bias in the tropical middle troposphere that could result in cold bias in temperature at those levels. Model cold bias is however, not constant across the region and seasons. The bias is higher in the wet season and lower in the dry season. The cold bias is particularly high in the highlands of Mexico where precipitation is overestimated in the wet season. Excess precipitation in the region may result in anomalously wet soils, which would lead to low sensible heat flux and therefore lower surface temperatures. But a similar mechanism cannot explain the cold bias in Central America, which occurs in spite of simulated precipitation being severely underestimated in this region.

Although PRECIS has successfully captured various precipitation patterns in the CAM region, there are considerable differences in the precipitation amounts between the model and observations. PRECIS amounts are smaller (larger) than the observed (GPCC) precipitation in the wet (dry) season. A dry precipitation bias in the wet season and a wet bias in the dry season indicate that PRECIS does not fully capture the precipitation variability in the region. The current suite of coupled global climate models (PCMDI models) has difficulties in realistically simulating regional precipitation patterns and their temporal variations. Precipitation has a heterogeneous spatial nature, which is a result of the complex interaction between several processes such as convection, cloud microphysics, boundary-layer processes to name a few. Errors in simulated precipitation fields arise due to incomplete understanding and representation of these processes in climate models.

Most global climate models underestimate precipitation in Central America partly due to underestimation of SSTs and coarse horizontal resolution. In particular, the Hadley Centre global model, HadCM3 severely underestimates cloud cover over most of the globe, especially over low-latitude oceans, which would result in underestimation of precipitation. Despite the difficulties in simulating PRCP amounts correctly, the regional model certainly shows an improvement over the predictions by the GCMs in the PCMDI data sets presented by Rauscher et al. (2008). PRECIS shows dry bias mainly in the late wet season when a significant fraction of total precipitation comes from tropical storms. The model's inability to simulate storms realistically might explain the dry bias. However, since the daily model output is unavailable in our analysis, this claim is difficult to assess. In general, models have a tendency to overestimate the frequency of light precipitation and underestimate the intensity of heavy precipitation over land (Sun et al. 2005), which can also be seen in the PDFs of simulated PRCP here. One of the other model validation approaches is to look at the model's skill at simulating known regional-scale circulation features. PRECIS was tested for its ability to simulate the annual cycle of PRCP, the Caribbean low-level jet and the response to ENSO variations. The bimodal nature of the annual cycle of precipitation is one of the unique features of this region and is well captured by PRECIS. The structure and variations in the Caribbean low-level jet are also well simulated by the regional model. The SAT variability in Central America is tightly coupled to the ENSO variations in the eastern equatorial Pacific. Since the baseline run is driven by the observed SSTs, the SAT variations in Central America indicate a strong influence of warm ENSO episodes during the simulation period from 1961 to 1990.

The warm phases of ENSO (the El Niño events), which could become more frequent as a result of increasing temperatures, have been observed to have negative consequences on the climate of Central America. Observations and our present-day simulation show a consistent pattern of positive SAT anomalies and negative precipitation anomalies over Central America during the warm phase of ENSO. The reverse is true for the cold phase (La Niña). To diagnose some of the biases detected in PRECIS, a detailed study of more PRECIS experiments with different boundary conditions is required. Nonetheless, detailed information on PRECIS biases and an overall success of the model in capturing the temperature and precipitation mean and variability patterns in Central America gives us confidence in interpreting climate change projections for the region.

We examined regional climate change projections under the A2 scenario (Karmalkar et al. 2010). Warming in Central America and Mexico as predicted by the regional model (PRECIS) is higher than the global average warming under the A2 scenario (**Figure 8**). In general, the warming is higher in the wet season (over 4 degrees C) than the dry season. The Yucatan Peninsula shows the highest warming, whereas the windward slopes of Costa Rica and Panama show the least warming within the model domain. A large reduction in precipitation in the wet season is projected for Central America and Mexico under the A2 scenario, which is likely related to southward displacement of the ITCZ and/or intensification of the North Atlantic Subtropical High. Parts of Central America that receive a considerable amount of moisture in the form of orographic precipitation show significant decreases in precipitation in the dry season. These projected changes in temperature and precipitation are similar to but greater than those observed during the El Nino events in recent decades, which have been shown to have adverse effects on certain species in the forests of Costa Rica. Therefore, projected climatic changes will likely have detrimental impacts on biodiversity, agricultural activities and the water resources of the region.

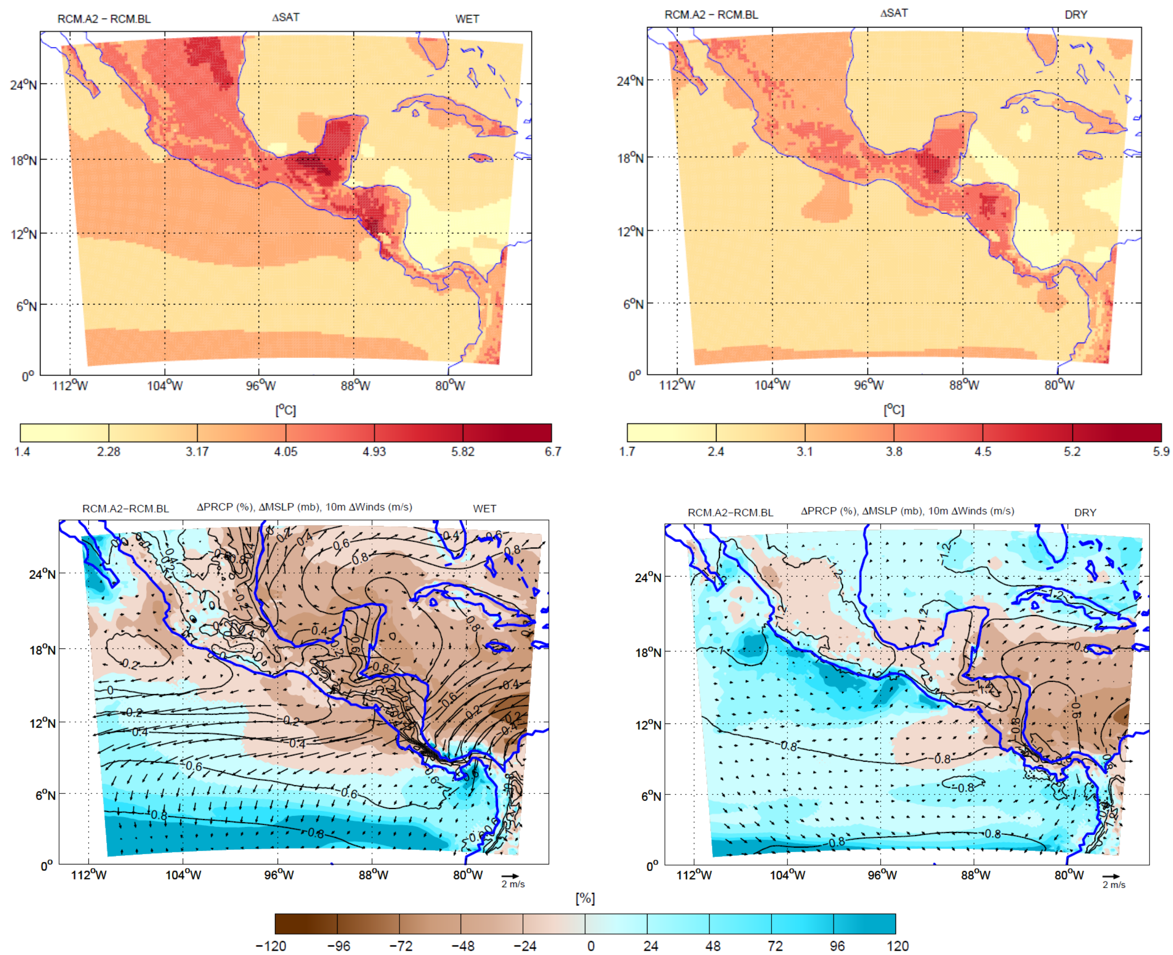

Figure 8. Projected % changes in seasonal temperature (°C) and precipitation (scenario A2-baseline) for wet season (**left**) and dry season (**right**). Lower figure colors: % change with respect to BL; MSLP contours in mb, and arrows = 10m winds, in m/s). Percentage changes within +/-20% are not significant at 95% level (Karmalkar et al., 2010b).

An increase in sea surface temperatures and lowland deforestation have both been suggested as responsible for the rise in lifting condensation level (LCL) (or cloud base heights) observed in the Monteverde region in Costa Rica. Since PRECIS does not account for the land-use change, it is possible to isolate the effect of SSTs on the change in LCL. Our analysis shows an increase in cloud base heights along the Pacific slopes of Monteverde Cloud Forest region due to warmer SSTs. However, a slight decrease in the cloud base heights is seen along the Caribbean slopes, which could be a result of increased moisture flux from the Caribbean. Based on our downscaling work for Costa Rica under the A2 emissions scenario, mean temperatures increase by 3.15K and 3.3K 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 probability distribution function (PDF) for high elevations lies completely outside the range of present day temperature PDFs.

Our analysis suggests a need for better understanding of the role that Pacific and Atlantic SSTs play in this region, particularly in terms of moisture transport, and the modification of vertical temperature profiles. We note that SST has been very high in the Caribbean Basin since the late 1990s, and this could have also impacted surface temperature—particularly maximum temperatures at high elevation in Central America (**Figure 9**).

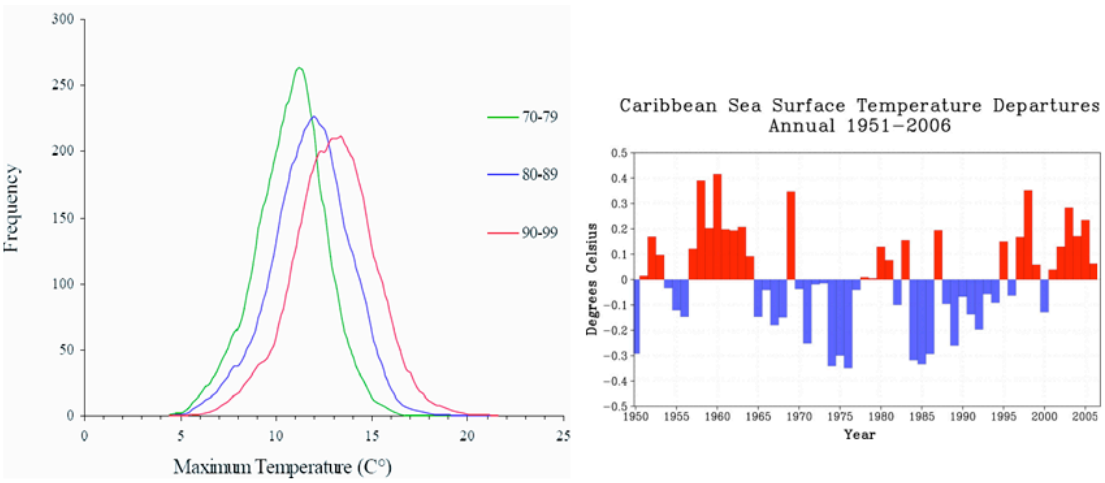

Figure 9. Frequency distribution of daily maximum temperature at Cerro de la Muerte (Costa Rica, 9˚ 42'N, 83˚ 45'W, 3130m asl) during the three decades, 1970-79, 1980-89 and 1990–99. [Courtesy of Dr. Jorge Amador, University of Costa Rica, San Jose] and time series of annual mean Caribbean SST anomalies spanning this interval.

2. Climate change and ecological thresholds

In contrast to the largest hemispheric and global scales, regional patterns of changes in mean temperature and precipitation in relation to global mean changes may result in a significant amplification of the warming signal at the regional scale. For example, the recent warming in the Caribbean region (**Figure 9**) has been accompanied by a sharp decline in precipitation in the Greater Caribbean Region as illustrated in **Figure 10**. For comparison, **Figure 11** shows decadal scale temperature change for the western United States. Note that increasing temperatures of the past few decades appear to be changing rapidly compared to the natural variability evident in the previous ~100 years. The last two decades of record, and the period 1995–2005, in particular, is almost entirely outside the range of values that may be considered indicative of natural climate variability and this has affected the frequency of extreme events.

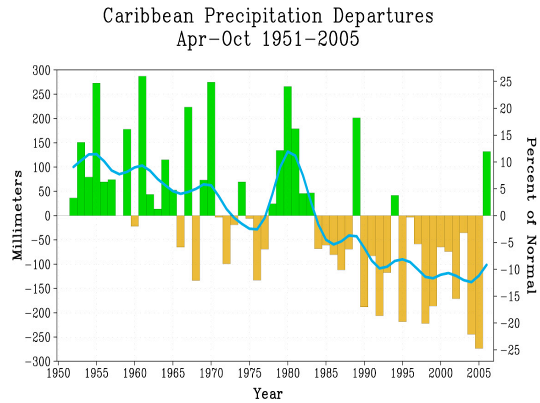

Figure 10. Land precipitation anomalies for the rainy season in the Greater Caribbean Region.

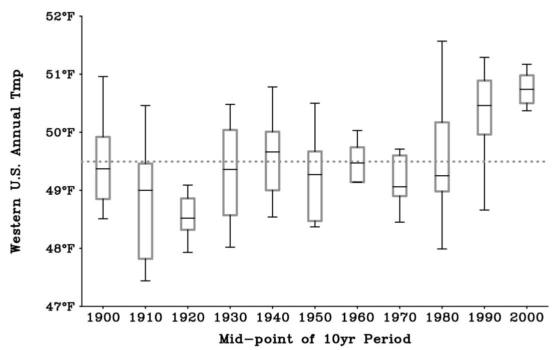

Figure 11. Decadal distribution of mean annual temperature for the western US, 1895–2005. Outer edge of boxes and inner black line represent the 25th, 75th, and median values of the annual means by decade, respectively. The inner (outer) fences approximate the 5th (95th) percentiles of the annual values for each decade.

3. Past climatic variations: climate change detection and attribution studies

Placing recent changes of climate in a long-term context is essential in order to assess the relative importance of anthropogenic versus natural climate forcing. We have undertaken a number of paleoclimatic studies to investigate this matter, with a focus on changes at the regional level (Bradley, 2007a; Diaz and Stahle, 2007). We are particularly interested in persistent (decadal and longer-term) climate changes recorded in different parts of the world during the pre-instrumental period, and how these may have impacted societies at the time (Bradley 2007b). Are these related to persistently anomalous circulation modes and/or SST anomalies? This question was addressed in terms of a multi-disciplinary analysis of major climatic events in the past ~1500 years in the Americas. We reasoned that severe and sustained climatic anomalies in the past must have affected societies living in the Americas during this time. The analysis emphasized both the timing of regional climate anomalies with respect to major cultural changes, and evidence that the climatic event was significant (abrupt, unprecedented and persistent) in the context of climate variability during this interval. Results were compiled in a special volume of the journal *Climatic*

Change, (titled, "*Climate and Cultural History in the Americas*") published in 2007 (Diaz and Stahle, 2007).

Many paleoclimate reconstructions (of both temperature and drought) rely on tree-rings and related studies. A book volume has been published that summarizes the current state of play in this field (*Dendroclimatology: Progress and Prospects*; eds. M. K. Hughes, T. W. Swetnam, and H. F. Diaz, 2010). Finally, we continued our long-standing collaboration with historical climatologists in Europe. This includes research on historical records of climate from the Americas and the development of an improved El Niño chronology since the 16th Century (Garcia et al., 2007) in collaboration with faculty of the University of Madrid and the publication of a volume on *Climate Variability and Extremes during the Past 100 Years* (Brönnimann et al., eds.) in collaboration with Swiss colleagues.

Our paleoclimate research activities have also involved a number of modeling studies, examining temperature changes at the hemispheric or global scale and investigations of regional climate variations in relation to specific forcings. Understanding the effect of volcanic forcing on the region using instrumental data from the last century is difficult because the sample size is small and most of the largest eruptions coincided with strong El Niños. With a much larger sample of explosive eruptions over the last millennium, model simulations reveal a clear pattern of reduced summer monsoon rainfall in southern China, and higher rainfall to the north. This is related to a weaker East Pacific High Pressure system, which reduces moisture advection from the south (**Figure 12a**). Those results are supported by historical records from China that show the same regional response pattern (**Figure 12b**).

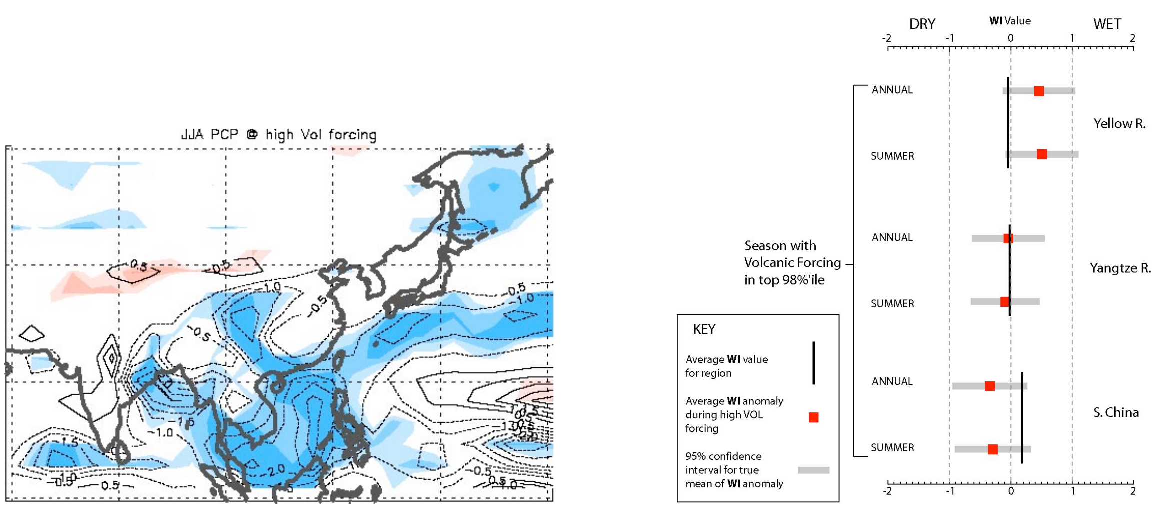

Figure 12. (**a**:**Left panel**): Summer (JJA) precipitation anomalies (mm/day) in the CSM simulations of the last millennium for those periods associated with major explosive volcanism.
(**b:Right panel**): Historical records of rainfall anomalies over China (North to South) during the same volcanic episodes as used in the CSM simulation.

Many studies suggest that temperature changes (on a hemispheric or global scale) over the last millennium were driven by volcanic and solar forcing; however, there have been relatively few studies that address regional scale changes during this time. The so-called "Medieval Warm

Period" (MWP) is of particular interest in this regard. We are currently involved in bringing different lines of evidence to bear in order to establish more accurately the regional patterns and temporal characteristics of the climate of this period and to understand its causes. It is clear that there were considerable climatic variations during Medieval time, and simply characterizing the period as the MWP is not helpful. We have compiled evidence indicating that climate in Medieval times was anomalous in many parts of the world, especially in terms of precipitation regimes, and we plan to continue further studies to understand this important period. Although cosmogenic isotope data indicate that solar activity was higher in Medieval time, it is not yet clear whether solar irradiance was higher, and if so, by how much. Solar forcing remains somewhat enigmatic, but our research shows that there does appear to be a coherent pattern in regional climate anomalies during times of reduced solar activity **(Figure 13**). This involves, *inter alia,* an expanded polar vortex, with westerlies displaced equatorward, and weaker East and South Asian monsoons (Bradley, 2007c). These preliminary findings are intriguing, and suggest that solar forcing may influence climate dynamics in complex ways, with important regional consequences. We plan further analysis of this matter by reviewing additional paleoclimate studies that claim a solar connection, to compare with published model simulations that involve changes in solar forcing.

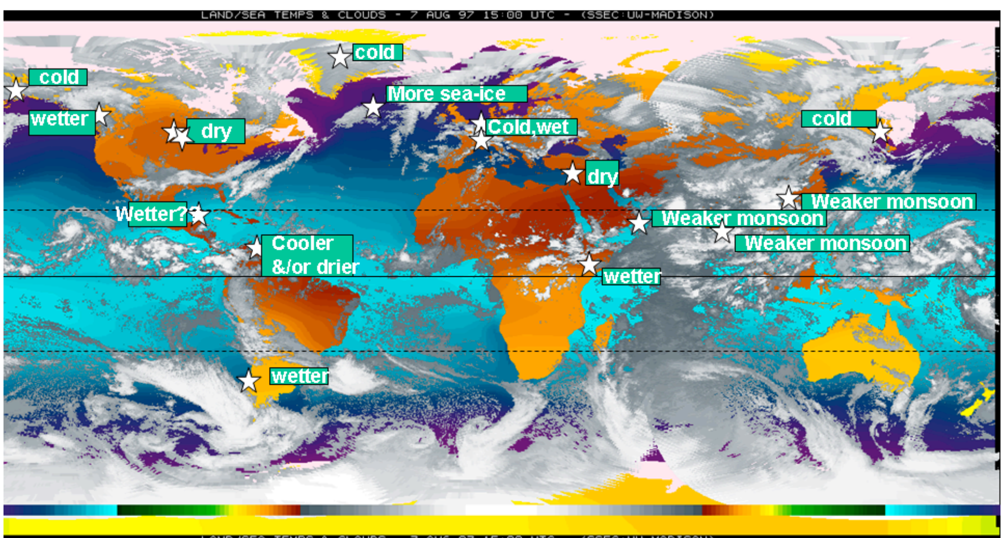

Figure 13. Climatic anomalies associated with periods of low solar activity, as derived from the paleoclimate literature (from Bradley, 2007c).

4. Temperature changes over the last 2000 years.

Surface temperature at hemispheric and global scale for much of the last 2,000 years were reconstructed using a greatly expanded set of proxy data for decadal-to-centennial climate changes (Mann et al., 2008, 2009). Our results extend previous conclusions that hemispheric-scale warmth of the past decade for the NH is anomalous in the context of the past 1,300 years from reconstructions that do not use tree-ring proxies (**Figure 15**). This conclusion can be extended back to at least the past 1,700 years if tree-ring data are used, but with a number of caveats relating to the nature of the tree ring records. When differences in scaling between previous studies are accounted for, the various current and previous estimates of NH mean surface temperature are largely consistent within uncertainties, despite the differences in methodology and mix of proxy data back to approximately A.D. 1000. The reconstructions appear increasingly more sensitive to method and data quality and quantity before A.D. 1600 and, particularly, before approximately A.D. 1000.

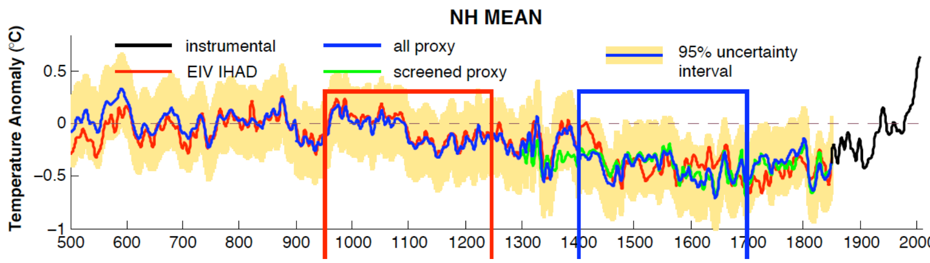

Figure 15. Decadal Surface Temperature Reconstructions averaged over the Northern Hemisphere. Shading indicates 95% confidence intervals. The intervals best defining the Medieval Climatic Anomaly (MCA) and Little Ice Age (LIA) are shown by red and blue boxes, respectively. For comparison, results are also shown for parallel ("screened") reconstructions that are based on a subset of the proxy data that pass screening for a local temperature signal.

This study was extended by looking at the spatial patterns of temperature anomalies in Medieval time, and during the "Little Ice Age" (Mann et al. 2009). We used a global climate proxy network to reconstruct surface temperature patterns over these intervals (**Figure 16**).

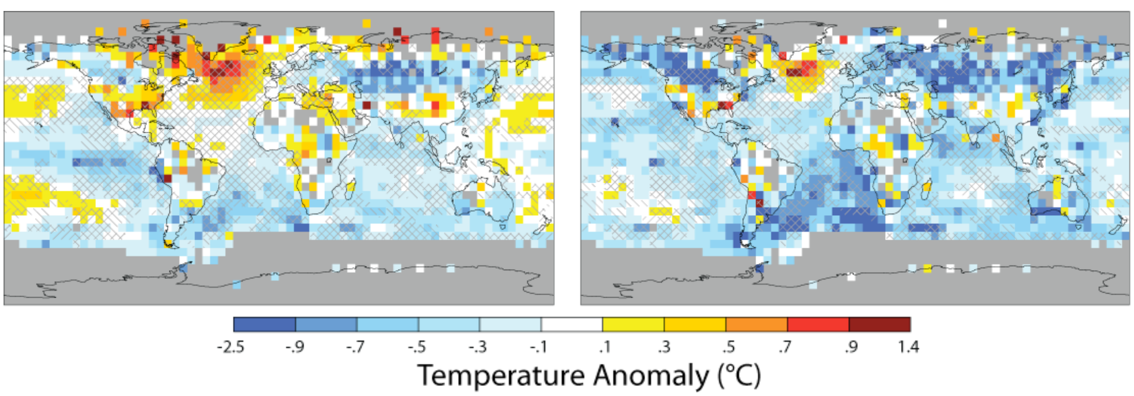

Figure 6. Reconstructed surface temperature pattern for (**left**) MCA (950 to 1250 C.E.) and (**right**) LIA (1400 to 1700 C.E.). Shown are the mean surface temperature anomaly (left) and associated relative weightings of various proxy records used (indicated by size of symbols) for the low-frequency component of the reconstruction (right). Anomalies are defined relative to the 1961–1990 reference period mean. Statistical skill is indicated by hatching [regions that pass validation tests at the P = 0.05 level with respect to RE (CE) are denoted by / (\) hatching]. Gray mask indicates regions for which inadequate long-term modern observational surface temperature data are available for the purposes of calibration and validation.

The Medieval period was found to display warmth that matches or exceeds that of the past decade in some regions, but which falls well below recent levels globally. This period was marked by a tendency for La Nina-like conditions in the tropical Pacific. The coldest temperatures of the Little Ice Age were observed over the interval A.D. 1400 to 1700, with greatest cooling over the extra-tropical Northern Hemisphere continents. The patterns of temperature change imply dynamical responses of climate to natural radiative forcing changes involving El Nino and the North Atlantic Oscillation-Arctic Oscillation. These paleoclimate reconstructions have important implications for future climate change. For example, if the tropical Pacific thermostat response suggested by our analyses of past changes applies to anthropogenic climate change, this holds profound implications for regional climate change effects such as future drought patterns.

Publications arising from current DOE project (2007–2010)

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