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Research for Mountain Area Development: Climatic Fluctuations in the Mountains of the Americas and Their Significance

Twentieth century temperature trends in the Western Cordilleras of the Americas broadly reflect the global signal of warming and decreasing diunal temperature range. Precipitation changes are more modest and vary strongly with region. Mountain glaciers have retreated considerably since the Little Ice Age in response particularly to the temperature rise and an upward shift in tropical freezing level over the last three decades. The changes are already affecting hydrologic regimes. Potential negative ecological consequences for the cloud forest ecosystem have also been suggested. Andean agriculture might benefit, however, from an upward shift in the zone of frequent frosts.

INTRODUCTION

The major mountain ranges of North America and South America present an almost continuous north-south barrier from the Arctic Circle to Tierra del Fuego. They are continuously highest in Bolivia – Peru, where individual peaks rise above 6000 m, although in Chile – Argentina around 32°S individual peaks reach almost 7000 m. The mountains are widest in the United States where the Cordilleras and the southern Rocky Mountains including the intermountain basins span some 1200–1500 km, compared with 700–1000 km in British Columbia. In South America, in contrast, the Andes are only some 50–100 km wide in central Chile – Argentina. In Alaska, the main ranges are oriented east-west. There are also high mountains and plateaus in Arctic and subArctic Canada from Ellesmere Island to coastal Labrador, with several major ice caps in the Queen Elizabeth Islands. The Appalachians in the eastern United States and the coastal mountains of southeastern Brazil (1) represent "Middle Mountains". Whereas the western mountains of North America are sparsely populated, the Altiplano of Bolivia – Peru has had a long history of settlement by indigenous peoples. Nevertheless, the mountains of western North America are heavily used for recreational purposes, year-round. These mountains also serve as the "water towers" of the populations in the lowlands of the western half of the country, through runoff from their winter snowpacks (2). About 67% of the annual precipitation falls as snow in the Sierra Nevada, 62–64% in most of the Rocky Mountains of western Colorado-Wyoming-Montana and, even in the mountains of Arizona and New Mexico, the proportion is 39% (3). Some 90% of the water use is for agricultural irrigation.

A generalized north-south profile of snowline along the Cordillera of the Americas (4) shows that it rises from near sea level around 80°N and 70°S to its highest levels around 25°N and 15°S rather than at the Equator. Indeed, the snowline exceeds 6000 m in Bolivia. In Bolivia and Peru, the snowline is around 5000 m or above in the Western Cordillera, but only 4400–4700 m in the Eastern Cordillera, reflecting the influence of moisture availability from the east (5). The altitude of the upper treeline broadly parallels that of the snowline. At 19°S in northern Chile, the treeline is as high as 4900 m (6). The rapid rise in the upper treeline northward from around 3100 m in Panama and Costa Rica to 3800–3900 m in Guatemala is noted by Hastenrath (7). The climatic aspects of ecological features in tropical mountains are thoroughly discussed by Sarmiento (8). In North America, treeline and snowline rise inland from the Pacific coast in response to higher summer temperatures and lower precipitation amounts (9). Superimposed on these large-scale patterns are local gradients related to climatic contrasts between windward/leeward slopes and sunny/shaded slopes (10). Because measurements are seldom available to document such topoclimatic contrasts by direct methods, ecological indicators are commonly used (11–13).

The interaction of orography with the prevailing wind systems and storm tracks has major consequences for continental and regional climates. In North America, the Cordilleras confine the maritime influences of the Pacific Ocean to a narrow coastal zone, while the Rocky Mountains exert considerable modifications on cyclonic systems and air masses (14). Indeed, the topographic barriers give rise to zones of lee cyclogenesis and downslope foehn (chinook) winds in Colorado and Alberta. There are corresponding effects to the east of the southern Andes. The Alaska Range presents a similar barrier to the northward movement of mild, moist Pacific air into interior Alaska. In the mid-latitude westerly wind zones of both hemispheres, precipitation amounts generally increase with elevation on the western slopes, although slope exposure and orientation are the most important controls (15). In northern South America, Central America and Mexico, the western Cordilleras also modify the tropical easterly winds. West slope foehn effects have been identified in Colombia and Venezuela (16) and hyperarid conditions prevail along the west coast of tropical South America. In these tropical areas, annual precipitation amounts typically show an altitudinal maximum between about 800 and 1200 m, near the mean cloud base. Amounts decrease at higher elevations due to subsiding air above the trade wind temperature inversion.

RECORDS OF CLIMATIC CHANGE

Instrumental Data

During the 20th century (1901–1997), the annual global surface temperature has risen by 0.62°C (17). Warming was greatest during the periods 1925–1944 and 1978–1997 and was most marked over the northern continents in winter and spring. Also, the four warmest years on record all occurred in the 1990s. In the context of this review, it is noteworthy that temperatures during 1978–1997 have risen in western North America, except in Alaska where there has been cooling in all seasons except summer. In western South America, there is cooling south of 35°S in summer. Both maximum and minimum temperatures have risen substantially during 1901–1997 in coastal Alaska, the Yukon and British Columbia, and in southern South America, while the diurnal temperature range (DTR) has decreased slightly in these same areas. A reduction in DTR is widely reported at lowland stations in many parts of the world (18). The 1° x 1° grid box results of Jones et al. (17) can be augmented by a few case studies in the mountain regions of the Americas. Records beginning in the mid-1940s at stations in Bolivia, Colombia, and Venezuela all show sustained increases in minimum temperatures after the 1960s–1970s (19, 20). The records for La Paz, where measurements are available for 1918–1990, confirm little change in diurnal temperature range until the 1960s.

In Canada, precipitation records for the mountain regions of southern British Columbia (SBC) and northern British Columbia – Yukon (NBC-Y) show statistically significant increases in all seasons except summer. Mekis and Hogg (21) report decadal increases of 3.0% for annual precipitation and 4.8% for snowfall in NBC-Y with corresponding winter values of 5.8% and 5.6%, respectively, during 1939–1995. In SBC, the decadal increases are about half as great, but they have operated over the last century, 1895–1995. These results are based on careful application of corrections to the gauge measurements of precipitation. Changes in snowfall are based on consistent ruler measurements of snow depth and density data.

Annual precipitation records in southern South America, some beginning in the late 19th century, show negative trends west of the Andes, but increases east of the Andes (22). The increases mostly occur during the 1950s–1960s in the form of a jump, which amounts to 20–30% difference in 30-yr averages over northern Argentina west of Paraguay and to the west of Buenos Aires. However, at the only mountain station included in the analysis, La Quiaca (22.1°S, 65.6°W, 3454 m elevation), the main change around 1942 only amounts to 6%. The authors suggest that the positive changes in the east may be related to an increase in sea surface temperatures with increased moisture advection, whereas the decreasing trend west of the Andes may be the result of an eastward expansion of the subtropical anticyclone.

There are almost no permanent mountain observatories in the Americas, in contrast to the case in the European mountains, and most weather stations are located in the valleys. The few mountain sites that exist in North America are either university-maintained research facilities, such as Niwot Ridge, Colorado and Plateau Mountain, British Columbia, or special installations of agencies such as the US Forest Service or the Natural Resources Conservation Service of the US Department of Agriculture. Hence, detailed assessment of changes is impossible. In South America there are a few high altitude stations in different parts of the Andes, but the data do not seem to be readily available. An automatic weather station has recently been installed at 6500 m on Mt. Sajama, Bolivia (23).

A comprehensive examination of the climatological records for high elevation stations in North America, from the late 19th century to 1990, shows differing signatures of global warming according to region (24). In the Canadian Rocky Mountains (up to 10 stations, with an average elevation of 1055 m), temperatures were 1°C below the 1951–1970 average during the 1890s at the only 2 stations with records. The most prominent warm interval in the annual record (+1°C) is in the 1920s–1930s, with cold intervals around 1950 and 1970, followed by recent warming in the 1980s. In the US Rocky Mountains (with 30+ stations from 1910–1970 and an average elevation of 2377 m), temperatures were below the 1951–1970 average from 1890 to the early 1930s, and again in the 1970s, with warmer conditions during 1935–1945, the 1950s and 1980s. A record for 1934–1990 based on 2 to 4 stations in northern South America (average elevation 1708 m) shows a cool period 1945–1955 and maximum warmth in the 1980s.

In terms of changes in temperature *versus* elevation, only zonal averages for 30–70°N are available (24). Linear trends for 1951–1989, determined for stations in different elevation bands, show that daily maximum temperatures have increased slightly between 500 and 1500 m, but not at higher elevations. Daily minimum temperatures are higher between 500 m and at least 2500 m elevation than at the surface (Fig. 1). It is widely observed in middle latitudes that daily minimum temperatures have tended to rise over the last 30 years while maximum temperatures have remained unchanged or even decreased slightly, resulting in a reduction in the diurnal temperature range (DTR) (18, 25). There is evidence of this pattern in the Colorado Rocky Mountains. For 3 pairs of stations located at around 3200 m in the Colorado Rocky Mountains and at 1200–1500 m on the adjacent high plains, Brown et al. (26) show that the plains-mountain lapse rates have weakened in the daytime, but steepened during the night. A possible explanation of this is an increase in cloud amount, although data to test this hypothesis for Colorado are unavailable. On a global scale, the decline in DTR over the last 40–50 years appears to be driven by increase in cloud cover, augmented in some areas by increased precipitation and soil moisture (27). Low clouds have most effect on temperatures and the reduction in daytime maxima may be enhanced in mountain re-

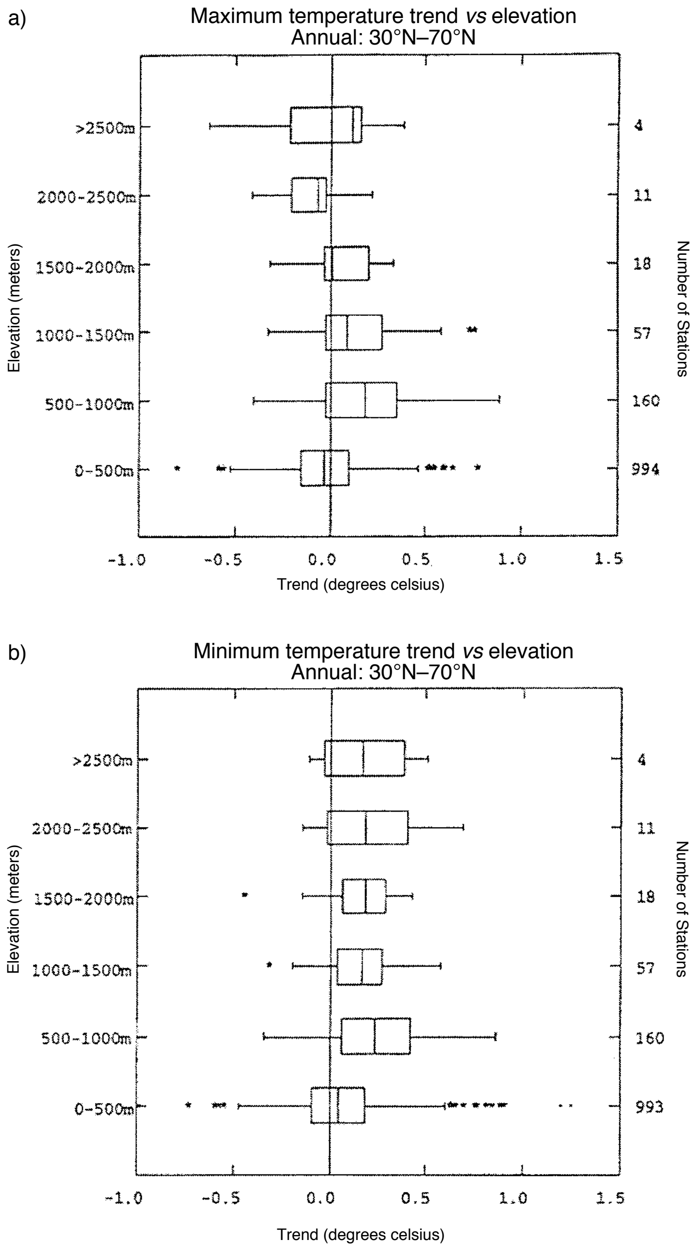


Figure 1. Linear trends (°C per decade) in mean maximum and mean minimum temperature for 1951–1989 versus elevation. Annual values are shown for 30°–70°N. The box indicates the central 50%, the outer bars the 95th percentile. Asterisks denote values exceeding this limit and the dots exceed the 99th percentile (24). (Reproduced with kind permission, Kluwer Academic Publishers from *Climatic Change 36*, p. 275, 1997).

gions by more frequent cap clouds. The almost 50-year record on Niwot Ridge, Colorado, has been re-analyzed by Pepin (28), updating the earlier work of Barry (29) and Greenland (30). He finds a complex pattern of cooling at 3750 m since 1952, but warming between about 2500 and 3000 m. The high level cooling parallels an increase in precipitation over the last 45 years (31), supporting a simple conceptual model of potential change in mountain climate and associated hydrologic responses suggested by Barry (32).

Proxy Records

Proxy evidence of climatic change is fortunately widespread in the Americas. For the mountain areas it includes records of glacier advances and retreats, ice cores in high elevation ice caps, and dendrochronology. The snowline in the Andes near Quito is estimated to have risen since the late 18th century by 300 m (225 m) in the Western (Eastern) Cordillera, respectively, based on moraines and historical information (33). Glacier recession in the last few decades has been pronounced in the Sierra Nevada de Merida, Venezuela (34), paralleling observations in equatorial East Africa. For 3 glaciers in the Cordillera Occidental, Peru, with equilibrium line altitudes around 4900 m, the mass balances between 1979 and 1983 were negative (35). Kaser et al. (36) report a general shrinkage of glaciers in the Cordillera Blanca, Peru, over the last 5 decades. Recession is mainly influenced by temperature. Accumulation on these tropical glaciers occurs almost exclusively in the wet season and in the firn area. Ablation occurs throughout the year but rates are higher during the wet season.

Interestingly, a study of the freezing level in the free air, as measured by balloon soundings at 65 radiosonde stations between 30°N and 30°S (37), shows evidence of a dramatic rise in freezing level during 1958–1990 in the inner Tropics, amounting to 100–150 m (Fig. 2). Moreover, South American records suggest a correlation of freezing level height with an abrupt increase in sea surface temperatures in the eastern equatorial Pacific in the mid-1970s (38). One possible explanation for this warming in the Andes is the increased frequency of El Niño conditions (Fig. 3). Independent evidence of regional tropospheric warming found in the radiosonde record has been obtained by Toumi et al. (41). Using station pressure observed at mountain stations, a procedure based on the hydrostatic relationship indicates the amount of warming below the station level and permits the derivation of an effective surface temperature. However, their paper only includes results for Europe and Asia.

In the southern Andes, all outlet glaciers of the North Patagonian Icefield (47°S) have retreated since the first observations in the 1920–1930s, with increased recession after 1975 according to Lliboutry (42). The Fitzroy glaciers on the east side of the much larger South Patagonian Icefield showed little change from the 1930s to 1952. However, most glaciers shrank during 1944–1945 to 1985–1986 (43), and a number of outlet glaciers show surface lowering (44).

In middle and higher latitudes of western North America, most mountain glaciers are shrinking and have negative mass balances (45, 46). Luckman (47) concludes that for the Canadian Rocky Mountains about 25% of the ice-covered area during the Little Ice Age maximum, some 130–150 years ago, has disappeared. In the Wind River Range, Wyoming, the remaining mass in the Dinwoody glacier is about equivalent to that lost during 1958–1983; if the present trend were to continue, the glacier would disappear in about 27 years (48). The two largest valley glaciers in British Columbia, the Grand Pacific and the Melbern glaciers in the St. Elias Mountains, lost over 50% of their volume over the last few hundred years (49). Retreat and thinning of the Melbern glacier has formed a huge glacial lake. The Lemon Creek Glacier, in southeast Alaska lost 10.3% of its area and 14.6% of its volume between 1957 and 1989 (50). The McCall glacier in the Brooks Range had an average negative mass balance of 15 cm for 1958–1972, 33 cm for 1972–1993 and 60 cm for 1993–1996 (51). However, in the maritime climatic regimes of the coastal Pacific Northwest, glacier advances occurred as a result of increased winter snowfall in the 1970s-1980s. The Wolverine glacier in southern Alaska (52) exemplifies this effect. Hodge et al. (53) examine the climatic controls of mass balance changes on the continental interior Gulkana glacier, and the maritime Wolverine and South Cascade glaciers, showing a regime shift in 1989 that led to large positive balances during 1989–1995. On annual to decadal time scales, mass balances are inversely related between southern Alaska and Washington State as a result of the Pacific storm track location. A deep Aleutian low, associated with the positive mode of the Pacific-North America planetary wave pattern, gives above (below) average winter precipitation in Alaska (Washington) according to Walters and Meier (45).

Glacier fluctuations in the western Cordilleras of the Americas, poleward of 32°S and 47°N where there are detailed and well-dated records, suggest broad synchroneity in advances over the last millenium. Luckman and Villalba (54) report advances during the 13–14th centuries in the Canadian Rocky Mountains, coastal Alaska and Patagonia, some evidence of extended glaciers during the 14–16th centuries, and Little Ice Age advances in the 17th–early 20th centuries. The longest and most temporally detailed records are those from tropical ice caps in Peru and Bolivia. The ice core stratigraphy yields records of annual accumulation (55) while the oxygen-18 isotopic record indicates

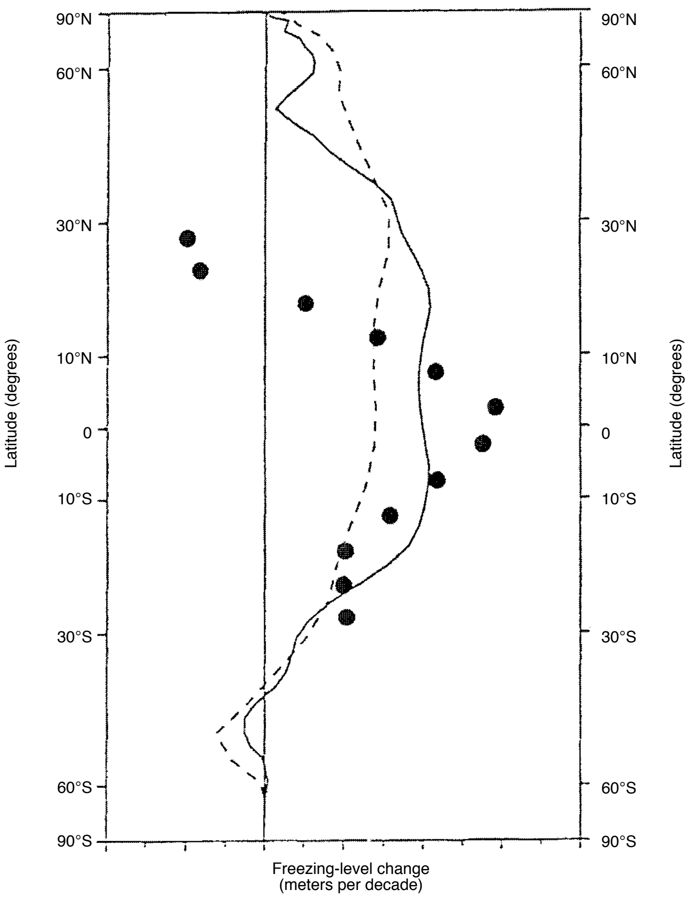
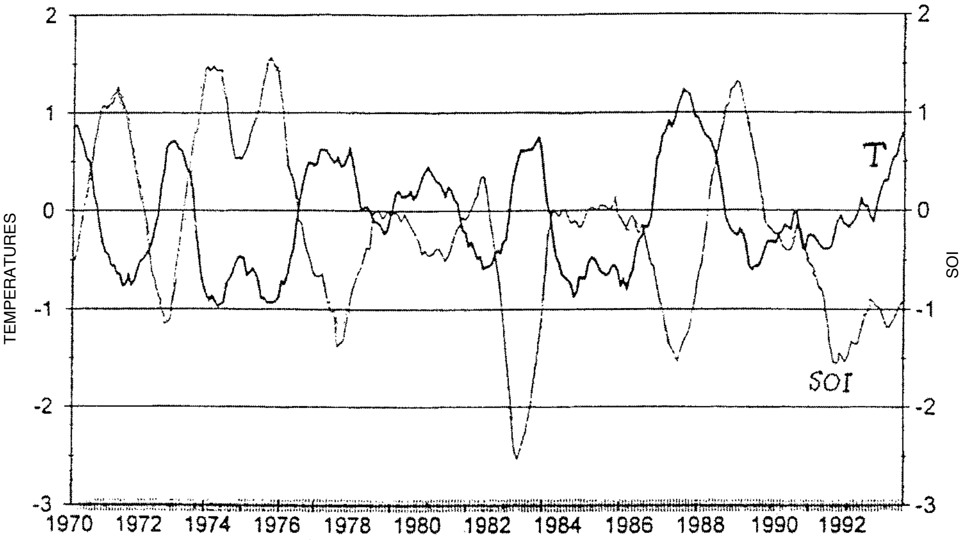


Figure 2. Linear trends (m per decade) of the changes in freezing-level height as observed in radiosonde data for 1970–1986 (dots) and simulated in an 18-yr GCM calculation for T-21 spectral resolution (dashed) and T-42 spectral resolution (solid)(37). (Reproduced by permission from *Nature 383*, p. 154, copyright 1996, Mac Millan Magazines Ltd.).

Figure 3. Interannual temperature variations in the central Andes exhibit strong dependence on the El Niño-Southern Oscillation (ENSO). Temperature deviations from monthly mean at Querococha, Peru (3955 m) are inversely correlated with the Southern Oscillation Index (SOI) (39, 40). An increase in frequency of warm (El Niño; negative SOI) *versus* cold (La Niña; positive SOI) ENSO conditions in recent decades might therefore have contributed to an observed ~130 m rise in freezing level regionwide (37).



the temperature of the precipitating clouds. Thompson (56) demonstrates that temperatures were below average between AD 1550 and 1880 (the Little Ice Age) and above average after 1930 and generally between AD 1110 and 1540. Rapid transitions between these episodes are indicated. It is noteworthy that recent warmer conditions at the site of the well-known ice core on the Quelccaya ice cap have totally destroyed the stratigraphy through meltwater percolation (Fig. 4). The inferred 1300 m rise in the percolation zone altitude is an order of magnitude greater than the rise in tropical freezing level noted above.

A 3500 yr water level record for Lake Titicaca has been obtained from sediment cores by Abbott et al. (58). Five intervals of low lake level, implying a negative moisture balance of precipitation minus evaporation, are identified as a mid-Holocene dry phase before 3500 yr BP and around 2900–2800, 2400–2200, 2000–1700, and 900–500 yrs BP. The abruptness of these shifts in level suggests that they may result from changes in atmospheric circulation, perhaps related to El Niño – Southern Oscillation (ENSO) events. It is interesting to note that the last dry interval coincides with higher temperatures in the Quelccaya ice core.

Tree ring records from the subalpine treeline in the Andes of northern Patagonia (41°S) provide information on spring-summer temperature and snow cover duration for the last 250 yrs (59). From a reconstruction of mean annual temperatures, they find anomalous warmth since 1977, although high temperatures also occurred from 1768–1777, 1799–1803 and in the 1910s. Their reconstruction of snow-cover conditions shows that durations were above the long-term mean from 1780 to 1830, in the 1890s and in the late 1910s–early

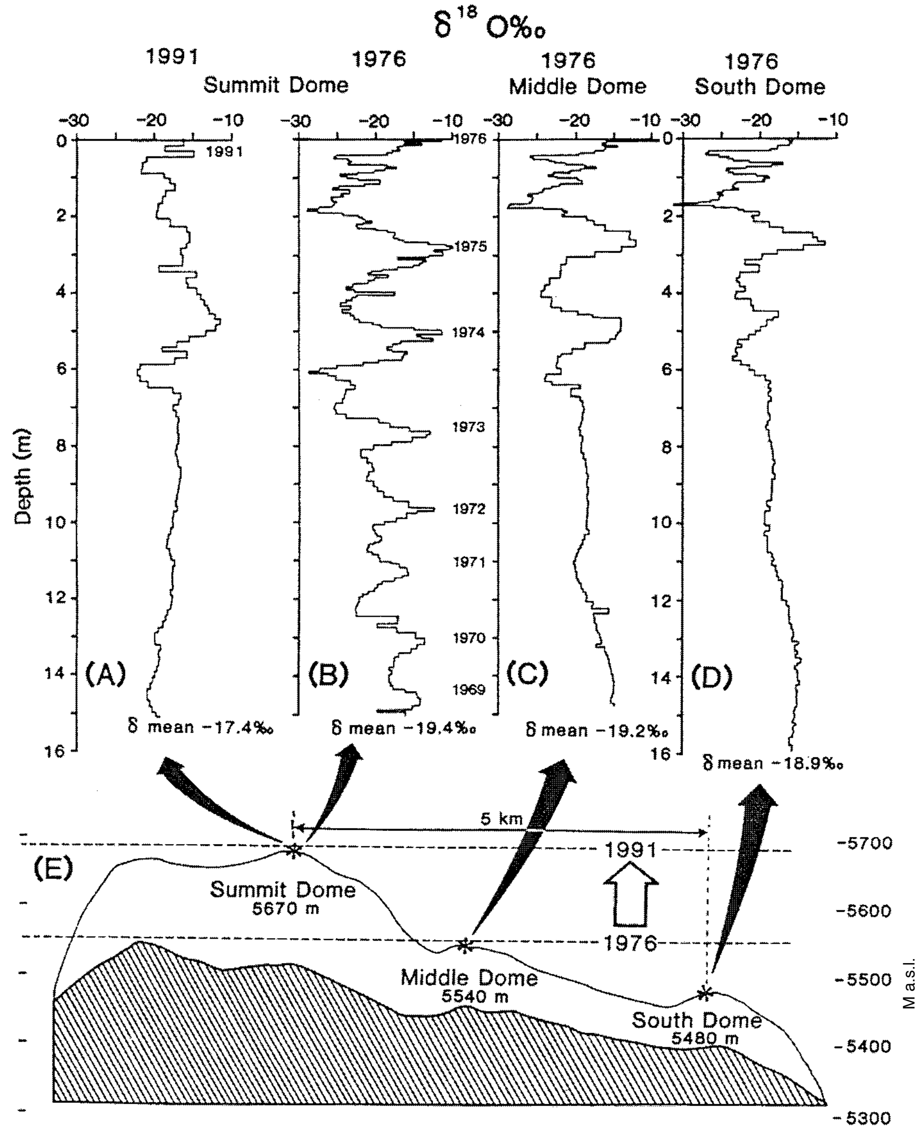


Figure 4. The recent onset of significant melting at the summit of the Quelccaya Ice Cap, Peru (5670 m) is identifiable in snow stratigraphy measurements of Thompson et al. (57). The depth profiles (A-D) show variations in the Oxygen-18 isotope which relates to the temperature of the precipitating clouds at the time of snowfall. Cycles in ^{18}O variations thus serve as indicators of annual layering, best represented by the summit data in B obtained in 1976. Significant melt destroys this signal by the downward percolation of water through the snowpack. This blurring has become evident in the summit stratigraphy by 1991 (A) indicative of warming since the 1976 profile in B. (Reprinted from Global and Planetary Change, 7, Thompson et al., Recent warming: ice core evidence from tropical ice cores. p.152, copyright 1993 with permission from Elsevier Science).

1920s. During the last 50 years, there has been some tendency for a longer snow-free period. Records from the subtropical treeline in northwestern Argentina (60) show an increase in precipitation over the last three decades, that is unprecedented over the last 200 yrs. It is associated with the increased transport of moist air from the Brazilian-Bolivian lowlands. In contrast, tree growth was suppressed between 1850 and 1890. A time series of monthly precipitation for La Quiaca (22°S, 3440 m on the Bolivian Altiplano) shows an advance of about a month in the onset of the summer wet season since the mid-1970s, compared with the beginning of the century; a similar pattern is found at Jujuy (24°S, 1280 m) in northwestern Argentina.

POTENTIAL IMPACTS OF CLIMATIC CHANGES ON THE HYDROLOGIC CYCLE

Various studies have been made of the potential impacts of global warming on the hydrologic regime. Runoff models incorporating changes in climatic parameters show that runoff is sensitive to seasonal changes in precipitation, the timing of the accumulation and ablation seasons, and changes in snowline elevation (61). For the western United States, CO_2 doubling is projected to cause reductions in snowfall combined with increased winter rainfall and earlier, faster snowmelt. These changes lead to increases in spring runoff with reduced summertime flows (62). The effects of a temperature increase on snow cover and runoff were studied in 3 contrasting basins—the humid Illecillewaet in British Columbia, the subhumid Kings River in California, and the semiarid Rio Grande—using the Snow Runoff Model (63). The greatest decrease in snow water equivalent occurs when winter temperatures are near freezing. In watersheds with seasonal snowfall, according to Gleick (64), the timing of runoff is more sensitive to changes of temperature rather than precipitation, because the timing and rate of snowmelt is strongly dependent on temperature.

Stream discharge appears to have increased as a result of glacier recession in the Cordillera Blanca, Peru (35). The effect of glacier recession on the hydrology of basins in the high Andes has been explored by Ribstein et al. (65). Measurements are for a 3 km^2 basin in the Cordillera Real, Bolivia at 16°S, that is 77% ice-covered and has an elevation range between 4830 and 6000 m. Over 80% of the annual precipitation falls during October - March, and about 75% of the runoff takes place in these same months. El Niño warm events (negative Southern Oscillation In-

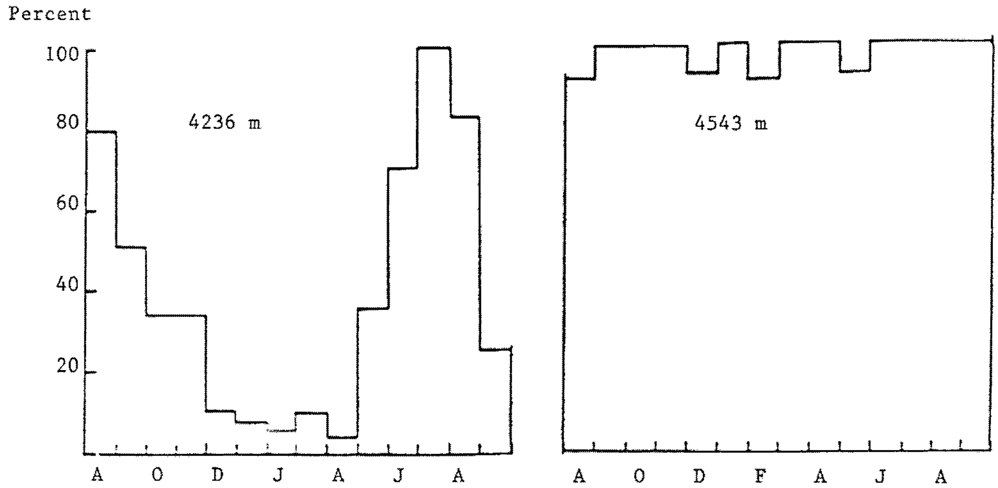
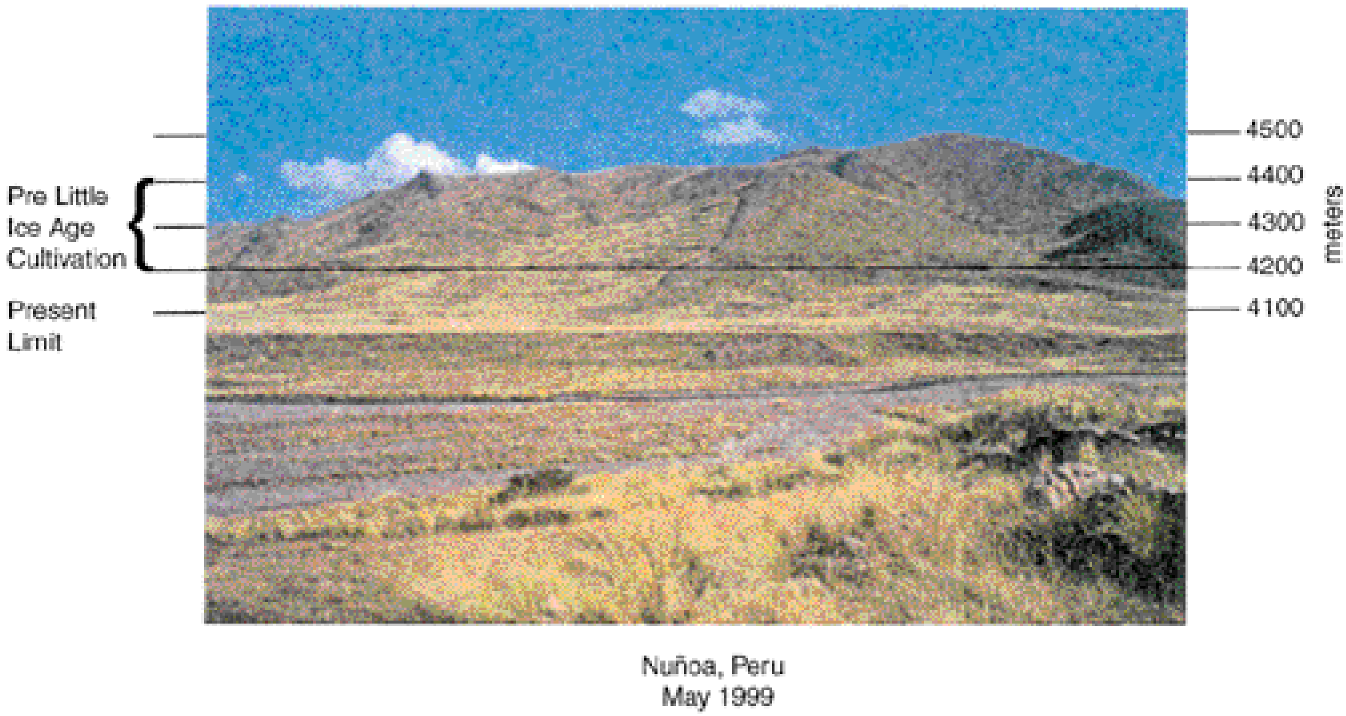


Figure 5a. The temperature dependence of the altitude limit for cultivation is suggested by the frequency of daily temperature below 0° C from August 1964–1965 at 4236 m and 4543 m around Nuñoa, Southern Peru (70, 71).
Figure 5b. Disused agricultural terracing on a mountainside near Nuñoa between about 4200 m and 4400 m where year-round frosts inhibit crop growth both on the valley floor and upper ridges. Agricultural productivity in such mild thermal belts, which are found throughout the Andes and other mountain areas, are highly sensitive to climatic shifts in temperature. These fields likely became nonproductive during the Little Ice Age when freezing levels were shifted downward. Ongoing warming now suggests cultivation might again become possible. Photo: A. Seimon, May 1999.



dex) are shown to be correlated moderately with warm, dry weather in the tropical Andes. Such climatic conditions, which need not be associated with ENSO, cause increased runoff from glacier melt but decreased runoff from precipitation. Discharge measurements near the glacier tongue for a near normal year (1992–1993) show an annual precipitation of 1060 mm and runoff of 1080 m. In 1991–1992, however, when the glacier terminus retreated 10–20 m, the precipitation on the glacier averaged about 916 mm, but the runoff was 1793 mm. In the near term, such enhanced runoff seasons are likely to occur in years with positive temperature anomalies (40).

In Peru, much attention is given to recurring catastrophic events resulting from glacier–lake flood outbursts and ice avalanches from ice-covered volcanic peaks. Such events are not determined by climatic change, although in some instances a threshold may be exceeded as a result of a weather extreme. Major flood events involving large loss of life occurred in or near Huaraz on the Rio Santa, west of the Cordillera Blanca in 1702, 1725, 1883, and 1941. Major ice avalanches from Huascaran peak in 1962 and 1970 caused massive loss of life at Yungay. Following protective measures, including the draining of several glacier lakes, no destructive floods have occurred in this area since 1972 (35).

ECOLOGICAL CONSEQUENCES

The observed recent increases in temperature on tropical mountains are thought to be responsible for concomitant shifts in the cloud base. Model simulations by Still et al. (66) suggest that tropospheric warming has raised the mean cloud base height of orographic clouds, as a result of lower relative humidity. Such changes are likely to have potentially significant impacts on the altitudinal belt of tropical cloud forest. An evaluation of this hypothesis has been carried out using rainfall and temperature data collected in highland Costa Rica in the Monteverde Cloud Forest Preserve (67). The site is located 3 km west of the topographic divide, at 1540 m elevation. Orographic clouds are formed in the easterly trade winds on the Caribbean slope of the Cordillera and extend westward across the divide. The frequency of dry days is taken as an inverse index of 'mist' (or light drizzle) and fog-droplet interception (10). The latter has been shown to be a major component of precipitation in Hawaii and in the cloud forests along the coast ranges of northern Colombia and Venezuela (68, 69). In Monteverdi, an increase in the frequency of dry days and in the length of dry spells is observed during the January-April dry season, 1973–1998, even when ENSO-scale fluctuations are removed from the time series. Moreover, the annual minimum in daily-average stream flow also shows a strong declining trend. Diurnal temperature range (DTR) has decreased at Monteverde, associated with higher minimum temperatures, and this decrease affects both dry and wet days. This change may reflect increasing cloudiness, as noted earlier. Thus, the trends in DTR suggest that the reduced frequency of mist cannot be attributed to a decrease in the frequency of orographic cloud formation, or an eastward shift in the western cloud edge, such as might occur with enhanced lee subsidence. Ecological effects linked to the climatic and hydrological changes are elaborated by Pounds et al. (67). These include a drastic decline in the number of anuran (frogs and toads) species, corresponding decreases in lizard populations, and increases in colonization by cloud forest-intolerant bird species. Habitat alteration is not implicated because the region has not undergone any major deforestation in recent decades.

HUMAN CONSEQUENCES

The relatively large populations inhabiting high altitudes (3000–4500 m) along the Andean Cordillera live with an enhanced risk of being strongly impacted by climatic changes. Even relatively small shifts in temperature and precipitation result in significant impacts upon humanity since the upper limit of cultivation and degree of aridity are determined by the mean climate state. There is evidence that human settlement patterns have been influenced by such shifts in the past and are likely to be so in the future as well. The present-day altitudinal limit of cultivation in the Peru-Bolivia Altiplano region is at about 4000 m, the limiting factor being the recurrence of freezing conditions (Fig. 5). The Incan Empire rose to dominance and flourished under warm conditions that preceded the Little Ice Age. The cooling that followed caused extensive agricultural tracts to fall out of production. The warming presently observed suggests that these areas may again be tilled leading to an increase in agricultural potential, a positive impact for the regional inhabitants.

Conversely, the ongoing deglaciation resulting from the rapid regional warming, holds significant potential for negative impacts on humanity. In Peru, for example, 90% of the electricity supply is provided by a network of hydroelectric generating stations, most of which tap meltwater sources. Because precipitation in the central Andes is highly seasonal, with the bulk falling in a distinct wet season extending from October through April, runoff from rainfall quickly diminishes in the following dry winter period greatly reducing the water for riparian systems.

The most sustained flows during the dry season are therefore found in rivers that contain extensive snow cover and glaciation in their catchment basins. A reduction in glacial extent thus affects the amount and timing of meltwater runoff during the dry season when such flow is required to sustain hydropower operations. The situation has become sufficiently critical in Peru to prompt a transition towards gas-powered thermoelectric generation stations. Agricultural operations in the Andes also utilize the gradual release of snow runoff to sustain crops during the lengthy May-October dry season. Rising snowlines diminish this supply and hold significant potential for negative impacts upon agriculturalists, especially the impoverished peasantry of the drought-prone Altiplano. This has already presented a problem in the past during El Niño-related droughts when wet season snowfall is often well below normal over the Altiplano. The retreating glaciation now suggests that the problem is being exacerbated and that the increasing numbers of peasant farmers are at risk from water shortages. Furthermore, the reponderance of El Niño *versus* La Niña conditions in the past few decades has been increasing the frequency of drought years.

CONCLUDING REMARKS

Climatic changes in the mountains of the Americas are not easily documented because of the sparse station networks. Changes in precipitation and moisture balance cannot generally be addressed. Common features of the mountain regions include the overall warming trend over the last century and the anomalous global warmth of the 1980s–1990s. There is also a widely observed decrease in diurnal temperature range. However, there is considerable regional variation in the timing of the changes making general conclusions difficult. The most compelling evidence is provided by a variety of proxy records. These indicate predominant and widespread glacier recession during the 20th century, with an apparent recent acceleration in low latitudes, as the freezing level rises, in response to higher tropical sea surface temperatures. Some consequences are already evident in changes in hydrological regimes and an apparent upward shift in the orographic cloud band that is responsible for the cloud forest ecosystem. The global context for the potential impact of climate changes on the environment and society are presented elsewhere (72, 73).

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