paper 4

# GLOBAL CHANGE, CLIMATE VARIABILITY AND IMPACTS:

## SOME EXAMPLES FROM THE AMERICAS

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**ABSTRACT:** This paper presents some discussion and examples of ongoing climate changes in the Americas based mainly on studies carried out by one of the IAI's Collaborative Research Networks. Tree rings and long instrumental climate records have been used to document temperature and precipitation changes in the Americas over the past several hundred years and to explore some of the causes of this variability. Implications and impacts of these changes for stream flow, water supply and human health effects are illustrated with examples from the Cordillera between Alaska and Patagonia. It is concluded that while increasing temperatures are a concern, changes in precipitation will have far greater impacts on humans and the economy.

***Keywords:*** climate change, tree rings, drought, streamflow, glaciers

## 1. Introduction

Historically, climate variability has usually been considered in terms of time series of observations for a particular place. However, climate actually varies simultaneously in both time and space and at many different scales. Internal mechanisms related to changes in oceanic and atmospheric circulation, for example, those related to El Niño - Southern Oscillation (ENSO),the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO), may simultaneously have different (often opposite) effects in different geographical areas whereas other causes such as solar or orbital variability have a more uniform spatial footprint. This paper presents some examples of climate change and its impacts based on studies conducted by one of the Collaborative Research Networks (CRN) funded by the Inter-American Institute for Global Change Research (IAI). A major goal of CRN03 *The Assessment of Present, Past and Future Climate Variability in the Americas from Treeline Environments* was to examine climate variability based on annually resolved proxy climate records from tree-ring sites along a latitudinal transect of the American Cordilleras between Alaska and Tierra del Fuego (Luckman and Boninsegna, 2004). This transect allows examination of many topics including large scale links in the climate system; temperature variability

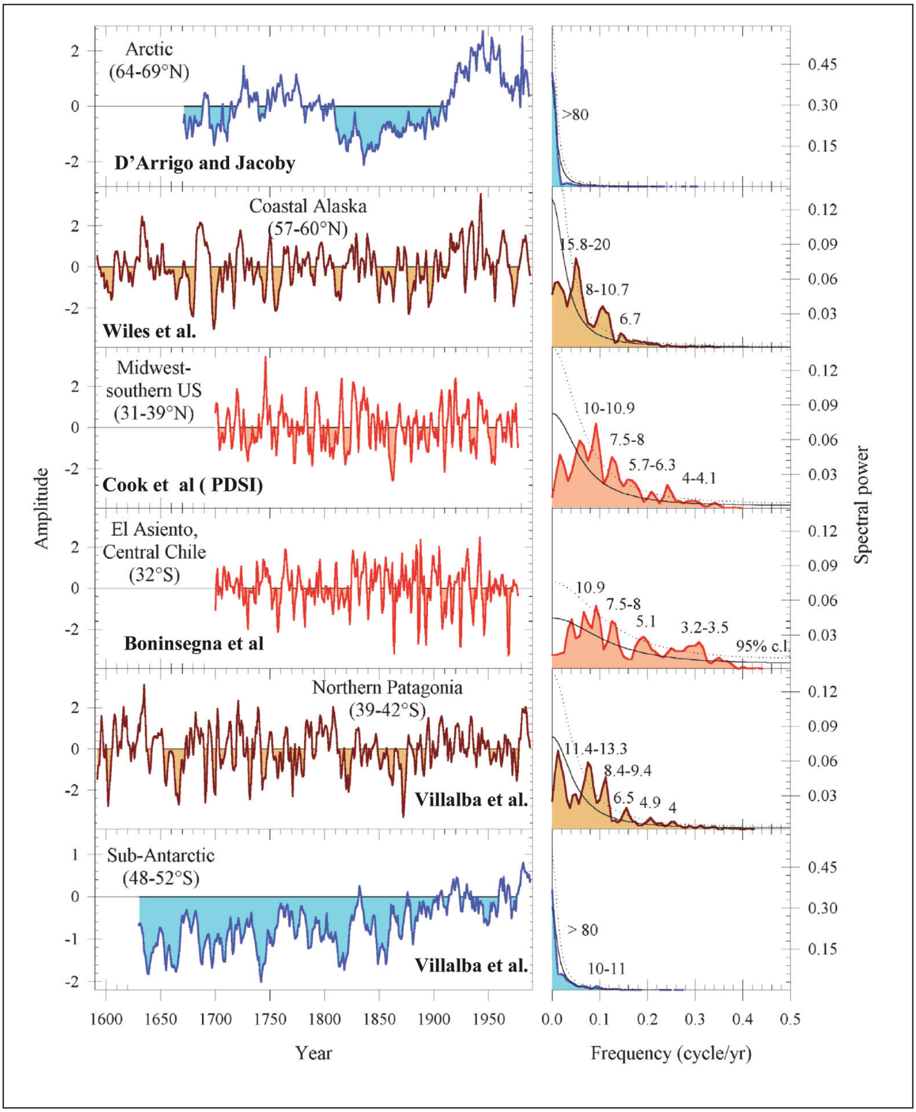


***FIGURE 1***

Latitudinal patterns of climate variability. The series are; Arctic—mean annual temperatures (Jacoby and D'Arrigo 1992); Coastal Alaska- spring and summer temperatures (Wiles *et al*, 1995); Midwest-southern US—Palmer Drought Severity Index (Cook *et al.*, 2004); Chile—moisture-sensitive ringwidths (Boninsegna, pers comm.) and Patagonia (both diagrams)—mean annual temperatures (Villalba *et al* 2003). The right-hand diagrams show the dominant frequencies in each series and how they vary with latitude.

over time and space; changes in precipitation, stream flow and water supply at inter-annual or longer-term frequencies; and the impacts of climate changes on glaciers.

## 2. Temperature Variability

Figure 1 shows proxy climate series derived from tree-ring sites along this transect which demonstrate latitudinal variations in climate variability across both hemispheres. The series shown are, from top to bottom, mean annual temperatures in the Arctic; spring and summer temperatures in Coastal Alaska; Palmer Drought Severity Index for the southwest USA; moisture sensitive tree-ring widths from Chile and mean annual temperatures for both Patagonian records. The right-hand diagrams clearly show how the dominant frequencies vary with latitude - reflecting changes in the interaction of different atmospheric and oceanographic systems. The most poleward series in both hemispheres are dominated by low frequency, longer term changes, the sub tropics are characterized by a high frequency ENSO signal and the mid latitudes contain a mixture of the two patterns. The strong hemispheric symmetry demonstrates the importance of the Pacific and tropics as drivers of climates in both hemispheres.

Figure 2 further demonstrates these relationships, indicating the strong correlations between tree-ring reconstructions of temperatures from the Gulf of Alaska and Patagonia over the last 400 years. Correlations between these series are highly statistically significant and both are strongly negatively correlated with strontium/calcium ratios (a proxy for sea surface temperatures, the record shown is inverted) from corals at Rarotonga (Linsley *et al.*, 2004) in the central Pacific. This indicates that sea surface temperatures in the tropical Pacific are linked to temperature variation in both the northern and southern hemispheres.

One of the most significant recent examples of these changes in climate was the 1976 Pacific climate shift associated with the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002). Some of these effects are demonstrated in Figure 3 by the synchronous changes in ringwidths and instrumental temperature records from sites at opposite ends of the transect plus the strong reduction in winter mass balance (snowfall) at Peyto Glacier in Western Canada (50˚N). Ebbesmeyer *et al.*(1991) composited records for the eight year

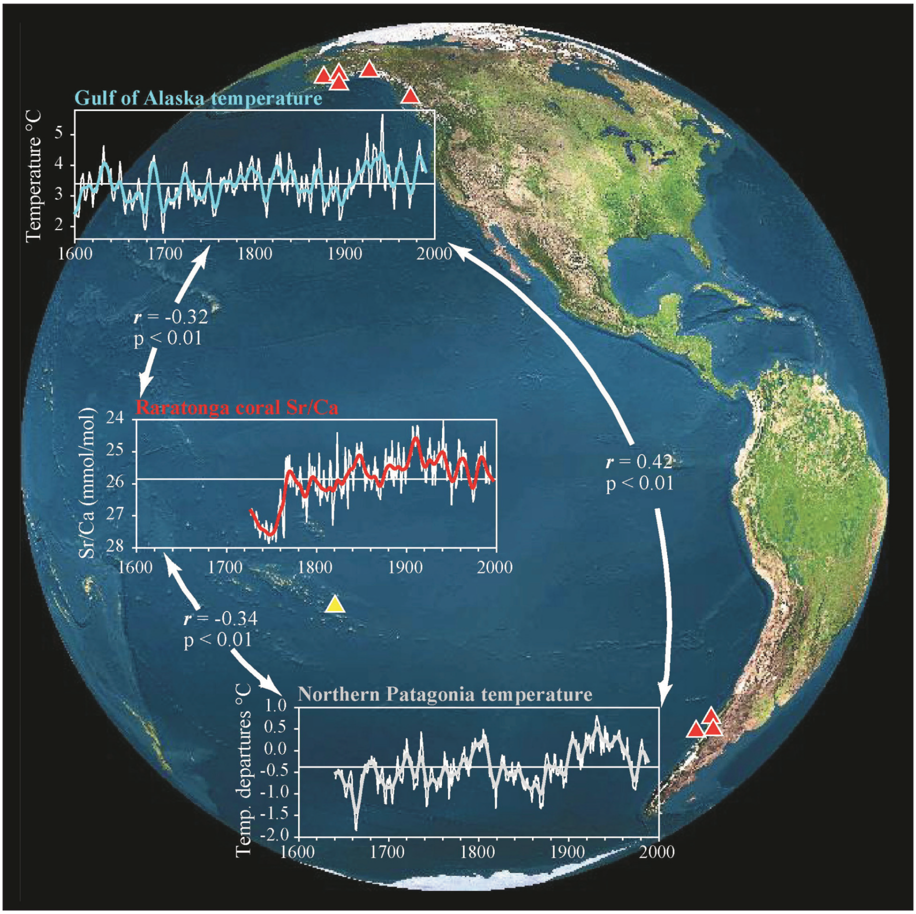


***FIGURE 2***

Reconstructed temperatures from the Gulf of Alaska and northern Patagonia for the last 400 years and correlation with strontium/calcium ratios in Rarotonga corals (a proxy for SST: record shown inverted). Data sources are; Alaska-Wiles *et al*, 1998, Rarotonga- Linsley et al 2004, Patagonia- Villalba *et al*, 2003. Source: Villalba *et al.*, in press with kind permission from Springer Science and Business Media.

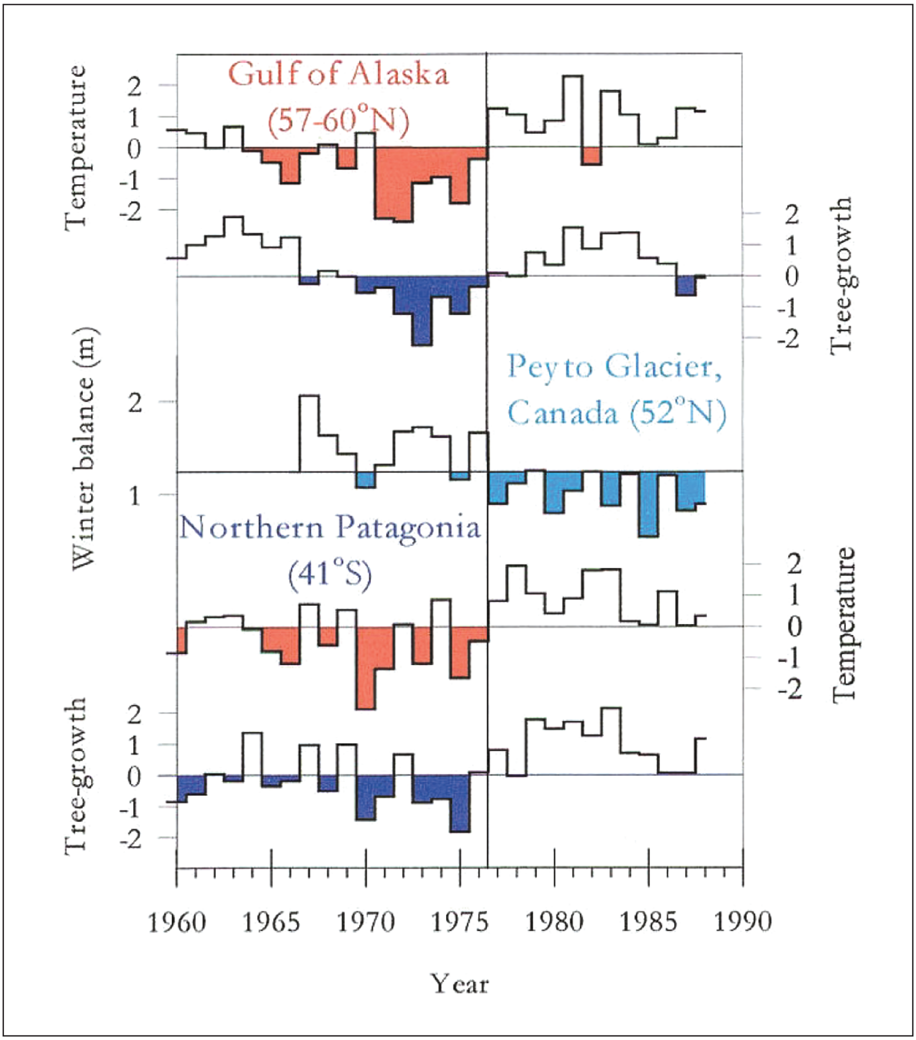
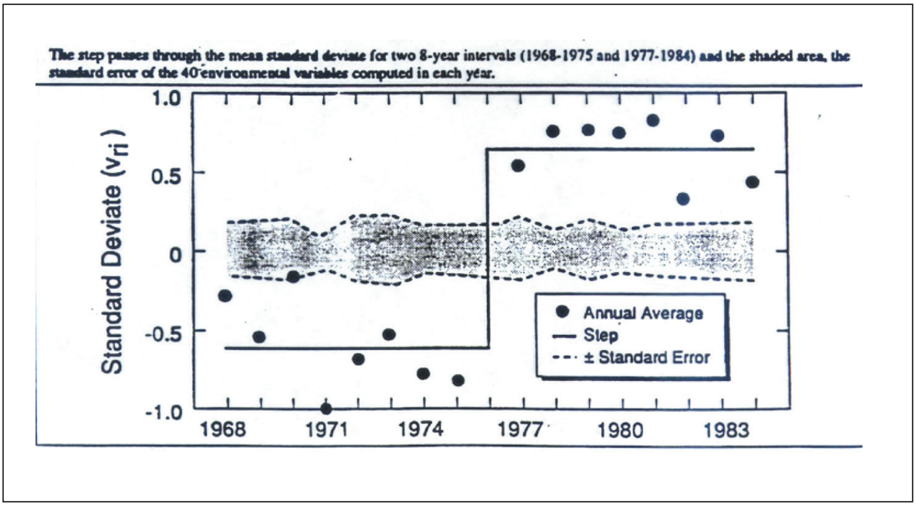


*FIGURE 3*

Records of temperature and tree ring widths in the Gulf of Alaska and northern Patagonia, together with mass balance for the Peyto Glacier in Alberta, Canada.

periods before and after 1976 to develop a standardized impact factor from 40 environmental variables that shows the magnitude of this change (Figure 4). This measure includes a wide variety of climate variables including global annual air temperatures, the Southern Oscillation Index, several streamflow and snowfall indices from western America plus measures of Arctic sea ice cover. These indicators also include several measures of biological and ocean productivity (Alaska salmon catch; Salmon migration on Vancouver Island; Dungeness crab catch and mollusc abundance in Puget Sound) that demonstrate both the biological and related economic impacts of this change. Although most of these indicators are from western North America, similar changes probably occurred throughout the Pacific Basin as the Sea Surface Temperature (SST) changes were basin wide. Figure 5 compares temperatures before and after the shift indicating that equatorial areas of the Pacific became much warmer with two major cold pools in the northern and southern Pacific.

Figure 6 shows the winter sea surface temperature anomaly pattern of the positive phase of the Pacific Decadal Oscillation (left side in red) and a time



The step passes through the mean standard deviate for two 8-year intervals (1968-1975 and 1977-1984) and the shaded area, the standard error of the 40 environmental variables computed in each year.

**FIGURE 4**

17-year time series of the standard deviate averaged by year for 40 environmental variables representing the 1976 Pacific climate shift. Source: Ebbesmeyer *et al*, 1991.

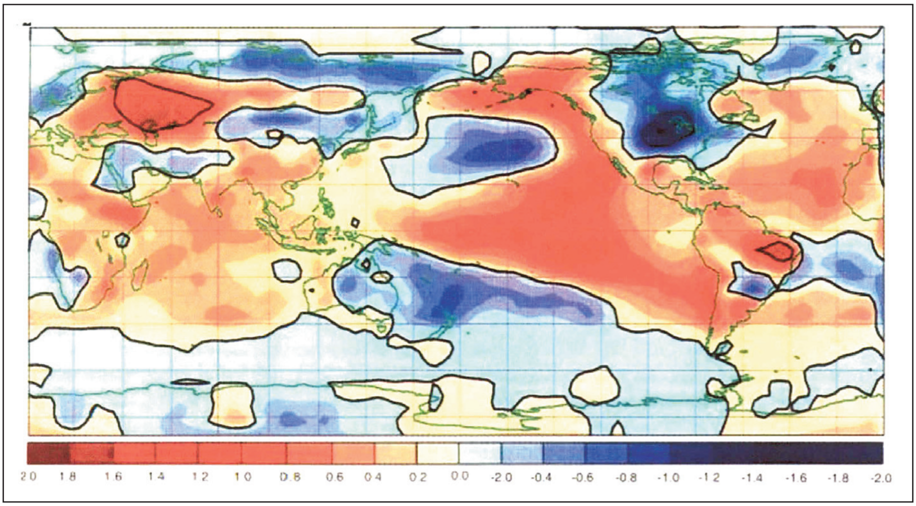


***FIGURE 5***

Ocean surface temperature differences before (1971 to 1975 mean) and after (1977 to 1982 mean) the 1976 Pacific Decadal Shift. Source: Graham from Science 267:666-671 (1995). Reprinted with permission from AAAS.

series of the PDO index indicating three shifts over the past century. The left hand diagram shows the SST anomaly pattern associated with El Niño and the Niño 3.4 SST time series. The ocean temperature patterns associated with ENSO and PDO are similar but occur at different frequencies. The PDO variability modulates the effects of ENSO such that when the two patterns are in phase the associated anomalies are more marked (see Gershunov *et al.*, 1999). Figure 7 shows the frequency of heavy precipitation events in the USA during La Niña events grouped according to the state of the PDO. When the two patterns are in phase (La Niña/negative PDO or El Niño/Positive PDO) the anomaly pattern associated with the effects of La Niña or El Niño are intensified. In the La Niña case in Figure 7 it is very dry in the American southwest and much wetter in the Pacific Northwest and the northeast United States. When the two are out of phase the anomaly pattern is much weaker. Several attempts have been made to reconstruct the Pacific Decadal Oscillation (PDO) record before 1900, but do not yield consistent results. PDO type variations do occur in the paleorecord but seem to vary in intensity and it is not clear whether the 20th century pattern is stable over time.

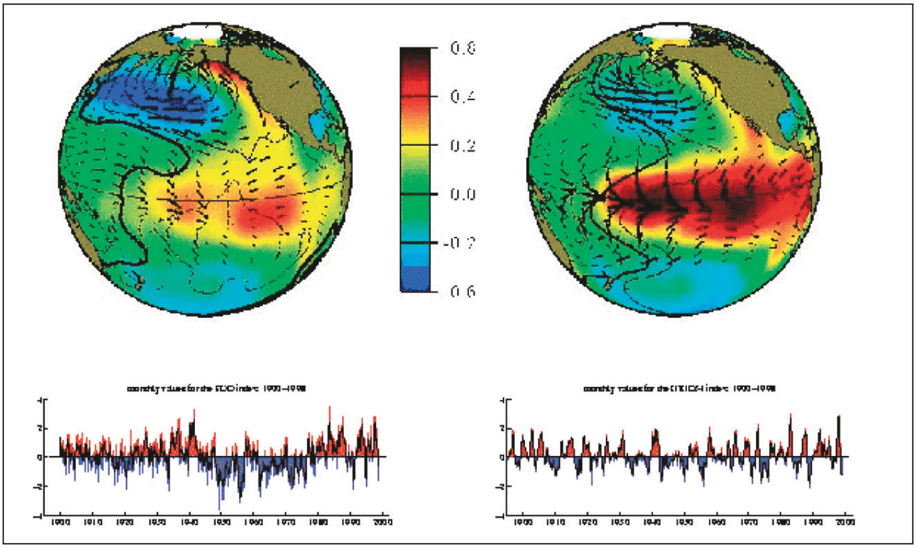


***FIGURE 6***

(Above) Comparison of Sea Surface temperature anomalies during the warm phase of the PDO (left) and El Niño (Right, warm Phase of ENSO): (Below) Time series of the PDO Index and the Niño 3.4 Index (sea surface temperature). Source: obtained from the University of Washington's Joint Institute for the Study of the Atmosphere and Oceans web-page with permission from Nathan Mantua.

Longer temperature reconstructions have been developed for several sites along the transect. Figure 8 shows a reconstruction of summer temperature variation for the last millennium at the Columbia Icefield area of the Canadian Rockies that is believed to be regionally representative and correlates with other Northern Hemisphere temperature reconstructions. Several of the major cooler intervals and the timing of glacier advances are associated with periods of low sunspot activity indicating solar variability has been a major control of low frequency changes in temperatures over most of this period.

## 3. Precipitation Variability

Most climate change discussions have been focused on potential changes in temperature. However, from a social perspective, changes in precipitation are more important because they have drastically greater impacts on the

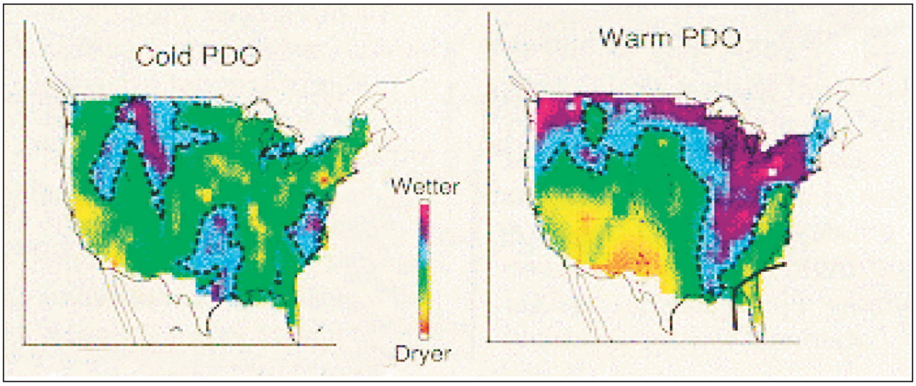


**FIGURE 7**

Heavy precipitation frequencies for the United States of America during La Niña events associated with different phases of the PDO between 1933 and 1993 (after Gershunov *et al.*, 1999).

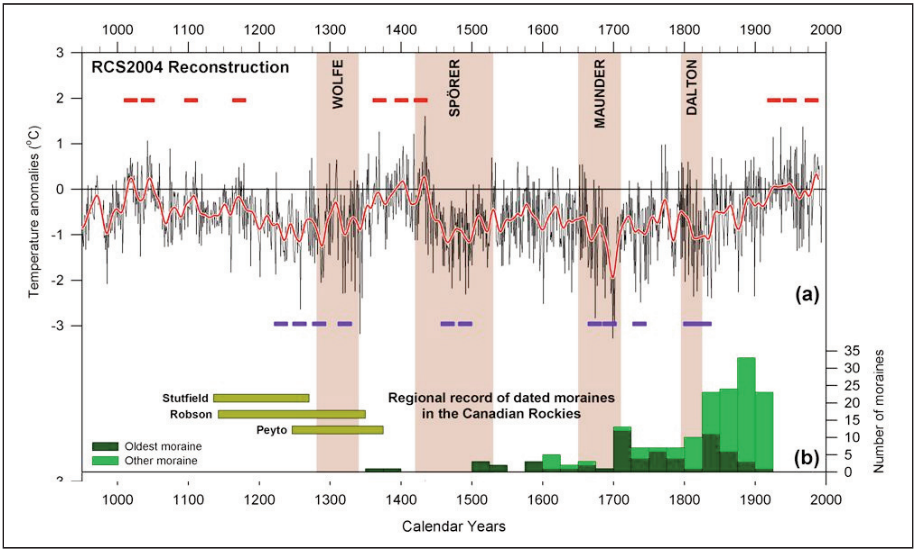


**FIGURE 8**

Maximum summer (May-August) temperature anomalies (from the 20th century mean) at the Columbia Icefield, Alberta, Canada. The ten warmest and coldest twenty year periods are shown as red and blue bars respectively. Dates of moraine formation and periods of glacier advance in the 13th century are also shown. (Luckman and Wilson, 2005).

biosphere and the human economy. As Barnett *et al.*(2004) state: "*Even with a conservative climate model, current demands on water resources in many parts of the (US) West will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy. These results do not envision an easy future for users and managers of …water resources, but it is our contention that better information about this future will prepare us to do a better job in facing its challenges*". Water stress will become a very significant problem throughout the Americas, particularly in areas where there is already a severe water shortage.

Precipitation variability can be reconstructed at two significant timescales, low frequency regional droughts identified by paleodata and high frequency variability driven by El Niño - Southern Oscillation (ENSO) events. The inter-annual variation of precipitation throughout most of the area from 40 degrees north and south is essentially controlled by ENSO in the tropical Pacific. Figure 9 uses proxy tree-ring data to examine some of these linkages.

Major droughts on the Canadian prairies have been reconstructed from tree ring data gathered from a number of sites in the Canadian province of Alberta and adjacent areas. This area was investigated by the Palliser Expedition in the late 1850s with regard to potential agricultural use and reported to be unsuitable. Later expeditions in the 1870s painted a different picture, indicating conditions more like the Canadian province of Ontario - green and lush. The main settlement of the Canadian prairies followed between 1890 and 1920. Figure 10 shows the period from the 1870s through to 1910s was one of the wettest periods in the last 300 to 400 years in this area. In the 1920s and 1930s, the North American prairies became a dust bowl and there have been several subsequent major droughts. If a long term precipitation data set or an historical perspective had been available prior to European settlement of this region reservations would have been expressed about developing major agricultural activity in parts of this region. With anticipated warming it is likely that drier conditions such as those that prevailed in the 1600s and 1700s are much more likely to be typical for this area and water use and conservation will become increasingly important issues.

Expansion of the use of tree-ring networks allows the reconstruction of past spatial and temporal patterns associated with extended wet and dry periods. Figure 11 shows significant dry periods of greater than 5 and 10 years duration reconstructed from tree rings across the southern Canadian

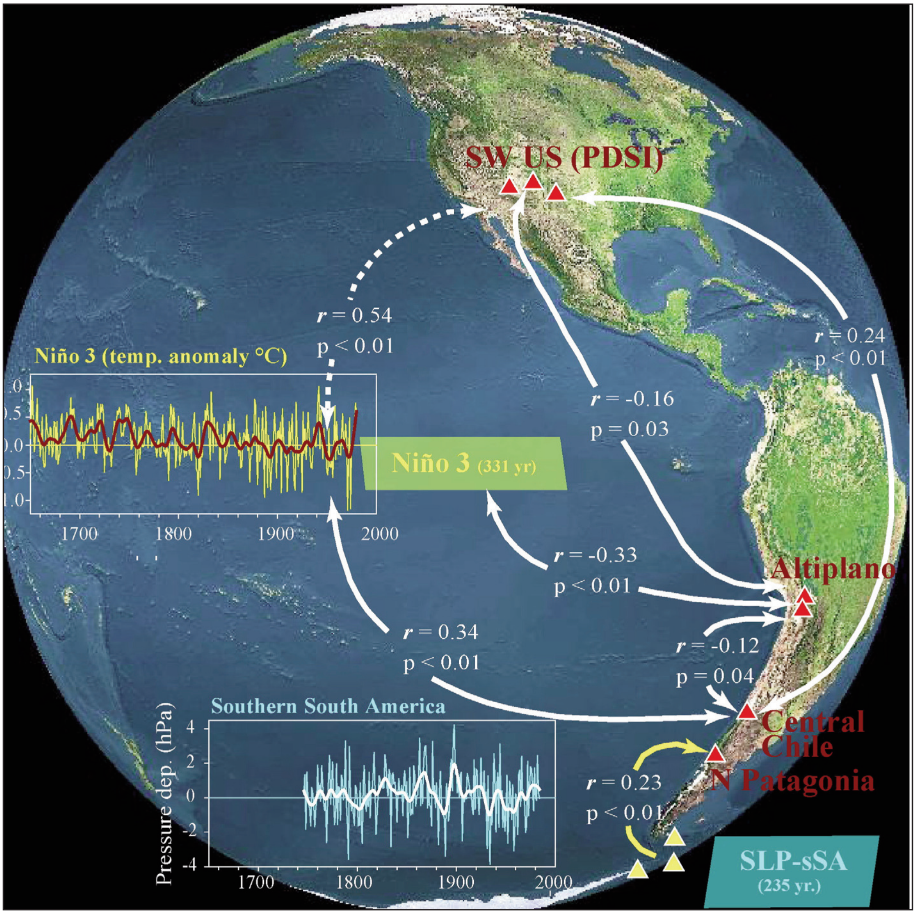


***FIGURE 9***

Linkages between proxy records of Tropical Pacific SST and precipitation in the western Americas (Villalba *et al.*, in press with kind permission from Springer Science and Business Media.). Data Sources: Niño 3 temperatures Mann *et al.*, 2000. PDSI Cook *et al*, 2004. Polylepis tarapacana tree-ring widths, Bolivian Altiplano, Argollo *et al*, 2004; Austrocedrus chilensis tree-ring widths, El Asiento, Central Chile, Lequesne, pers. comm.

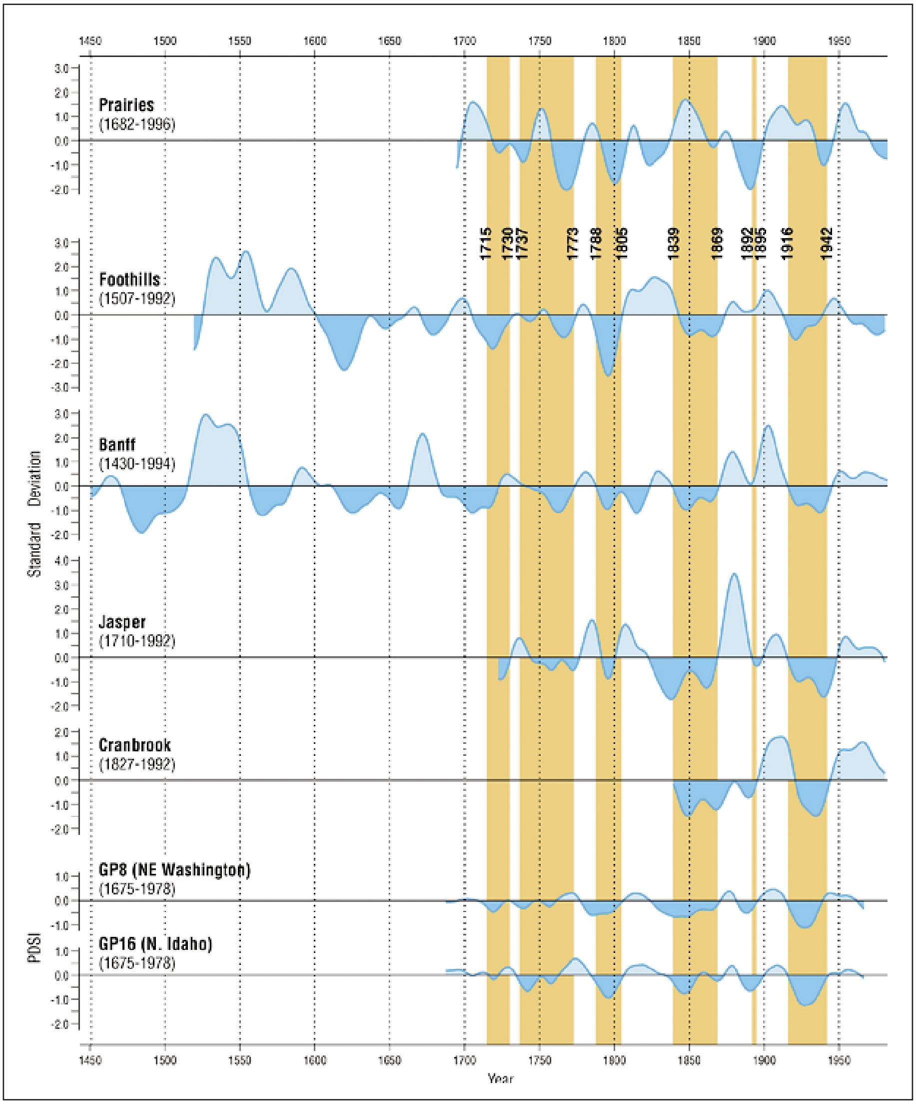


**FIGURE 10**

Major droughts on the North American Prairies reconstructed by tree rings. The vertical bars represent periods when the majority of these reconstructions show below normal precipitation. Reproduced from Watson and Luckman, Dendroclimatic reconstruction of precipitation in the southern Canadian Rockies (©Sage Publications, 2001) by permission Sage Publications Ltd.

Cordillera during the last 300 years (Watson and Luckman, 2005). This indicates that although the 1917 to 1941 drought was the longest during this period, its spatial expression differed between the 1920s and the 1930s. There were also several shorter, more intense dry periods, for example, during the 1790s, when major stabilized dune fields in the prairies became active.

Cook *et al.*(1999) used tree-ring data to develop a gridded database of the Palmer Drought Severity Index for the coterminous United States for the last 300 years. Recently this has been updated and extended using, *inter alia*, data from the CRN project, and now covers the area from the Yucatan to the Yukon (Figure 12). These data allow exploration of the spatial extent and duration of drought, placing twentieth century records in a long-term context (Fye *et al.*, 2003). The long data series from the western USA now shows the extent of significant droughts in the 12th and 13th centuries and even a major 8th century drought that had important impacts on the cultural history in pre-Hispanic America.

Some of these data come from Douglas fir tree rings which are moisture sensitive and have been used to produce precipitation reconstructions of several hundred years in western America between British Columbia and Mexico. In Mexico, seasonal precipitation (and therefore drought) has been reconstructed from the latewood part of tree rings from trees growing in a small stand of Douglas fir at Cuauhtemoc la Fragua in Puebla. The main food crop in eastern Mexico is maize grown using dry farming techniques that depend on summer rainfall. As latewood width and maize yield are both strongly correlated with summer precipitation, this latewood series can be used to reconstruct maize yields over a large region for the past 500 years, identifying periods of low yield (drought) that resulted in regional famines (Figure 13). This reconstruction can subsequently be verified from colonial and Aztec records providing important insight into the cultural and economic history of this region (Therrell *et al.*, 2004). These records show a surprising 52 year drought cycle corresponding with the "one rabbit" year of the Aztec calendar (Therrell *et al.*, 2006). The cause of this apparent cyclicity has not yet been determined.

These records can also demonstrate important linkages between climate and disease. Cocolitztli is an hemorrhagic fever where victims bleed from every orifice of their body and die within four days. The human population of

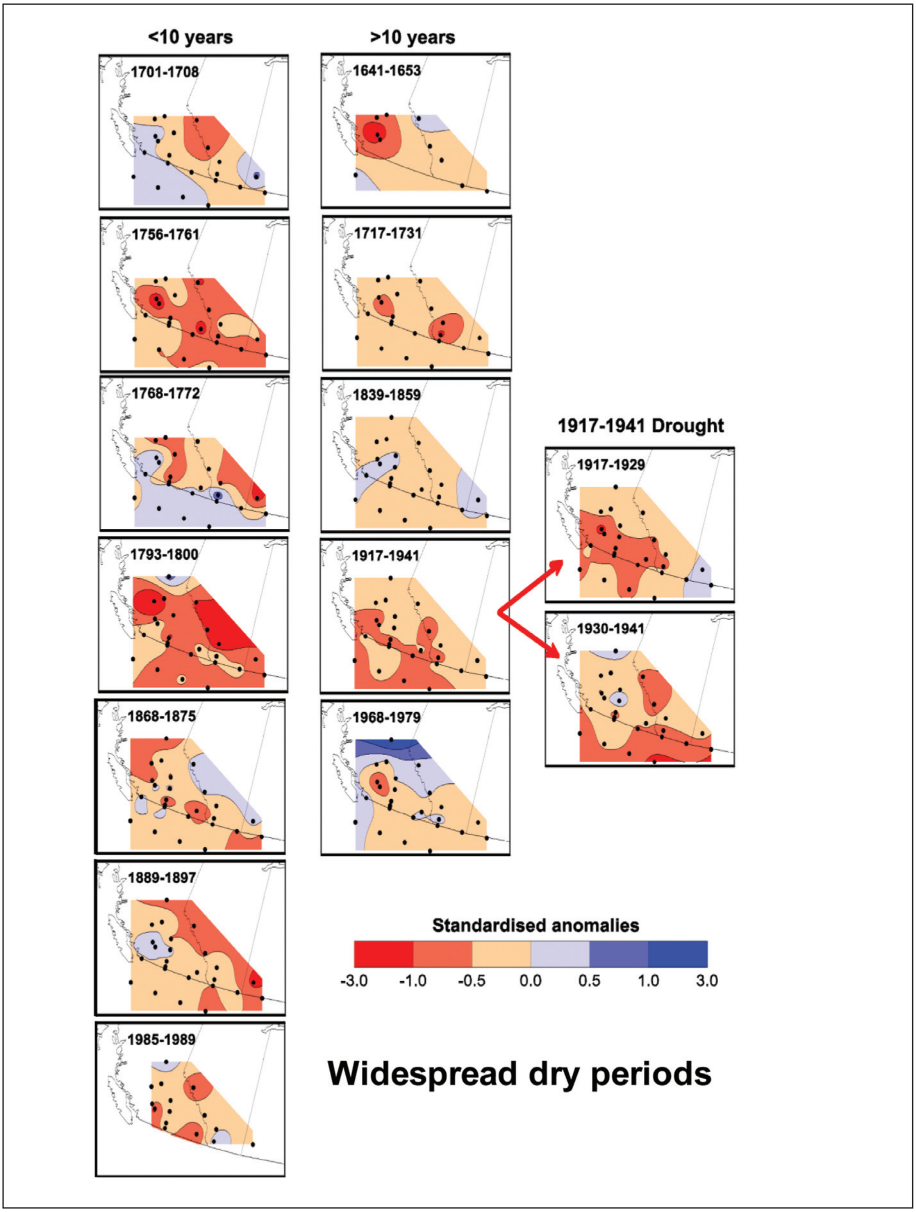


***FIGURE 11***

Dry periods of southwestern Canada over the last 300 years. Source: Watson and Luckman, 2005.

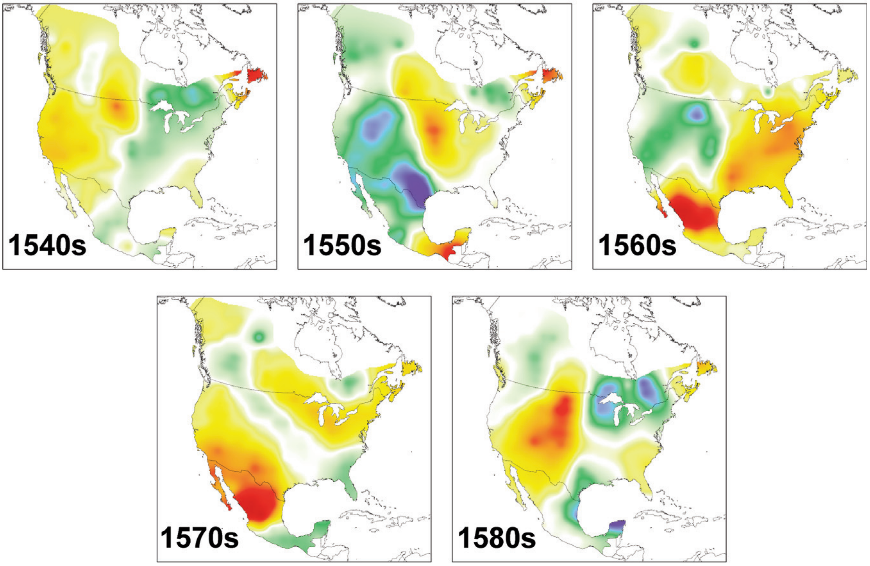


**FIGURE 12**

Patterns of the major 16th century "Megadrought" in North America based on the Palmer Drought Severity Index. Red and yellow shading indicates below average PDSI; blues and greens reflect wetter areas (Cook *et al.*, 2004; Stahle, pers. comm.).

Mexico was decimated by cocolitztli epidemics in 1545 and 1576 (Figure 14). It is estimated that 12 to 15 million deaths occurred in 1545 and half the remaining population died in the 1576 epidemic. Comparison of the timing of these outbreaks with a precipitation reconstruction and evaluation of more recent smaller outbreaks indicates that the epidemics come one year after major droughts, probably due to the spread of the vector for the disease (possibly rodents) during the subsequent wet period.

A second example of climate/disease interactions comes from northwestern Argentina (Figure 15). Local parish records indicate significant mortality events in the human population of these parishes during the 1860s-1880s. Examination of tree-ring records from sites in the Puna above these villages and from sites in the semi-arid woodlands (Yungas) at lower elevations indicate relatively high precipitation in the 1830-50s followed by an extended

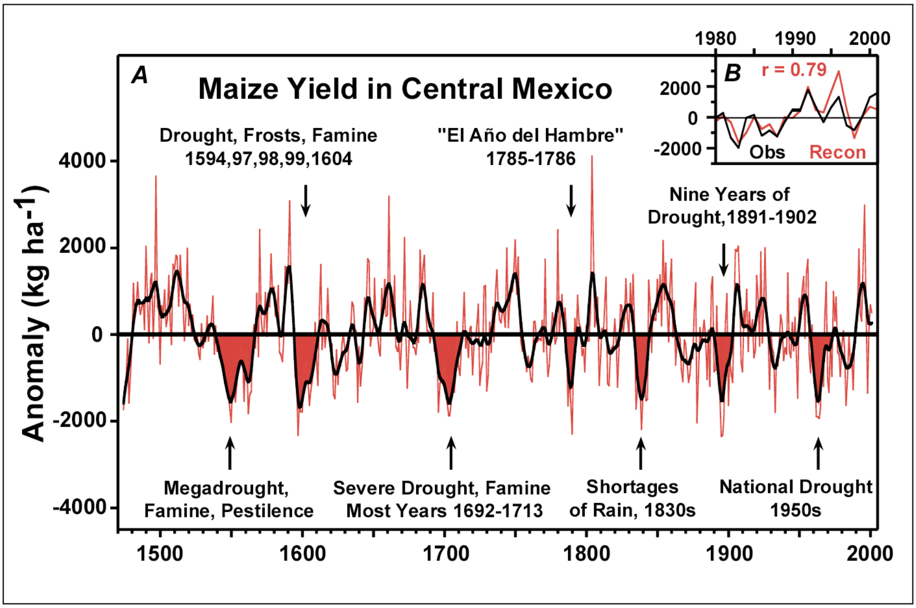


*FIGURE 13*

Maize cultivation is 84 percent "rain-fed" and yield correlates with April-June rainfall and tree-ring latewood width of Douglas fir at Cuauhtemoc la Frangua. Crop data are regional averages of four states (Mexico, Puebla, Tlaxcaca and Veracruz). Source: Therrell *et al.*, 2006.

drought. The significant death toll is thought to result mainly from disease associated with water borne infections spread to humans by water contaminated by the forced common use of shrinking surface water sources by livestock and human populations (Gil Montero and Villalba, 2005).

Tree rings can also be used to reconstruct long streamflow records that are critical for water planning. The best known example is from the Colorado River Basin where the allocation of flow between the seven US states and Mexico in 1922 was based on available flow records from 1905-1920. Subsequent tree-ring based streamflow reconstructions (Stockton, 1975, Woodhouse *et al.*, 2006) and instrumental records show that this period was the highest flow in the last 500 years and that the allocation of flow to the USA exceeds both the 20th century mean and the mean of the 500 year long proxy record, resulting in considerable friction about water rights.

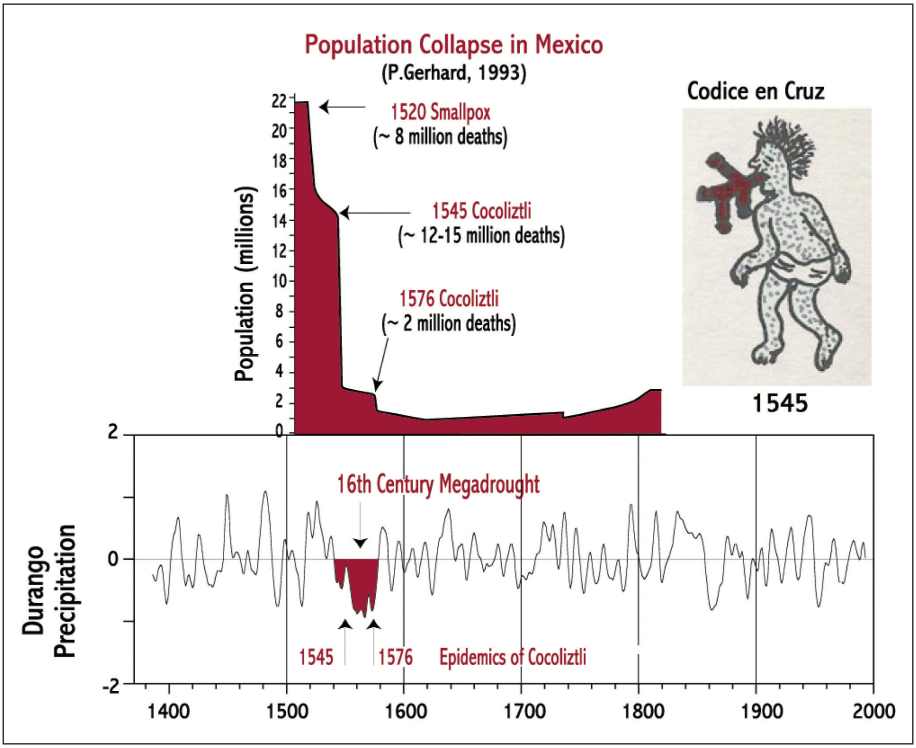


**FIGURE 14**

Comparison of estimated human population changes between ca. 1500-1800 in Mexico with a reconstructed winter-spring precipitation record derived from tree-ring chronologies in Durango, Mexico. Source: Stahle *et al.*, 1999; Acuña- Soto *et al*, 2002; see also Figure 12)

On a smaller scale many rivers in Mexico have limited streamflow records. Figure 16 shows a reconstruction of stream flow from the Rio Nazas in north eastern Mexico, showing major drought events (Villanueva-Diaz *et al.*, 2005) and significant high frequency variability related to ENSO. In both the instrumental and reconstructed records, winter discharge in El Niño years is about three times that in La Niña years, and it is about twice the average of other years. This information is critical for water planning as El Niño and La Niña events can be predicted prior to the winter season and quotas for the following years adjusted accordingly rather than, as presently happens, using the previous year's discharge to determine the current year allocations.

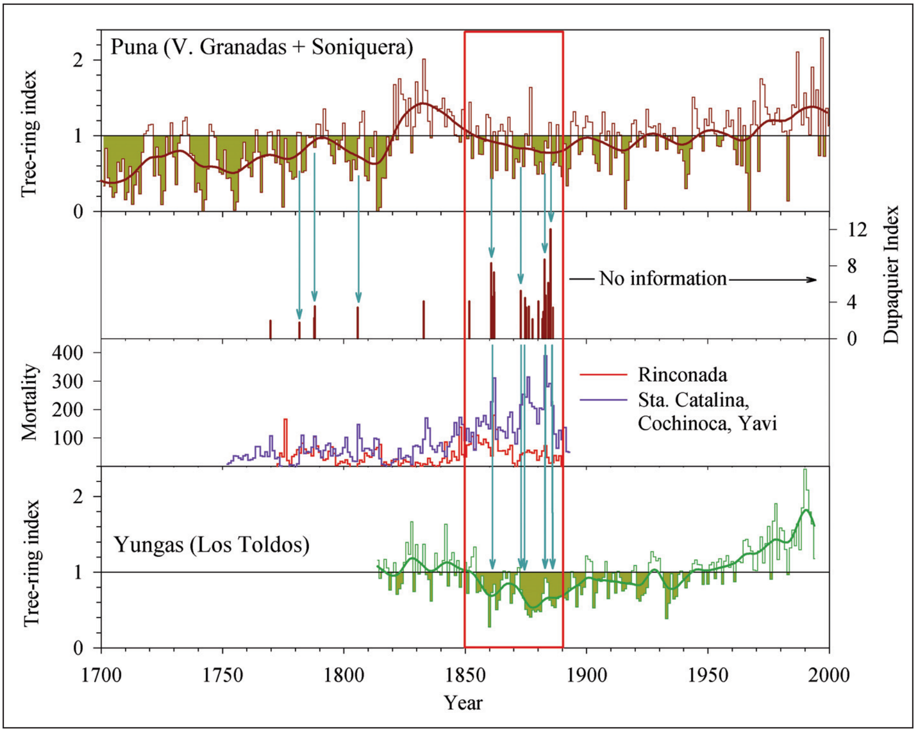


***FIGURE 15***

Comparison of tree-ring and human mortality data for northwest Argentina 1700 to 2000. Source: Gil Montero and Villalba, 2005.

These proxy records underscore the importance of the long term perspective on hydroclimate variability. Rio Puelo flows from Argentina into Chile and the short instrumental streamflow record is strongly correlated with the Antarctic Oscillation. However, the reconstructed, tree-ring based streamflow for the last 400 years shows a strong, 84 year periodicity that increases in amplitude over this period (Figure 17). The strong negative trend of this observational record covers only a part of this pattern and is likely not representative of the long term (and future) variation in flow of this system.

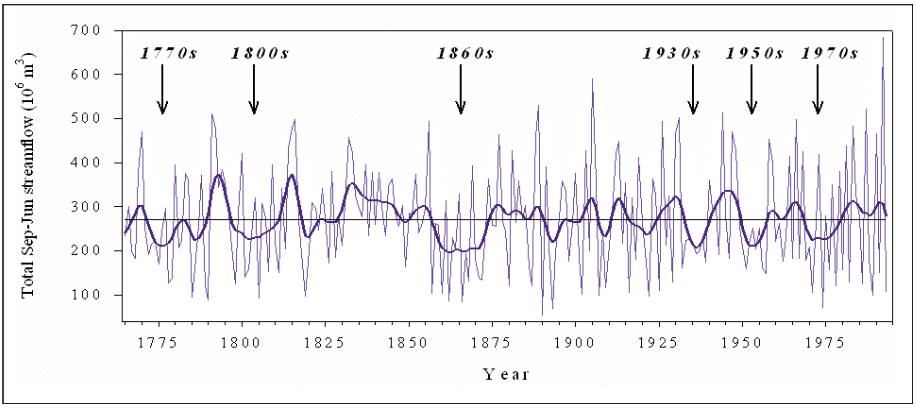


**FIGURE 16**

Reconstruction of stream flow from the Rio Nazas in Mexico, showing drought events from 1775 to 1995 and the complex pattern of high frequency variability. Source: Villanueva *et al.* 2005.

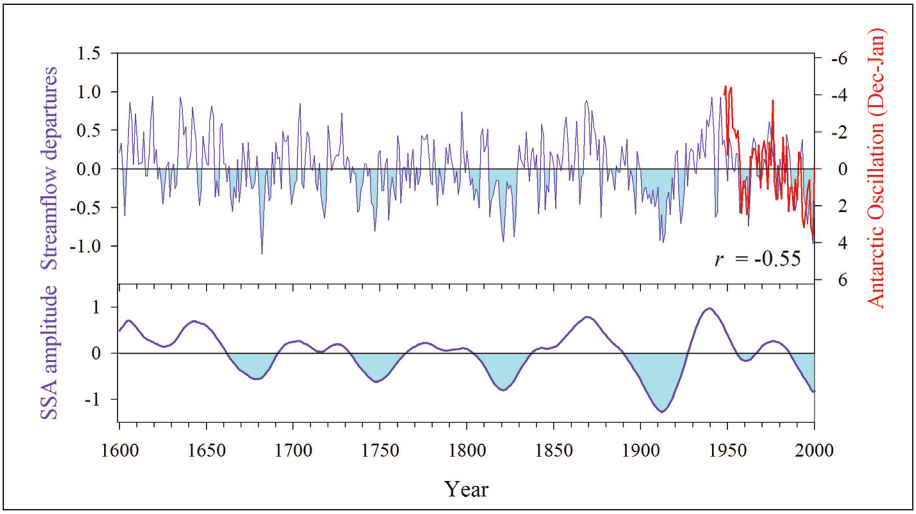


**FIGURE 17**

Streamflow departures for the Rio Puelo using measured and proxy data, 1600 to 2000, and correlation with the Antarctic oscillation. (Lara *et al.*, 2005)

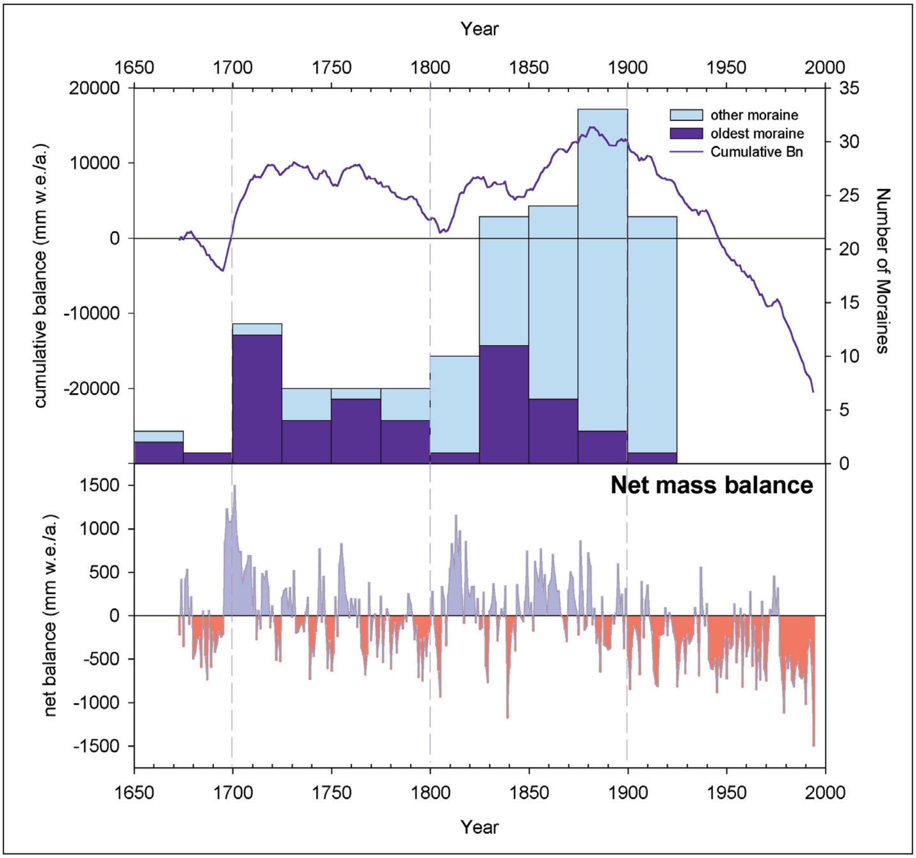


**FIGURE 18**

Comparison of the reconstructed Peyto Glacier mass balance with the dated moraine sequences from the Canadian Rockies. (Watson and Luckman, 2004)

## 4. Changes in the Cryosphere

Changes in the cryosphere and glacier recession provide some of the most visual and dramatic evidence of climate change. Paired photo comparisons provide powerful evidence of these changes. For example, about 70 percent of the ice mass of Peyto Glacier in Western Canada has been lost in the last 100 years. Detailed measurements of mass balance (winter accumulation minus summer melting) provide the best indicators of the relations between glaciers and climate. Although they clearly show the effect of the 1976 climate shift on winter balance (Figure 3) the measured series is relatively short (less

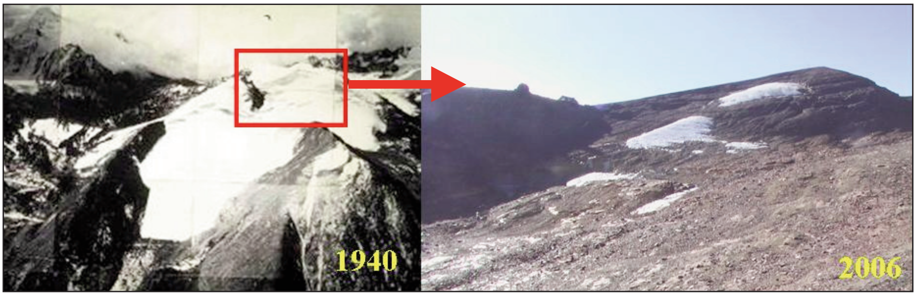


***FIGURE 19***

Chacaltaya Glacier (Bolivia) in 1940 and 2006. Photographs courtesy of Bernard Francou and Edson Ramirez.

than 40 years at Peyto). Tree-ring based reconstruction of the winter (accumulation) and summer (ablation) balances have been developed for the last 300 years and show good agreement with the timing of known periods of glacier advance in this region (Figure 18). They indicate that, since the late 1880s, glacier mass has been progressively decreasing, and at an accelerating rate.

These longer term reconstructions also allow the evaluation of the role of ENSO and the PDO in changing mass balance. Winter balances (and regional snow packs) are lowest in the Canadian Rockies when El Niños are combined with a positive PDO and greatest where La Niña and the (negative) PDO are in phase (Watson *et al.*, 2006). These variations have significant impacts on snowpacks and the annual regime of rivers draining to the adjacent lowlands and the Prairies, as the streamflow during periods of peak water demand is mainly fed by snow or glacier melt. The significant reduction in glacier areas will also impact late summer flows to which glacier melt is a primary contributor. In parts of the cordillera many small glaciers have already disappeared and the rapid reduction of tropical glaciers is a major cause for concern in the high Andes where summer glacier melt is a vital component of water supply. The Chacaltaya Glacier in Bolivia was about 15 x $10^6$ cubic meters in 1940, reduced to two small ice patches in 2006 (Figure 19) and will probably completely disappear by 2007 or 2008. Along with a number of other small glaciers, it represented a major source of water for the 1.5 million people of La Paz.

## 5. Conclusions

Temperature changes are a significant component of future climate scenarios but changes in precipitation, water availability and growth in demand can generate potentially far greater impacts on the biosphere and on human/economic activity. In many areas of the Americas mountains act as "Water Towers" and supply water to adjacent drier lowlands that is critical for population and economic activities in areas such as the Canadian Prairies, the Argentinean Pampas, the Altiplano or the Central Valleys of Chile and California. Most work on these potential problems has come from the data rich areas of North America or Europe - comparative examples or available data do not exist for many areas of Latin America.

Analysis of existing records and paleoenvironmental reconstructions offer the chance to develop longer data sets that characterize the full spectrum of precipitation, temperature, streamflow and glacier variability in these regions. Better estimates of past and present streamflow and precipitation regimes (and, in some cases glacier change) are necessary to identify and model the major causes of variability. Understanding this variability is a key to water resource planning and mitigating the effects of future changes.

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