Mountain “Water Towers” and Global Change- documenting hydroclimate variability in the American Cordillera

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Abstract In many parts of the western Americas cordilleran runoff is the primary source of water for adjacent semi-arid lowlands. Climate and land use changes are resulting in changes in the amount, seasonality and variability of streamflow, which, combined with increasing demand, creates significant problems for contemporary and future water management. This session focuses on past, present and future changes in hydrologic variability with examples from the mountain areas of the USA, Mexico, Bolivia, Chile and Argentina. It examines the contribution of glaciers, snowmelt and anthropogenic activities to these changes; discusses the causes, nature and range of variability at centennial-annual timescales; illustrates the impacts of these changes on society and explores the implications of these changes for future water management in the adjacent lowlands. Critically, these studies demonstrate the nature and range of hydroclimatic variability that must be accommodated in meeting sustainable future water management needs in these regions.

Introduction

In many parts of the western Americas cordilleran runoff is the primary source of water for adjacent semi-arid lowlands. This illustrates the concept that mountain areas function as “Water Towers” (Liniger et al., 1998, Messerli et al., 2004), storing and then releasing water to the surrounding areas. Ongoing climate and land use changes are resulting in changes in the amount, seasonality and variability of streamflow, which, combined with increasing demand, creates significant problems for contemporary and future water management.

The Inter-American Institute for Global Change Research’s Collaborative Research Network CRN2047 “Documenting, understanding and projecting changes in the hydrological cycle in the American Cordillera” was formed in 2006 and involves 19 principal investigators from seven countries across the Americas. The project examines past and current hydroclimate conditions, snow pack and glacier history in case studies from the American cordillera in Canada, the United States, Mexico, Bolivia, Chile and Argentina using tree-ring data, precipitation and streamflow records, glacier studies and basin-wide hydrological balances. This session will present selected results from these studies, focusing on case studies of past, present and future changes in hydroclimate variability at centennial-annual timescales and their impacts on society. Critically, these studies demonstrate the nature and range of hydroclimatic variability that must be accommodated in meeting sustainable future water management needs in these regions

Water is a critical resource for all forms of life and therefore water availability and security will be critical problems to be faced with ongoing global changes. The underlying controls of water-related problems are related to hydroclimate variability i.e. the seasonal and long term availability of surface or groundwater from precipitation, snowmelt, glaciers or groundwater. In managing water supplies, understanding the natural variability of available sources and the climatological conditions that lead to this variability are critical. Though it is recognized that there are a wide range of social, economic, political and legal issues surrounding access to and availability of water, these issues are not addressed in this paper. Hydroclimate varies continuously over time and spatially and provides the physical constraints on available water for human use and activity. Planning the sustainable use of water depends on understanding and managing this variability, monitoring ongoing changes and adjusting appropriately. In this regard it is critical to point out the range of variability in the existing instrumental or documentary records provide a very limited sample of hydrological variability and thereby possible future changes. One of goals of the CRN project has been to reconstruct past hydroclimate variability whilst simultaneously trying to reconstruct and understand the local and regional climatic patterns that control and give rise to that variability. This involves sampling variability at all timescales- including low frequencies at decadal-to-centennial timescales that only proxy data can provide.

The controls of natural variations in streamflow over time can be attributed to three major sources- changes in temperature, changes in atmospheric circulation patterns (i.e. precipitation) and changes in land surface cover. Although each will briefly be described below, in reality they interact continuously resulting in the complex patterns of variability we see in the hydroclimate records across the Americas.

Temperature –related changes

Throughout the cordillera streamflow regimes may be divided into three broad categories: basins where streamflow is basically dominated by rainfall variation, basins that experience a snow-rainfall mixture and basins with a strong nival (major glacier fed) regime. The greatest immediate effects of future temperature changes will be on those drainage basins (mainly in western US, Canada, Bolivia, Central Chile and Argentina) where the melt of winter snowpack sustains 60-80% of summer streamflow and thereby water supplies for irrigation, power generation and human consumption. This is a common condition for many valley or lowland sites that receive their water from rivers draining the American Cordillera. Warmer winter conditions will change rainfall/ snowfall relationships, reduce total snowpack plus the period of seasonal snow cover and result in changes in the altitude of the zero isotherm in the mountains at all seasons. More fall-winter precipitation as rain rather than snow increases winter runoff and decreases spring and summer snowmelt and hence river discharge volumes, resulting in earlier runoff peaks and a changing seasonality of flows. For example runoff in 30% of 37 Andean rivers in Central Chile is now peaking significantly earlier in the year (Cortes and McPhee, 2010) and similar results have been well documented in North America (Stewart et al., 2005). Modeling of future streamflows in the Maule and other catchments in Chile indicate reductions of 20-30% over the next century (based on the A2 SRES scenario) with a concomitant reduction of up to 20% in hydroelectric generating capacity.(Ayala et al, 2010, see also Vicuna et al 2010) Higher spring and summer temperatures will also increase surface evaporative losses, further reducing summer flows.

Glacier changes

Change in glaciers and glacier mass loss are visually dramatic and have attracted significant attention in discussions of climate change. Glacier area loss in the mountains of British Columbia and Alberta in Canada averaged about 0.6% per year between 1985 and 2005 and doubled after 2000 (Bolch et al 2010). Glacier recession is almost universal throughout the Americas and the South Patagonia Icefield lost almost ~490 km^2 (ca 3.7%) of its area since 1986 (Skvarca and Marinsek, 2010). The major hydrological contribution from glacier melt per se (as distinct from total discharge from glaciers) is in augmenting low flows in late summer when the melt of glacier ice and firn contributes significantly to sustaining flows (Figure 1). This is particularly critical in the high tropical Andes where glaciers are small, shrinking rapidly and provide critical water resources for both humans and agriculture. However, although this late summer flow from glaciers is important, the changes in contributions from snowmelt in these environments are orders of magnitude greater and likely to be much more significant in terms of water supply. In many basins with small amounts of glacier cover, the augmentation of summer low flows by glacier melt is likely only to be a short term effect as glaciers disappear (e.g. Marshall et al., in press).

Precipitation related changes

Temporal variability of precipitation and streamflow is partially random interannual variability but there is also systematic variability that depends on the nature and interaction between various critical atmospheric and oceanic circulation patterns that influence precipitation. Much climate variability is driven from the tropics and, in the Americas, specifically by conditions within the Pacific. Year to year variability in mid-low latitudes is dominated by ENSO but at high latitudes the low frequency variability is a stronger influence where changing large scale pressure patterns set up periodic or quasi-periodic patterns of varying duration and spatial extent (PDO,

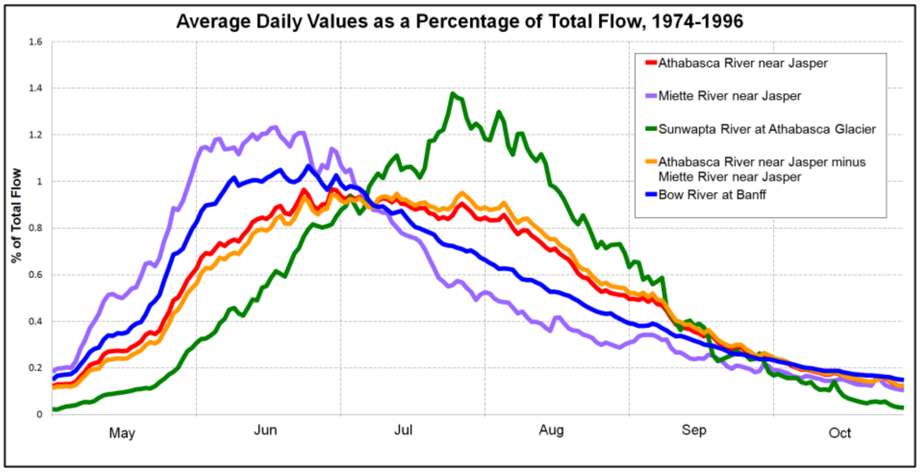


Figure 1 Average daily flows of selected rivers in the Canadian Rockies showing the seasonal influence of glacier melt. The Miette and Sunwapta are tributaries of the Athabasca and the Sunwapta gauge is about 1km downstream of the Athabasca Glacier. Sunwapta flow is May-October only.

Basin	Area (km^2)	% Glacier Cover	Discharge m^3/s	Median Flow date
Athabasca at Jasper	3872	6.8	86	July 18
Athabasca Above Miette	3243	8.1	75.6	July 21
Miette at Jasper	629	0.3	10.4	June 28
Sunwapta	29.3	ca.75	2.5	July 28
Bow at Banff	2210	2.6	38	July 9

AAO, NAO, PNA etc.). Many of these low frequency patterns are associated with specific atmospheric circulatory patterns and changes in the dominant pattern may lead to distinct “shifts” in climate such as the 1976 Pacific climate shift of the Pacific Decadal oscillation (PDO) in the North Pacific. For example, streamflow records in the Central Andes of Chile and Argentina show regime shifts with a 31% decrease (28% increase) in mean flows that are synchronous with the 1946-7 (1976-7) shifts of the PDO (Masiokas et al, 2010). In Canada, winter mass balance (essentially snowfall) at Peyto Glacier in Alberta showed a 33% decrease (from 1.5 to 1.0m water equivalent per year) between the decades before and after the 1976 shift. Contemporary variability can be assessed from instrumental and streamflow records though over most of the continent records are rarely >100 years for precipitation and >50 years for streamflow and often much less In many more remote areas such records are extremely sparse or absent and proxy records may be the only available source of data. Available instrumental data can only allow the characterization of variability and trends over the period of record but there are significant questions as to the representativeness of these records or their short period trends and whether such limited sample sizes cover the full range of variability. Longer records of both precipitation and streamflow have been developed for many sites throughout the Americas extending back 500-1000 years using tree rings (Figures 2 and 3). These show strong patterns of low frequency (decade-to-century scale) variability that are not captured in the instrumental records and are particularly significant in determining the magnitude and frequency of drought events. Changes in the low frequency patterns of sea surface temperatures in the Pacific generally result in latitudinal shifts of storm tracks, often leading to bi-polar patterns e.g. dry (wet) conditions in the US SW and Mexico correspond with wetter (drier) conditions in the NW USA and SW Canada (British Columbia, see Pederson et al., 2011) or, in the Southern Hemisphere, dry (wet) periods in central Chile alternate with wetter (drier) conditions on the Bolivian Altiplano. These changes or shifts are embedded within the available instrumental records and can strongly influence the trends from short instrumental records that do not capture this multi-decadal variability. For example streamflow of the Rio Puelo in Chile shows a strong declining trend over the last 50 years which is strongly correlated with the Antarctic Oscillation (AAO, Figure 2). However, the tree-ring based reconstructed record for streamflow shows a strong 84 year periodicity (Lara et al, 2008). The

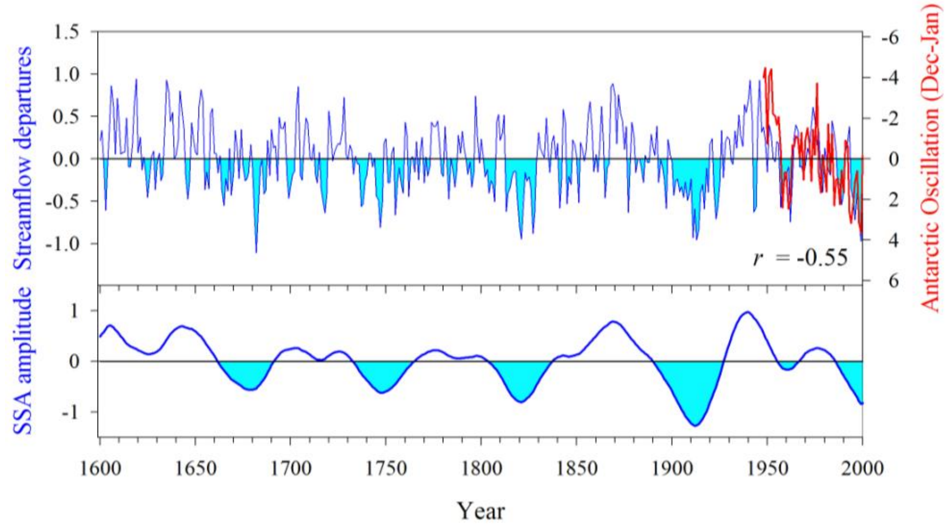
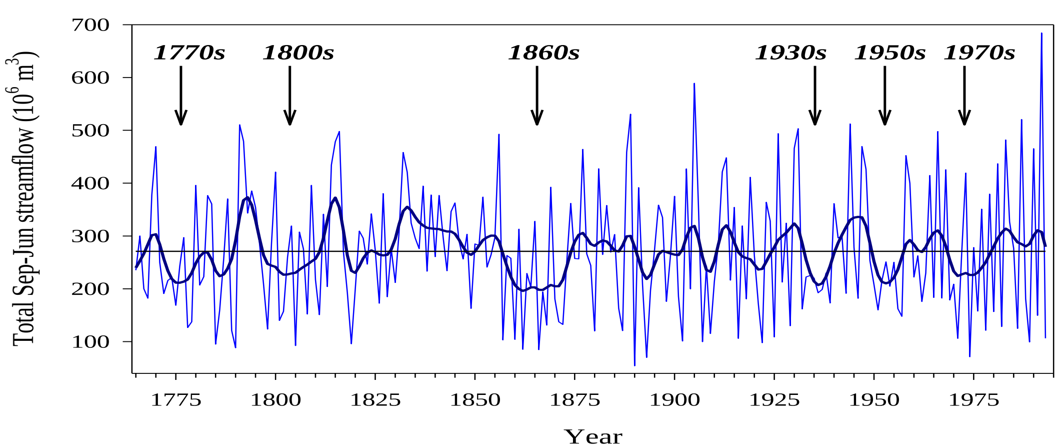


Figure 2: The tree-ring based reconstruction of Rio Puelo (Chile, ca. 40-41°S) discharge (1600-1999) is dominated by an 84-year periodicity (Singular Spectrum Analysis-lower graph) that explains 21% of the variance. This mirrors changes in the Antarctic Oscillation suggesting circulation changes may be highly significant factors in determining decadal scale trends in precipitation and streamflow (after Lara et al, 2008)

Figure 3 (below) Reconstruction of September- June streamflow of Rio Nazas, Durango, Mexico (ca 26°N) showing strong ENSO related interannual variability. Mean precipitation/ streamflow values in El Niño years average 2-3 times those in La Niña years. However, significant low frequency variability also exists indicating other controls of streamflow variability that result in decadal scale droughts in this record. (after Villanueva-Diaz et al, 2005)



recent streamflow record falls entirely within the falling limb of the last of these cycles and thus any extrapolation of the instrumental trend is unlikely to be a good predictor of future streamflows in this system. In many cases, therefore, recent trends developed from short instrumental records are an artifact of the length of available record and do not reflect the long-term trend or inter- to multi-decadal variability evident from longer proxy records.

The low frequency background patterns can modulate the high frequency variations in precipitation leading to changes in the character of these high frequency events. The pattern of Sea Surface Temperature (SST) anomalies associated with ENSO and the PDO in the Pacific are very similar but ENSO shifts have a periodicity of 4-7 years whereas PDO shifts are ca 30 years apart. Where the two patterns are "in-phase" the resulting anomalies are likely to be more extreme. For example, the most extreme precipitation anomalies in the western United States occur in La Niña years during periods of a negative PDO (Gershonov et al, 1999). In similar fashion, the most severe warm season droughts in Mesoamerica tend to develop when El Niño events are coupled with cold sea surface temperatures in the Atlantic. Millennial length tree-ring reconstructions of drought in Mexico allow the investigation of the types of atmospheric circulation that resulted in the classic droughts associated with the Mayas, Toltecs and Aztecs (Stahle et al, 2011).

Land use change

In addition to changes in streamflow due to climate-related variability, there may be changes in the response of hydrological systems as a result of surface changes within the catchments e.g. the drainage of wetlands, regulation of flows and transformation of the surface vegetation cover. Studies in Chile reveal reduction in low flow amounts in basins with exotic forestry plantations compared to flow in similar basins with native forest cover (Little et al., 2009). Similarly there have been many studies showing changes in hydrological response with conversion from forest to agricultural or urban land uses in Mexico and elsewhere. In addition many computer models suggest that a future warmer world will experience more extreme precipitation events resulting in greater flood hazards, particularly in those basins with significant modification of their surface characteristics.

Concluding Remarks

Stationarity never really existed in climate or hydrological systems – it was only, conveniently, assumed to be so. Future climates will continue to show the existing modes of low and high frequency variability superimposed on the effects of global warming and exacerbated by hydrologic changes due to land cover changes (both agricultural and urban). However, there will always be extreme events not known from the available records. It is critical to examine the full range of extremes from both historical and proxy records to determine any recent changes in the frequency and magnitude of extreme events. Although computer models may successfully reproduce the long term trends in future climate it is important that they also reproduce the variability: estimates of the extreme values of these conditions (maximum and minimum values, duration of dry and wet intervals etc) are the most critical. Although the mean conditions are a useful guide in planning for future conditions it is the extreme events that will ultimately result in the greatest economic, social and biological effects.

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