Recent and historic Andean snowpack and streamflow variations and vulnerability to water shortages in central Chile and central-western Argentina

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Abstract
River flows in the populated, semi-arid regions of central-western Argentina and central Chile (28°-37°S) are strongly dependent on meltwater from Andean winter snowpack. Analysis of instrumental snowpack and streamflow records for the past 60 and 100 years, respectively, shows strong intra- to multi-decadal variations with the driest (wettest) conditions occurring between 1954-68 (1977-87). Multi-proxy reconstructions of snow accumulation for the past 850 years indicate that variations observed in the last century are not particularly anomalous when assessed in a long term context. Current and projected population growth and water demand suggest that the vulnerability of these regions to one or more years with low snow accumulation in the Andes is likely to increase. Information on past hydroclimatic variations together with projected water needs may help improve water management practices and minimize the threats of future extended droughts in these semi-arid regions.

Keywords
Snowpack variations, central Andes, water resources vulnerability

1. Introduction

The winter snowpack in the Andes between 30° and 37 °S is the primary source of surface runoff and wate r supply in the adjacent lowlands of central Chile and central western Argentina (Fig. 1). The socio-economic, environmental and recreational benefits provided by the mountain snowpack are enjoyed by over 10 million people and include freshwater supply for human consumption, irrigation, various industries, tourism and hydro-electric generation. Given the strong, direct relationship between winter snowpack and spring-summer river discharges, winter snow accumulation has been routinely monitored for over five decades at several key locations to estimate warm season and annual water supplies on both sides of the Andes (Masiokas et al. 2006; hereinafter M06). Major rivers in this region have also been monitored for several decades using a relatively small but well maintained network of gauging stations. For some of these rivers, mean monthly streamflow records span almost the entire 20th century and are of excellent quality. This is a rarity for Andean South America that generally lacks long, good quality hydroclimatic data. However, despite the crucial socio-economic importance of the mountain meltwater, little is known about the main patterns of intra- to multi-decadal (IMD) variations in river discharges and winter snow accumulation in this region.

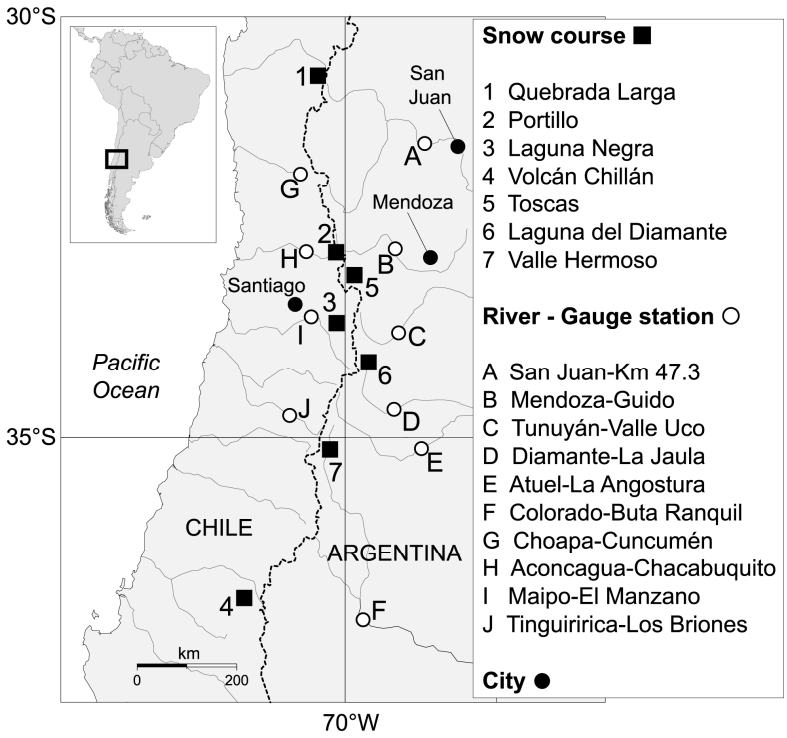

Figure 1. Location of snowpack and gauge stations used in this study. In this region the hydrological divide is also the international boundary.

M06 developed the first regional composites of maximum winter snow accumulation and mean warm season and annual river discharges using data from both sides of the Andes (30°-37°S) in Chile and Argentina. In addition to demonstrating the remarkable association between mountain snowpack and surface runoff in this region, they provided a comprehensive assessment of the main relationships between the inter-annual variations in snowpack and large-scale atmospheric indices and variables. The study generally corroborated the results from previous related studies in showing that ENSO-related features in the tropical Pacific and tropospheric conditions at higher southern latitudes are major factors driving the year-to-year variations in winter snowpack levels in this portion of the Andes. The influence of ENSO-related features on surface runoff is also well known for this region. Several studies have noted similarities between the periodic or quasi-periodic hydrologic variability in this area and the characteristic periodicity of ENSO variations. However, studies of temporal variations of streamflow records are relatively scarcer, have mainly focused on individual river basins, and are generally limited to linear trend analyses of mean monthly, seasonal or annual series. Overall, these analyses provide useful preliminary assessments of the main temporal and frequency characteristics of these records but are limited by assumptions that regional hydroclimate varies in an idealized linear or cyclic manner. In addition, they provide little insight about the specific location, extension and magnitude of extreme dry/wet intervals or the existence of regime shifts in the available instrumental record. Masiokas et al. (2010) extend the analyses in M06 and focused on the main IMD variations in mountain snow accumulation and river discharges using an updated dataset from Chilean and Argentinean sites. The low frequency patterns identified in the instrumental records revealed an interesting resemblance with patterns observed in the Pacific Decadal Oscillation (PDO). This issue is briefly discussed

here as it provides potentially useful evidence for future analyses intended to identify the most important factors driving IMD variations in local hydroclimatic records.

Recent analyses using the available snowpack data have resulted in multi-proxy reconstructions of snow accumulation for the past 850 years (Masiokas et al. in preparation). To a large extent, all these different records share a common regional hydroclimatic signal, and were specifically collected and combined in an attempt to extend as far back as possible, and as reliably as possible, the information on snowpack variations in the Andes. Analyses of current and projected population growth and water demand suggest that the vulnerability of these regions to one or more years with low snow accumulation in the Andes is likely to increase. Information on past hydroclimatic variations together with projected water needs may help improve water management practices and minimize the threats of future extended droughts in these semi-arid regions.

2. Data and Methods

The analyses of instrumental hydrological data used the longest and most complete snowpack and streamflow records from both sides of the Andes between 30° and 37°S (Fig. 1). As in M06, the maximum value of snow water equivalent (MSWE) in each year was used as a surrogate for total snow accumulation at each site. Mean annual streamflow data are calculated using the July-June mean monthly values. In general, these river discharge records have not been affected significantly by human activities and are thus relatively free of inhomogeneities. The overall good quality of the data is corroborated by the strong similarities at both inter-annual and longer timescales between individual time series and also between the regional streamflow and snowpack composites. The composite series cover the intervals 1951-2010 and 1909-2009 for snowpack and streamflow, respectively.

Complementary and annually-resolved quantitative reconstructions of snowpack variations for the high arid Andes of central Chile and central-western Argentina were developed that cover different time intervals ranging from 135 to 852 years in length. The reconstruction proxies used include a regional composite of central Chile winter rainfall variations and a network of precipitation-sensitive tree-ring width chronologies from the western foothills of the Andes. We also incorporate for validation purposes instrumental data and historical information on wet and dry years in central Chile, historical accounts of snow accumulation levels along the main pass connecting Chile and Argentina since colonial times, and a record of streamflow variations since AD 1600 from the eastern Andean foothills in Argentina. The target or predictand series in both reconstruction models is the regionally-averaged snowpack series developed from records of maximum winter snow equivalent data from this portion of the Andes.

Finally, we analyze local records of recent water needs and supply for the most populated basins in the semi-arid province of Mendoza, in an attempt to identify a minimum level of discharge required for “normal” socio-economic functioning of these water-stressed regions. Contrasting the current needs with natural variations in the instrumental and reconstructed hydrologic records offers the opportunity of a) assessing the relative severity of recent dry periods in a long term context and b) identifying possible extreme scenarios that may occur in the region based on past hydrologic estimates.

3. Results

Examination of the individual snowpack and mean annual streamflow records indicates broad similarities especially in the river flow data. Overall, the similarities in these series support the assertion that despite the low number of stations used in their construction, these simple mean series are relatively reliable, regionally representative records. The regional snowpack series showed a non-significant positive linear trend. The linear trend in the mean annual regional streamflow record is also non-significant but of opposite sign. However, marked year-to-year fluctuations are evident in these records. Time series analysis techniques indicate that the inception (conclusion) of the driest period of the 20th century in this portion of the Andes was coincident with a shift towards extended negative (positive) conditions in the PDO in the mid 1940s (1976). This suggests that the PDO may have been a major forcing for the occurrence of this well-defined dry interval in this area. It is well known that, although not perfect, there is a relationship between warm (cool) ENSO events in the tropical Pacific and wet (dry) conditions in this portion of the Andes. The correspondence observed between the extended “cool” PDO levels between 1944 and 1976 and the below-average winter snowpacks and annual discharges recorded during this interval resembles this relationship but over the multi-decadal timescale characteristic of the PDO.

A recently developed time series analysis technique was used for identifying and testing the statistical significance of the most important concentrations of snowy and dry years in the instrumental snowpack and streamflow series. This relatively simple technique not only allows the identification of the onset, duration, magnitude and statistical significance of extreme dry/snowy periods in the reconstructed series, but it also allows an easy, objective assessment of the relative magnitude of conditions during recent decades

compared with those from earlier decades/centuries. These analyses identified the driest period in the instrumental series between 1954 and 1968 and the snowiest interval between 1977 and 1987. The mean annual regional streamflow series showed two significant regime shifts in mean conditions in 1945, when levels dropped by ca. 31%, and in 1977 when they increased ca. 28%. Using a 10-year reference period, we evaluated the significance of all "moving decades" throughout the instrumental records and found very similar patterns.

We present the first attempts at reconstructing and analyzing quantitatively the variations in snow accumulation over the past two to eight centuries in the Andes of Chile and Argentina between 30° and 37°S. The multiple verification tests performed on the reconstructions offers some confidence on the relative reliability of these time series. The first reconstruction approach based on central Chile rainfall data shows exceptional skill for modelling Andean snowpack variations, but due to the limited availability of instrumental rainfall data prior to the 20th century, the reconstructed time series only extends back to AD 1866. Despite its relative shortness, this first reconstruction could be of great interest for local water resource managers interested in high quality mountain snowpack data for planning infrastructure and for developing a better understanding of Andean hydroclimatic variability over the past 145 yrs. The second, tree-ring based reconstruction approach is less accurate in modelling the instrumental snowpack record over the calibration period, but nonetheless it allows a quantitative assessment over a much longer time period providing evidence of snowpack changes since AD 1150. The relatively lower skill of this model is very likely due to the differential tree-growth response to extreme dry vs. extreme wet or snowy conditions. As with other precipitation-sensitive tree-ring species, the chronologies usually reflect the dry to extreme dry conditions better than extreme wet years for which the soil moisture content exceeds the physiological needs of the trees. However, despite this inherent limitation, this reconstruction offers the unique possibility of assessing in a quantitative and objective manner the history of snowpack fluctuations over the past 850 years in this Andean region. To our knowledge this record is the first annually-resolved mountain snowpack reconstruction covering most of the past millennium in the Southern Hemisphere.

Time series analyses of the instrumental vs. the reconstructed series indicate that variations observed in the last century are not particularly anomalous when assessed in a long term context. Longer and more severe droughts than those observed in the instrumental record probably occurred several times during the past millennium. The most notorious extreme dry intervals are concentrated between the late 16th century and the mid 18th century. The reconstructions also provide evidence for extended periods of high snowpack levels that probably surpassed those recorded during the past six decades in the Andes. A extreme snowy period concentrated at the turn of the 20th century is the most recent period with values significantly higher than those observed in the 1980s in the instrumental data. However other periods such as the peaks in the late 1400s, during the early and late 1600s, and during the mid 1700s and mid 1800s also appear to have been at least as extreme as the early 20th century period and well above the highest levels seen in recent decades in the instrumental record.

Evaluation of water budgets at key basins showed that annual volumes of water required in the main oases in the Province of Mendoza exceed those provided in "normal" years by mountain snowmelt. In all cases, groundwater pumping is absolutely necessary for meeting the growing needs of this region´s irrigation-dependent agricultural system. Population growth in recent decades the provinces of central-western Argentina has been ca. 10% decade^{-1}. Assuming these trends will continue in the future, water needs

4. Conclusions

- Integration of Chilean and Argentinean hydrological data proved useful and provided reliable, regionally representative records
- Regional snowpack and annual streamflow records show striking similarities that highlight the strong common hydrologic signal in this region and the good quality of the original data
- Two significant regime shifts in 1945 (-) and 1977 (+) were identified that mark the transition between three well defined low frequency modes of variability.
- The highest concentration of extreme dry (wet) conditions occurred between 1954 and 1971 (1977 and 1987)
- In addition to ENSO, PDO may be influencing decadal hydrological patterns in this region
- Good quality, multi-centennial quantitative annually-resolved snowpack reconstructions are possible at these latitudes

- There is a great variety of “proxies” which can provide complementary information

- Two original, complementary snowpack reconstructions were developed that cover the periods AD1866-2000 and AD 1150-2001

- These reconstructions can provide important information on past hydroclimatic variations in the southern Andes

    - Provide a long term context of natural variability for local water management plans
    - Paleoclimate research
    - Climate modeling

- Results from innovative time series analyses indicate that variations observed in the instrumental period (60-100 yrs) are not particularly anomalous when assessed in the context of the past two to eight centuries

- Data from the main rivers in Mendoza indicate water needs in the oases are higher than the volumes provided by surface runoff in normal years
    - Improving efficiency can help reduce vulnerability to the highly variable water regimes in the region

- Groundwater is crucial in all river basins, especially during extreme dry years
    - Stronger controls and conservation and restoration policies are urgently needed to preserve this key resource

- Population growth projections suggest that water needs and associated conflicts between water-dependent sectors will likely increase in the future

5. References

Compagnucci, R.H., and W.M. Vargas, 1998: Inter-annual variability of the Cuyo rivers' streamflow in the Argentinean Andes mountains and ENSO events. Int. J. Climatol., 18, 1593-1609.

Dettinger, M.D., D. S. Battisti, R.D. Garreaud, G.J. McCabe, Jr. and C.M. Bitz, 2000: Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas. Interhemispheric Climate Linkages, V. Markgraf, Ed., Academic Press, 1-16.

Escobar, F., and P. Aceituno, 1998: ENSO influence on Andean winter snowfall in central Chile (in Spanish). Bull. Inst. fr. études andines, 27(3), 753-759.

Mantua, N.J., and S.R. Hare, 2002: The Pacific Decadal Oscillation, J. Oceanogr., 58, 35-44.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production, Bull. Amer. Meteor. Soc., 78, 1069-1079.

Masiokas, M.H., R. Villalba, B.H. Luckman, C. Le Quesne, C., and J.C. Aravena, 2006: Snowpack variations in the central Andes of Argentina and Chile, 1951–2005: Large-scale atmospheric influences and implications for water resources in the region, J. Clim., 19, 6334-6352.

Masiokas, M.H., R. Villalba, B.H. Luckman, S. Mauget (2010), Intra- to multidecadal variations of snowpack and streamflow records in the Andes of Chile and Argentina between 30° and 37°S, J. Hydrometeorol., 11(3), 822-831.

Masiokas, M.H., Villalba, R., Christie, D., Betman, E., Luckman, B.H., Le Quesne, C., Prieto, M.R., Mauget, S. (In preparation). Andean snowpack since AD 1150 inferred from rainfall, tree-ring and documentary records.

Mauget, S.A., 2003: Intra-to multidecadal climate variability over the continental United States: 1932-99, J. Clim., 16, 2215-2231.

Mauget, S.A., 2004: Low frequency streamflow regimes over the central United States: 1939-1998. Clim. Change, 63, 121-144.

Mauget, S. (2011) Time series analysis based on running Mann-Whitney Z Statistics, J. Time Ser. Anal., 32, 47-53.

Rutlland, J., and H. Fuenzalida, 1991: Synoptic aspects of the central Chile rainfall variability associated with the Southern Oscillation. Int. J. Climatol., 11, 63-76.