5.14 Recent and Historic Andean Snowpack and Streamflow Variations and Vulnerability to Water Shortages in Central-Western Argentina

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5.14.1 Introduction

In many mountainous regions of the world the accumulation of snow during winter constitutes the main (and sometimes the only) source of streamflow during subsequent warmer months and throughout the year. The dramatic changes in topography within short distances in mountain ranges usually force air masses to release their moisture as they ascend and move across the highest peaks and intermontane valleys. With freezing temperatures, this precipitation usually occurs as snow, and this water can accumulate and remain frozen until warmer conditions start the seasonal, gradual melting of the snowpack that feeds many creeks and rivers in high-elevation regions. This capacity of mountainous areas to accumulate and store water as snow and ice during winter and subsequently release it as meltwater during warmer months, when it is most needed by human populations in adjacent areas, has been recognized and valued by ancient and modern societies in many parts of the world. In recent decades, the importance of mountains as storage and sources of water has been reaffirmed through numerous studies, and the expression 'water towers of the world' has been coined to reflect the crucial significance of these elevated regions to the population and environments in different continents (Viviroli et al. 2009, 2011). However, despite the well-known and generally undisputed importance of mountains as primary sources of freshwater, the number of detailed assessments of the main hydrologic patterns and the factors affecting mountain climate conditions remains limited in many regions. In such cases, the vulnerability of local human populations to water shortages has not been assessed through a comprehensive hydroclimatologic and socioeconomic approach that could help identify, for example, those social and economic sectors more vulnerable to extended droughts, or minimum water levels required for 'normal' operation of local societies.

This chapter provides an overview of recent empirical analyses of snowpack and streamflow records from the Andes between 30 and 37° S (Figure 1), which allow an assessment of the importance of the winter snow on regional river discharges and the identification of their main temporal and spatial patterns over the past 100 years. The relationships between mountain snowpack records and various large-scale ocean–atmospheric variables (such as sea-surface temperatures and the El Niño–Southern Oscillation, ENSO) are also assessed in an attempt to identify the main factors modulating snowpack variations in the Andes. Two complementaries, recently developed Andean snowpack reconstructions covering the past two to eight centuries, are subsequently examined and their main intra- to multidecadal (IMD) patterns identified using time series analysis techniques. Besides the more obvious application in local water management and regional development strategies, this information allows testing the relative significance of the patterns of snowpack observed during the instrumental period in a long-term context. This information may also be relevant for measuring the strength and time stability of the relationships between Andean snowpack and ENSO or other ocean–atmosphere features over most of the past millennium. Finally, the authors comment on the varying vulnerabilities to water shortages in the basin of Río Mendoza (one of the main rivers in central-western Argentina, Figure 1) and the potential benefits of integrating instrumental and reconstructed hydrologic data together with results from climate and climate-driven hydrological models into local socioeconomic assessments, water management practices, and adaptation planning.

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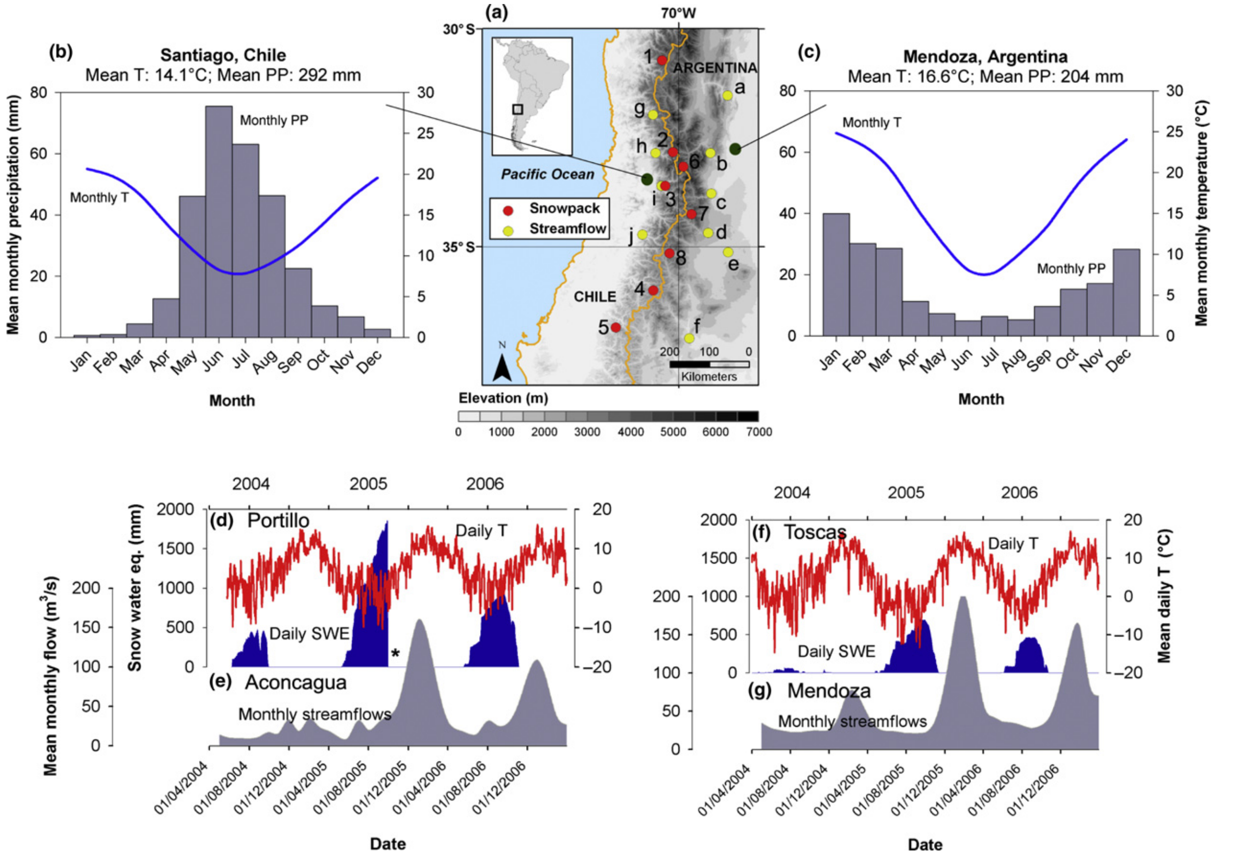

Figure 1 (a) Location of the stations with the longest and most complete snowpack and streamflow records (red and yellow dots, respectively) in the Andes of Chile and Argentina between 30 and 37° S. For station metadata see **Table 1**. (b, c) Climographs showing the climatic regimes characteristic of the cities of Santiago, Chile, and Mendoza, Argentina, on the western and eastern lowlands adjacent to the Andes. To facilitate the comparison of these diagrams, mean monthly precipitation (left *y*-axes) and temperature (right *y*-axes) are depicted using the same scale. The units for the precipitation axes are indicated in (b) and the temperature axes are labeled on the far right in (c). Note the different climatic regimes between these sites with a marked peak in precipitation during the austral winter (summer) for Santiago (Mendoza). (d) Mean daily temperatures (red line) and snow water equivalent (blue area) recorded at Portillo, Chile (station 2 in (a)) between 1 April 2004 and 31 March 2007. These years were selected because they provide a good indication of the range of conditions existing in the high arid Andes: the winter of 2004 was extremely dry, that of 2005 was extremely snowy, and that of 2006 was slightly above 'normal.' An asterisk (*) indicates partial lack of data for the 2005 snow season. (e) Mean monthly discharges for Río Aconcagua at Chacabuquito (station h in (a), located downstream of Portillo) between April 2004 and March 2007. Note the good correspondence between the amount of snow accumulated in the basin headquarters during winter and the streamflow recorded during the following warmer months. (f) Same as (d) but for the Argentinean station Toscas, on the eastern side of the Andes (station 6 in (a)). (g) Same as (e) but for Río Mendoza at Guido, downstream from Toscas (station b in (a)). The left axes in (d)–(g) are labeled on the far left and the right axes are labeled on the far right, and the data for Portillo–Aconcagua are depicted in the same scale as those for Toscas–Mendoza to facilitate the analysis of similarities and differences on both sides of the Andes.

5.14.2 Andean Snowpack Is a Crucial Water Resource in Vast Semiarid Areas of Southern South America

The portion of the Andes between 30 and 37° S in southern South America (Figure 1(a)) has a mean elevation of about 3500 m, with several peaks reaching over 6000 m. The weakening and northward displacement of the subtropical Pacific anticyclone during the austral winter enhances the westerly flow across central Chile, producing a marked cold season peak of precipitation in the lowlands and over the mountains to the east (Miller 1976; Aceituno 1988; Falvey and Garreaud 2007; Figure 1(b)). Owing to the high elevation and north–south orientation of the cordillera, most of the moisture from the Pacific air masses is released in the mountains and little Pacific moisture reaches the easternmost slopes of the Andes in Argentina. The semiarid region east of the cordillera experiences a continental regime with a marked warm season precipitation peak associated with moist air masses from the northeast as well as convective processes (Prohaska 1976; Figure 1(c)).

Several heavily populated cities (including Santiago de Chile, the nation's capital city, and the city of Mendoza, in central-western Argentina) and extensive agricultural areas are located in the lowlands flanking the Andes at these latitudes. Human activities in these productive regions are almost entirely dependent on the systematic use of mountain meltwater for human consumption, industries, irrigation, hydroelectric generation, and aquifer recharge. Collectively, over 10 million people live in these regions (INDEC 2001; INE 2003) and enjoy the socioeconomic, recreational, and environmental benefits provided by this natural resource. The dependence on Andean freshwater is even more evident along the eastern, drier Argentinean foothills and plains, which receive on average only 200 mm of precipitation per year (Figure 1(c)). The development of complex irrigation systems has allowed the existence of oases that stand out as islands of green amid vast oceans of dry lands, forming a territorial pattern common to human settlements across central-western Argentina. For example, in the Province of Mendoza oases represent only 3% of the total surface but contain about 98% of the population and concentrate a large share of the more dynamic socioeconomic activities. Given these particular environmental and socioeconomic conditions, water scarcity is not just a hydroclimatic phenomenon in this region. These Latin American drylands have been characterized as 'hydraulic societies' (Worster 1985), as social tissues are strongly associated with intensive use of water resources that historically have been adapted to 'control' a hostile natural environment. While the space becomes territory through water allocation, water appropriation and use gives rise to and reproduces a scheme of social and political relationships in which quotas of power are distributed. Although water deficits are structural, water shortage scenarios threaten local economies and anticipate increases in the frequency and intensity of social, political, and economical conflicts (Montaña 2008). In this context, efforts to bridge knowledge derived from natural and social sciences may provide very interesting perspectives, as better knowledge of the relative magnitude and temporal extension of past droughts (and their potential behavior in the future) constitutes a valuable resource to anticipate future vulnerabilities and develop adaptation strategies toward resilience.

As in many regions with snowmelt-dominated hydrologic regimes, in the Andes of central Chile and central-western Argentina there is a well-known, strong, direct relationship between winter snow accumulation and spring–summer river discharges (see, e.g., Figure 1(d)–1(g)). Local water agencies in Chile and Argentina are well aware of this relationship and have implemented a network of measuring stations that regularly monitor the accumulation of snow during the winter at several high-elevation sites. The snowpack information (which for some sites spans over five decades of continuous records) is routinely used to produce warm season and annual water supply forecasts for the main river basins on both sides of the Andes. Interestingly, however, besides these short-term forecasting products, very few analyses of instrumental snowpack variations are available for this portion of the Andes, and the main spatiotemporal patterns in these mountain snow records are only starting to be understood.

Major rivers in this region have also been monitored for several decades using a relatively small but well-maintained network of gauging stations. Some of the mean monthly streamflow records available for these rivers cover almost the entire twentieth century and are of excellent quality. This is a rarity for Andean South America, which generally lacks long, good-quality hydroclimatic data. There are also records from other smaller rivers and creeks that generally span for a few decades but in some cases contain periods with missing information. However, despite the existence of these valuable records and the well-known, crucial socioeconomic importance of mountain meltwater, the number of studies assessing the main patterns of IMD variations in river discharges is limited (see later).

5.14.3 Andean Snowpack and Streamflow Records Share a Strong Regional Common Signal

Masiokas et al. (2006) presented the first attempt to integrate snowpack records from Chilean and Argentinean stations and provided a comprehensive assessment of maximum winter snow accumulation data over the 1951–2005 period. Their results generally agreed with previous climatic and hydrometeorological studies showing a marked Pacific, ENSO-related influence on precipitation in this area (e.g., Rutlland and Fuenzalida 1991; Compagnucci and Vargas 1998; Escobar and Aceituno 1998; Montecinos and Aceituno 2003). However, their analyses provided further insight into the main temporal and spatial patterns in the snowpack records and their relationships with local climate, ENSO events, and large-scale atmospheric variables. Masiokas et al. (2006) also quantified the relationship between winter snow records and river discharges in the region and evaluated possible causes for the observed streamflow and glacier trends over the second half of the twentieth century.

Masiokas et al. (2006) showed that, despite the very low number of snowpack records existing in the Chilean and Argentinean sides of the Andes between 30 and 37° S, these records share a high percentage of common variance at interannual and longer timescales. These analyses were based on maximum winter snow water equivalent values (MSWE) as a surrogate for total snow accumulation at each site and a regional record developed from the six stations with the longest and most complete records. This dataset has subsequently been expanded and updated (e.g., Masiokas et al. 2010, 2012; Figure 2), although the number of stations remains small compared to other regions such as western North America or the European Alps (Figure 2(a) and 2(b); Table 1). Collectively, these records currently cover different portions of the 1951–2010 period, and despite the large latitudinal range of the stations the mean correlation coefficient from all possible paired combinations is 0.683. These individual snowpack records show a strong year-to-year variability ranging from 0% to over 400% of their long-term mean, and the snowiest and the driest winters are concurrently captured in most records throughout the region (Figure 2(a)).

Examination of streamflow records shows even stronger similarities than the snowpack records (Figure 2(b); Masiokas et al. 2010). The stronger streamflow similarities probably relate to the overall lower quality or regional representativeness of the snowpack data plus the different inherent characteristics of snowpack and streamflow interannual variations in this region. However, when the individual records are aggregated into regional averages, the similarities between the MSWE and the streamflow series are remarkable, with a very strong time-stable common signal at interannual and interdecadal timescales (Figure 2(c)). This result is not surprising given the predominant role of snowmelt in the river discharges of this region. It is interesting to note, however, that the first

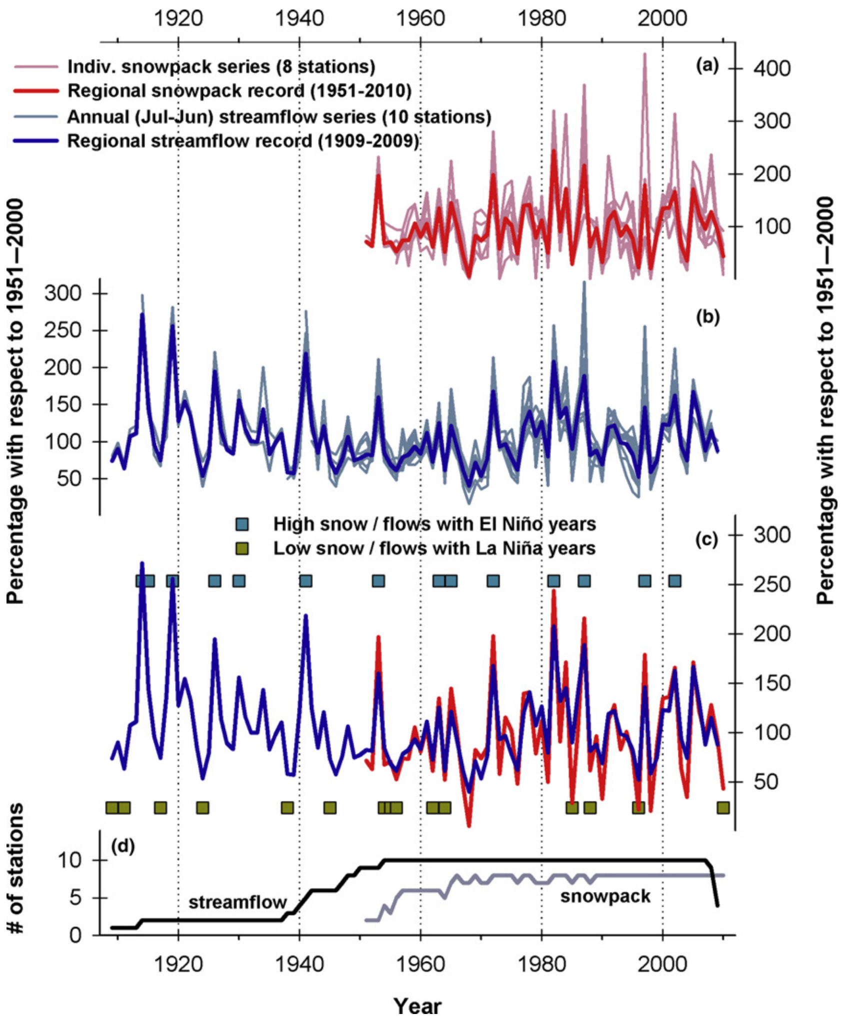

Figure 2 (a) Winter maximum snow water equivalent records (pink lines) for the eight snowpack stations shown in **Figure 1(a)**. The 1951–2010 variance-adjusted regional snowpack average is shown with a red line. (b) Jul.–Jun. mean annual series (light blue lines) of the 10 streamflow stations in **Figure 1(a)**, together with a regionally averaged river discharge record (blue line). (c) Comparison of the regional records of winter snowpack and mean annual streamflow (red and blue lines, respectively) shown in (a) and (b). The Nov.–Feb. river discharge record (not shown) portrays virtually identical features to the annualized data. El Niño years (Giese and Ray 2011; light blue boxes) generally coincide with above-average hydrologic measurements in the Andes. La Niña years (ochre boxes) usually reflect an opposite pattern – dry years in the Andes – but there are notable exceptions such as the extremely dry winters of 1968, 1998, and 2004, which did not coincide with La Niña events in the tropical Pacific. (d) Number of stations used to compute the regional snowpack and streamflow records in any given year. All series in (a)–(c) are expressed as percentages with respect to the 1951–2000 common period mean, but note the different scales used in each case.

integrative, quantitative analyses using data that cover the past several decades and from the eastern and western slopes were not performed until very recently (Masiokas et al. 2006, 2010).

As expected from a snowmelt-dominated regime, the late spring–early summer months (Nov.–Feb.; which account for almost 60% of the annual total flows) show the highest correlations with the snowpack record (Masiokas et al. 2006). The correlation between the MSWE record and the regionally averaged mean annual streamflows is almost high ($r = 0.922$, Figure 2(c)). These results clearly reflect the crucial influence of mountain snowpack on freshwater availability in the adjacent lowland areas in Chile and Argentina and suggest that, at a regional scale, *c.*85% of the streamflow variance observed over the past six decades could be explained by the snowpack record alone (Figure 2(c)). This also suggests that despite the low number of stations used in these analyses, the simple regional series depicted in Figure 2(c) can be considered relatively reliable indicators of the main interannual and interdecadal (IMD) hydrologic variations that occurred in this portion of the Andes approximately during the past 100 years.

As in many other mountainous areas of the world, in the Andes of central Chile and central-western Argentina the glaciers and periglacial features such as rock glaciers constitute important water resources and may contribute with significant amounts of meltwater to the surface runoff of a certain basin. The hydrological significance of the existing ice masses in this arid region becomes particularly important during extremely dry years when little or no solid precipitation occurs at the upper watersheds. Unfortunately, very few systematic, local assessments are available to properly evaluate the relative

Table 1 Snowpack and streamflow records used in this study

Variable	*Station*	*Latitude, longitude*	*Elevation (m)*	*Period*	*Average*	*Data source*
Snowpack	1–Quebrada Larga	30°43′ S, 70°22′ W	3500	1956–2010	222 mm	DGA
	2–Portillo	32°50′ S, 70°07′ W	3000	1951–2010	637 mm	DGA
	3–Laguna Negra	33°40′ S, 70°08′ W	2768	1965–2010	584 mm	DGA
	4–Lo Aguirre	36°00′ S, 70°34′ W	2000	1954–2010	943 mm	DGA
	5–Volcán Chillán	36°50′ S, 71°25′ W	2400	1966–2004	800 mm	DGA
	6–Toscas	33°10′ S, 69°53′ W	3000	1951–2010	295 mm	DGI
	7–Laguna del Diamante	34°15′ S, 69°42′ W	3310	1956–2010	453 mm	DGI
	8–Valle Hermoso	35°09′ S, 70°12′ W	2275	1952–2010	784 mm	DGI
Streamflow (river)	a–Km. 47.3 (San Juan)	31°32′ S, 68°53′ W	945	1909–2008	65.2 $m^3 s^{-1}$	SSRH
	b–Guido (Mendoza)	32°51′ S, 69°16′ W	1550	1909–2009	48.9 $m^3 s^{-1}$	SSRH
	c–Valle de Uco (Tunuyán)	33°47′ S, 69°15′ W	1200	1954–2009	28.6 $m^3 s^{-1}$	SSRH
	d–La Jaula (Diamante)	34°40′ S, 69°19′ W	1500	1938–2009	30.9 $m^3 s^{-1}$	SSRH
	e–La Angostura (Atuel)	35°06′ S, 68°52′ W	1200	1906–2009	35.2 $m^3 s^{-1}$	SSRH
	f–Buta Ranquil (Colorado)	37°05′ S, 69°44′ W	850	1940–2009	148.3 $m^3 s^{-1}$	SSRH
	g–Cuncumén (Choapa)	31°58′ S, 70°35′ W	955	1941–2010	9.6 $m^3 s^{-1}$	DGA
	h–Chacabuquito (Aconcagua)	32°51′ S, 70°31′ W	1030	1913–2010	33.0 $m^3 s^{-1}$	DGA
	i–El Manzano (Maipo)	33°36′ S, 70°23′ W	890	1946–2010	107.8 $m^3 s^{-1}$	DGA
	j–Bajo Los Briones (Tinguiririca)	34°43′ S, 70°49′ W	518	1942–2010	50.7 $m^3 s^{-1}$	DGA

The codes used in **Figure 1** are indicated together with the stations' names. The long-term average values at each site are expressed as millimeters of water equivalent for snowpack data and cubic meters per second for mean annual (Jul.–Jun.) streamflow records. DGA, Dirección General de Aguas, Santiago, Chile (www.dga.cl); DGI, Departamento General de Irrigación, Mendoza, Argentina (www.irrigacion.gov.ar); SSRH, Subsecretaría de Recursos Hídricos, Buenos Aires, Argentina (www.hidricos.gov.ar). See Masiokas et al. (2006, 2012) for more details. Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

contribution of glaciers vs. snow in a particular site at a given year (Milana 1998; Favier et al. 2009). It should be noted, however, that the hydrological contribution from glaciers is highly variable depending on the size and the glaciated area of the basin. For small basins with a large proportion of their area covered by glaciers and ice-rich periglacial features, the contribution from these ice masses is obviously very important, but as the area of the basin becomes larger, snowmelt becomes the main factor regulating streamflow and the contribution from glaciers is usually of secondary importance. The streamflow records shown in Figure 2(b) come from sites where the proportion between glaciated vs. nonglaciated area is relatively small and snowmelt is therefore the predominant factor modulating surface runoff.

Masiokas et al. (2010) extended the analyses they performed in 2006 and focused on the main IMD variations in snowpack and streamflow records using individual station data and regionally averaged series. They found that, except for three gauging stations that showed statistically significant, positive changes, linear trends in most snowpack and streamflow records are nonsignificant over the past 60–100 years of record. However, several important IMD features were identified embedded in these linear trends. These low-frequency features were more consistent and easier to identify in the streamflow series than in the snowpack data. As discussed earlier, this is probably due to the relative shortness and overall lower quality of the snowpack records, together with the more variable nature of snow accumulation at the selected locations.

The regional streamflow average depicted in Figure 2(c) was improved and updated from Masiokas et al. (2010) but essentially shows the same IMD patterns as discussed in our earlier study. In this regional series (and to a lesser extent in the individual river data, see Masiokas et al. 2010), two significant changes in mean conditions or regime shifts mark the transition between three well-defined periods (Figure 5(a)). The period between 1909 and 1944 can be characterized by wetter than normal conditions with a noticeable peak in 1914–1922. A significant drop in regionally averaged discharge flows can be observed between 1945 and 1976. This interval contains the highest concentration of extreme low flows: 4 of the 10 driest years on record occurred between 1954 and 1971 (Figure 5(a)). Conditions shifted again to above-average levels in 1977, and the 1977–1987 period is, on a regional basis, the overall 'wettest' period on record when compared to all other moving windows of 5–20 years in length between 1909 and 2009. After the extreme wet period ending 1987, the regionally averaged values dropped gradually and have fluctuated around the long-term average until recent times (Figure 5(a)). Analyses of the relative significance of all moving time windows of 5–20 years in length (Masiokas et al. 2010; Mauget 2011) indicate that despite the occurrence of some dry years after 1987, the average conditions of the past two decades cannot be considered statistically different from the long-term mean of the regional series. As expected, results for the warm season (Nov.–Feb.) regional series were extremely similar to those obtained for the annualized record (results not shown).

Other studies that have also assessed the temporal variability of streamflow records on this portion of the Andes have mostly focused on single-station records (rather than regional averages) and have generally assessed linear trends of mean monthly, seasonal, or annual series (e.g., Carril et al. 1997; Pellicciotti et al. 2007). Their results differ depending on the period or season of analysis and between river basins, but in general there is an overall agreement with the results discussed earlier, with most stations showing nonsignificant or marginally significant linear trends and with the period between the 1940s and the mid-1970s standing out as the driest interval for most sites (e.g., Carril et al. 1997). In contrast, Pellicciotti et al. (2007) report significant decreasing trends in 1970–2004 streamflows recorded at the upper section of the Río Aconcagua basin (upstream from station h in Figure 1). Other more recent analyses have provided complementary results regarding spatial and temporal patterns of variability and changes in the hydrological regimes of rivers flowing from the western Andean slopes in south-central Chile. Rubio-Álvarez and McPhee (2010) used seasonal and annual streamflow records from 44 rivers between 34 and 45° S and identified two main subregions with distinctive patterns of variability located north and south of the 37.5° S parallel. Annual streamflows in the northern subregion (which overlaps with the region of interest of this chapter, see Figure 1) showed a significant 10-year cycle, but no conclusive linear trends were found in this series or in the seasonal averages. Previous studies (Menegazzo and Radicella 1982; Compagnucci and Araneo 2005) based on streamflow records from the eastern (Argentinean) slopes have found that at these latitudes the rivers share a large percentage of common variance and could be considered relatively homogeneous over the instrumental period.

Cortés et al. (2011) analyzed the streamflow distribution throughout the year along the Chilean slopes of the Andes between 30 and 40° S. They found that the hydrological regimes of rivers north of 35° S were mostly dominated by snowmelt, whereas rivers further south (where the Andes have a lower elevation and the conditions are wetter, with rainfall distributed more evenly throughout the year) gradually shifted toward rain-dominated regimes. Analyses of the date marking the timing of the center of mass of annual flows for each water year (CT; Stewart et al. 2005) between 1961 and 2006 revealed no CT changes for almost all snowfed watersheds (14 of 15) in the northern sector, and a consistent pattern of streamflow timing toward earlier in the year (i.e., toward winter) in 22 of 25 rivers south of 35° S (Cortés et al. 2011). The fact that no changes in CT have occurred in the north despite the documented warming at high-elevation sites is interesting and contrasts with the results obtained in similar climatic regions in the Northern Hemisphere, where significant changes toward earlier streamflow timing associated with warmer temperatures have been reported for snow-dominated basins (Stewart et al. 2005; Fritze et al. 2011). Cortés et al. (2011) suggest that this situation is due to the overdominant role of precipitation on the hydrologic regimes of these snowfed basins, in which the effect of rising temperatures could be largely overridden by variability related to precipitation.

Indeed, other studies (see, e.g., Masiokas et al. 2006, 2012) have also found that variations in the regional snowpack and streamflow records are very closely linked to variations in winter and annual total rainfall in central Chile. These similarities are to be expected given the relatively simple nature of the hydrological system of this region, which is primarily driven by moisture coming from the Pacific in a succession of westerly frontal systems concentrated during the winter months (Falvey and Garreaud 2007). This situation alleviates to some extent the problem of constructing long, representative hydroclimatic time series, as it allows the use of a relatively limited number of station records to capture the main hydrologic patterns in this region. Moreover, this offers the possibility of inferring or validating the information provided by one variable (e.g., snowpack) using data from other remaining variables (e.g., central Chile rainfall and/or Andean streamflows). Masiokas et al. (2012) further propose that it is possible to use different precipitation proxies to extend back in time the information on snowpack variations in the Andes (see discussion of their results later).

5.14.4 Relationship of Local Hydroclimatic Variations with Large-Scale Atmospheric Features such as ENSO and PDO

The significant influence that tropical Pacific Ocean–atmospheric conditions exert on the study region's hydroclimatic variability has been known for decades. In their pioneering study of the 'Southern Oscillation,' Walker and Bliss (1932) include rainfall variations in central Chile and pressure changes in Santiago among the variables used to calculate the Southern Oscillation Index (SOI) for the austral winter. Many subsequent studies have assessed the relationship between ENSO and central Chile rainfall variations (e.g., Pittock 1980; Quinn and Neal 1983; Aceituno 1988; Rutlland and Fuenzalida 1991; Montecinos et al. 2000; Montecinos and Aceituno 2003; Quintana 2004). Additional analyses have also examined the influence of ENSO on Andean snow accumulation (Escobar and Aceituno 1998; Masiokas et al. 2006, 2010) and mountain river discharges (Waylen and Caviedes 1990; Caviedes 1998; Compagnucci and Vargas 1998; Norte et al. 1998; Waylen et al. 2000; Compagnucci et al. 2000; Rubio-Álvarz and McPhee 2010; Gimenez et al. 2010; Cortés et al. 2011). Most of these studies concur that El Niño events are generally associated with wetter-than-normal conditions in the study region, whereas during La Niña years drier conditions are more likely to occur. Cortés et al. (2011) found that CT time series of Chilean rivers in snow-dominated basins were indeed strongly correlated to various ENSO indices, with the annual streamflow center of mass occurring later (i.e., toward the summer) during El Niño years because of the excess in precipitation during the cold season. In addition, various analyses of historical ENSO variations (Quinn and Neal 1983; Ortlieb 1994, 2000) have relied on the warm/wet relationship between ENSO and precipitation levels in central Chile to identify and estimate the severity of El Niño years between the sixteenth and nineteenth centuries.

Masiokas et al. (2006) quantified the association between tropical Pacific ocean–atmosphere conditions and Andean snowpack variations using seasonally averaged $2.5° \times 2.5°$ gridded sea surface temperatures (SST) and sea level pressure (SLP) time series derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis global database (Kalnay et al. 1996). Figure 4 portrays the correlation between the regional MSWE series and Jun.–Sep. (midwinter) SST and SLP averages as reported by Masiokas et al. (2006). Together with results from earlier seasons (not shown) these correlation maps indicate that the strongest associations are concentrated during the winter months and mostly over the tropical Pacific domain. This interesting finding was corroborated with multiple regression analyses in which several large-scale, seasonally averaged climatic indices such as the Niño 3.4 index, the SOI, the Pacific Decadal Oscillation (PDO), the Antarctic Oscillation (AAO), and two indices indicative of Atlantic conditions were

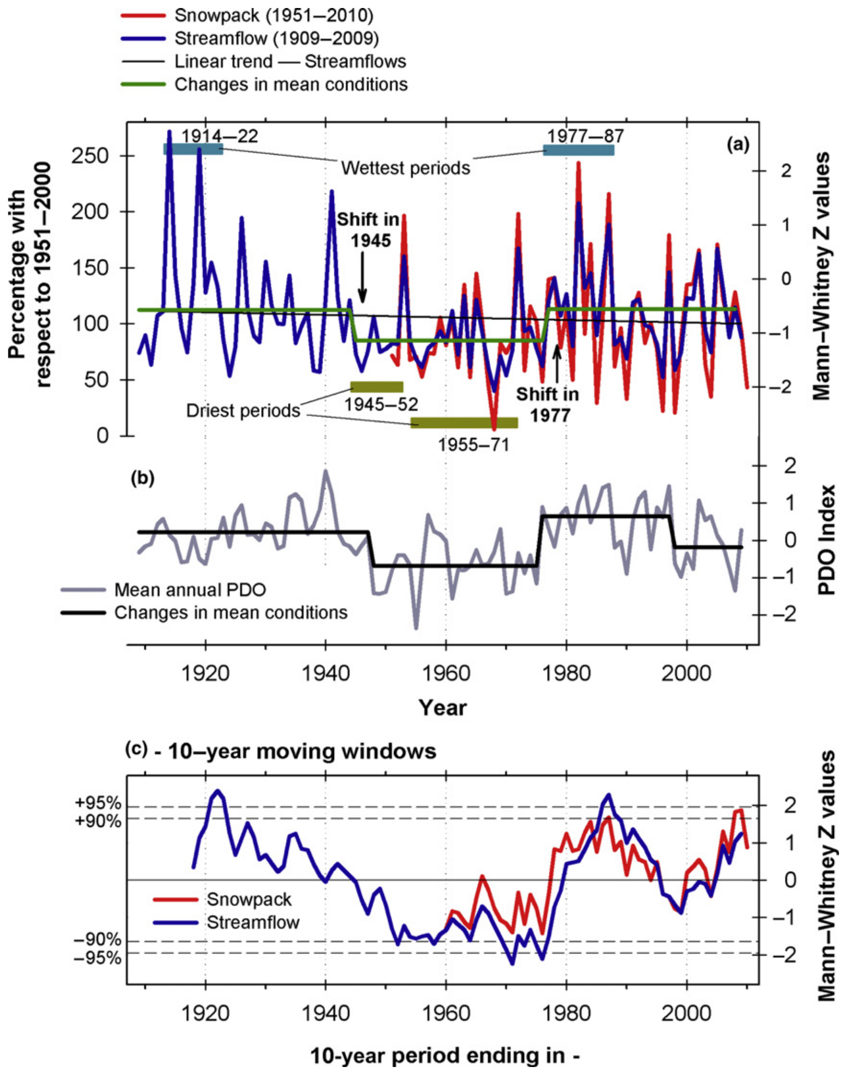

Figure 3 (a) Regional snowpack and streamflow records (red and blue lines, respectively) for the Andes of central Chile and central-western Argentina (**Figures 1 and 2**, data updated to 2009–2010 from those presented in Masiokas et al. 2010). Given the strong similarities between these records, only the temporal patterns of the longer streamflow series are shown in this figure. The least squares linear trend in regional river discharges is slightly negative but nonsignificant over the 1909–2009 interval. Regime shifts in mean flow conditions (green line) were calculated based on Rodionov (2004, 2006; refer to these references for details on this technique). Two statistically significant regime shifts were identified in 1945, when mean levels dropped 32%, and in 1977, when they increased 29%. The driest and wettest periods on record (i.e., those periods with the highest concentration of extreme high and low values in the record) are indicated by horizontal bars. These extreme intervals were determined from all possible nonoverlapping moving windows of 6–20 years in length using nonparametric Mann–Whitney tests and Monte Carlo simulations as described in Mauget (2003, 2004, 2011). Essentially this method samples data rankings over running time windows, converts those samples to Mann–Whitney *U* statistics, and then normalizes the *U* statistics to Z statistics using Monte Carlo generated null parameters. Based on the magnitude of the Mann–Whitney Z values this algorithm can identify time windows containing significant incidences of low or high data rankings. This is an objective, relatively simple, and statistically based way of detecting the driest and wettest intervals in these hydrological time series. (b) Mean values for 1909–2009 Jul.–Jun. of the PDO index (gray line) and shifts in mean regime levels (black line) identified in this series using Rodionov's technique. (c) Running 10-year samples of Mann–Whitney *Z* values as determined using Mauget's technique. Horizontal dashed lines indicate the 90 and 95% positive and negative significance determined from Monte Carlo simulations. Note the similar patterns of decadal-scale variations between the regional streamflow and snowpack records.

used as potential predictors of winter snowpack in the Andes (see Masiokas et al. (2006) for more details). The multivariate regression trials revealed that none of the seasonal values of these climatic indices for the Nov.–Apr. (early summer–late fall) period was significantly correlated with the snowpack record, and, therefore, they cannot be used as predictors of snow accumulation during winter in the Andes. In contrast, significant correlations were found between the snowpack record and the May–Jul. (early–midwinter) averages of the Niño 3.4, SOI, and the AAO indices. However, owing to intercorrelation among these variables only the SOI was included in a final regression model, which was able to explain about 44% of the variance in the snowpack record. Overall, these results present an important limitation for the prediction of winter snow accumulation using data from these large-scale climatic indices from the preceding months. Given the

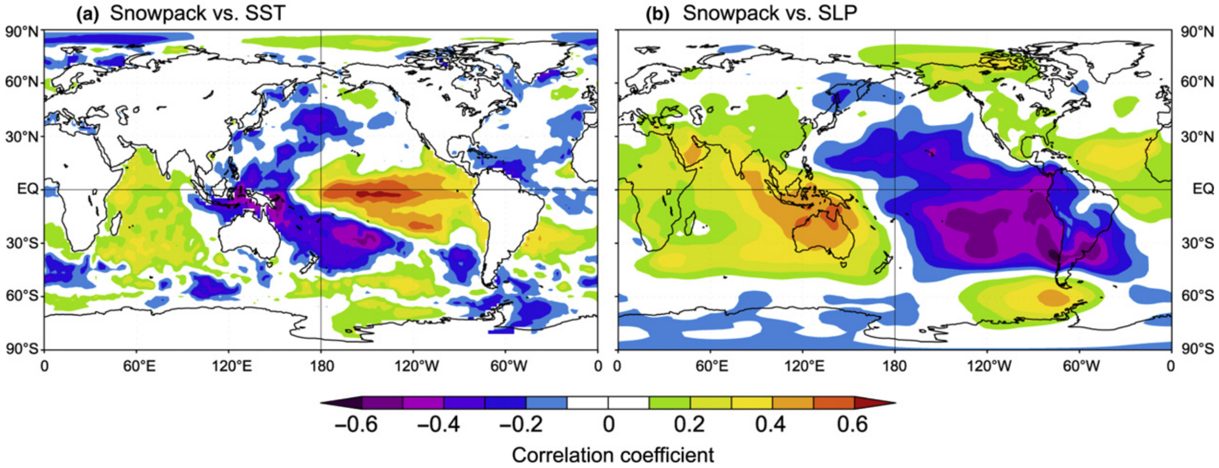

Figure 4 Correlation maps showing the varying spatial association between the regional snowpack series and seasonally averaged NCEP–NCAR reanalysis $2.5° \times 2.5°$ sea surface temperature (a) and sea level pressure (b) gridded data over the 1952–2003 interval. The maps were created using the linear correlation and mapping routines available at the website of the Earth System Research Laboratory, Physical sciences Division, NOAA [Available online at http://www.esrl.noaa.gov/psd/data/correlation/]. Note that (a) shows the well-known ENSO-like wedge pattern over the tropical and subtropical Pacific (e.g., Trenberth and Caron 2000; Trenberth et al. 2002). Strong positive correlations occur over the Niño 3 and Niño 4 regions, and negative correlations are mostly concentrated over the subtropical western Pacific Ocean. The pattern in (b) also shows a noticeable ENSO-related structure (Trenberth and Caron 2000). Figure modified from Masiokas, M. H., R. Villalba, B. H. Luckman, C. Le Quesne, 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.

socioeconomic importance of the Andean snowpack, improved predictive skills are desirable and more research is needed to identify better predictors of snowpack records from atmospheric variables or climatic indices from the period prior to the austral winter (e.g., McCabe and Dettinger 2002). Since the most serious challenges in managing the mountain water supply will likely occur during below-average snowfall years, special attention should also be paid to those large-scale atmospheric linkages associated with (or leading to) extreme dry years in the Andes. Masiokas et al. (2006) proposed the development of predictor series based on a north–south index utilizing SLP or geopotential height data from the subtropical Pacific off the coast of central Chile combined with those from the Amundsen–Bellingshausen Seas (Am–Be) in the southeast Pacific (Figure 4(b)). Blocking activity in the Am–Be area is strongly associated not only with ENSO variability (Renwick 1998) but also with snowpack high and low values in the Andes (see later). A better understanding of additional atmospheric teleconnections affecting conditions in the southeast Pacific (e.g., Jacobs and Comiso 1997; Marques and Rao 1999) may lead to improved predictive skills for estimating winter snowpack conditions in this region. Some studies have reported results that provide promising perspectives to tackle this issue. Berri and Flamenco (1999) found strong correlations between October and March streamflows of Río Diamante (station d in Figure 1) and the previous Mar.–Apr. and concurrent Nov.–Dec. Niño 3 SSTs and used this relationship to develop a multiple linear regression model of warm season surface runoff in this basin. More recently, Gimenez et al. (2010) used the winter values of the Multivariate ENSO Index (MEI) and snowpack data to predict Río San Juan streamflows (station a in Figure 1) at a 6-month lead time.

Enhanced blocking activity over the Am–Be area in the southeast Pacific is a known ENSO-related atmospheric teleconnection occurring during El Niño events (Karoly 1989; Renwick 1998; Kiladis and Mo 1998). In 1991, Rutlland and Fuenzalida and subsequently Montecinos and Aceituno (2003) reported that this enhanced blocking activity was closely related to above-average winter rainfall totals in central Chile. Masiokas et al. (2006) investigated the influence of these tropospheric circulation anomalies on Andean snowpack variations using peak winter (Jun.–Sep.) mean 500-hPa geopotential heights derived from the gridded NCEP-NCAR reanalysis dataset of Kalnay et al. (1996). For the 10 snowiest years Masiokas et al. (2006) found extensive and well-defined regions of averaged positive height anomalies (associated with enhanced blocking activity) concentrated between 60–70° S and 90–120° W in the Am–Be area and a concurrent weakening of the subtropical Pacific anticyclone around 30 and 40° S and 130 and 150° W (Figure 5(a)). Interestingly, the 10 driest years on record corresponded with an almost exactly opposite anomaly pattern, with negative winter 500-hPa geopotential height anomalies over the Am–Be region and positive anomalies in the subtropical South Pacific between 25 and 40° S (Figure 5(b)). These results confirmed the findings of previous studies (e.g., Rutlland and Fuenzalida 1991) and indicate that large-scale tropospheric circulation anomalies in the mid to high latitudes of the Southern Hemisphere are indeed a very important forcing that modulates snowfall in the Andes. Based on the maps in Figure 5, it seems reasonable that an increase in the number of blocking events in the Am–Be area and a weakening of the subtropical Pacific anticyclone during winter result in a northward migration of the westerly storm tracks, and above-average precipitation totals in the study area. The remarkably similar height anomaly pattern of opposite sign for the driest years (Figure 5(b)) suggests that a stronger Pacific anticyclone and depleted height anomalies in the SE Pacific during winter determine a southward displacement of westerly

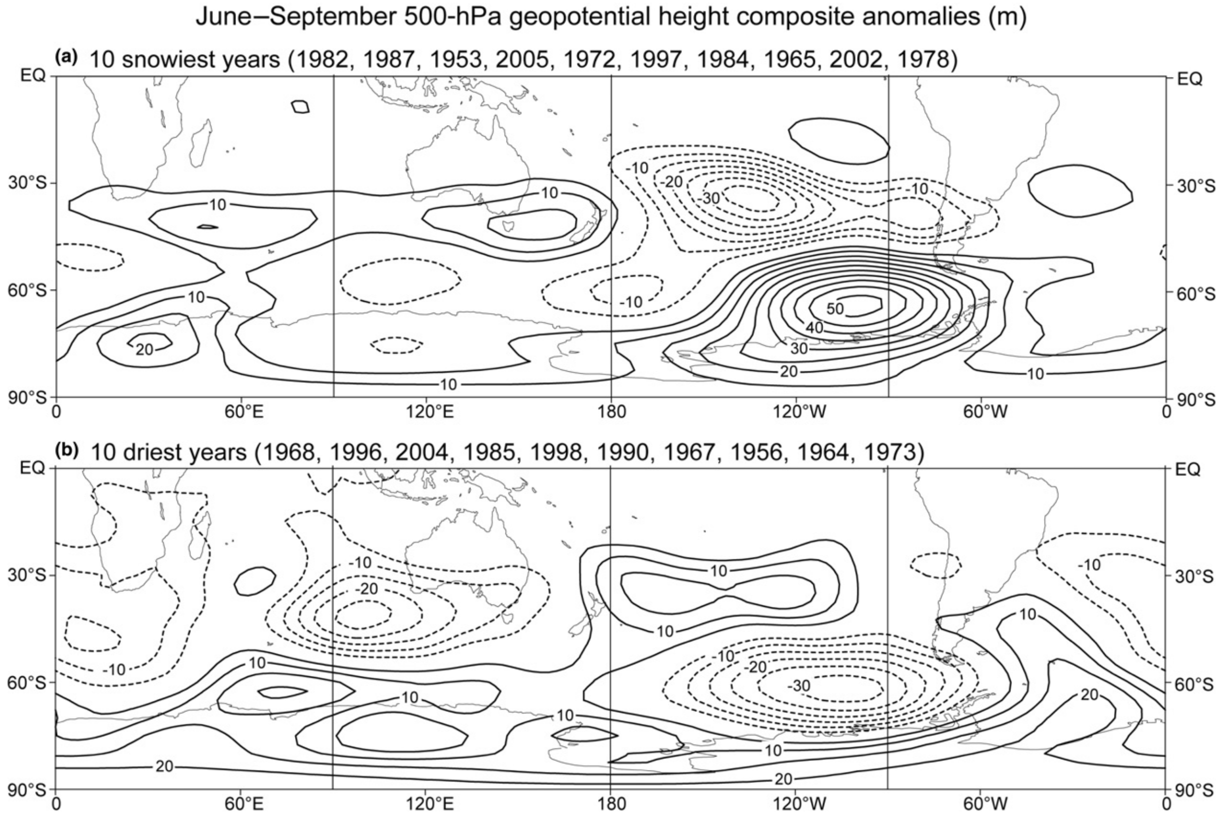

Figure 5 (a) Jun.–Sep. mean 500-hPa geopotential height anomalies for the 10 snowiest years in the central Andes as identified by Masiokas et al. (2006) for the period 1951–2005. Mean monthly gridded data were obtained from the NCEP/NCAR reanalysis global dataset (Kalnay et al. 1996). Contours are in meters with a 5-m contour interval, and zero lines are omitted. Positive (negative) contour anomalies are shown as solid (dashed) lines. (b) Same as (a), but for the 10 driest years in the central Andes. The maps were created as follows: for each event year and grid point, mean peak winter (Jun.–Sep.) height anomalies from the 1968–1996 reference period were calculated from monthly data and subsequently averaged to create separate composite 500-hPa height anomaly maps for the 10 snowiest and driest years on record. Figure slightly modified from Masiokas, M. H., R. Villalba, B. H. Luckman, C. Le Quesne, 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.

air masses with the resulting reduction in snowfall in the Andes (Masiokas et al. 2006).

As mentioned earlier, Masiokas et al. (2010) focused on the main IMD patterns in the snowpack and streamflow records. They found that the inception of the driest period of the twentieth century in this portion of the Andes was roughly coincident with a shift toward extended negative conditions in the PDO in the mid-1940s (e.g., Mantua et al. 1997; Mantua and Hare 2002; **Figure 3(a) and 3(b)**). The shift toward wetter conditions in 1977 in the Andes also corresponds with a very well-known regime shift toward more positive PDO levels in 1976–1977. Despite some discrepancies between the regional streamflow record and the PDO (especially noticeable on a year-to-year basis, **Figure 3(a) and 3(b)**) the occurrence of these relatively synchronous regime shifts in the 1940s and 1970s led Masiokas et al. (2010) to suggest that the slowly evolving patterns of the PDO may have influenced the IMD hydrologic behavior at these latitudes in 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 (**Figure 3**) resembles the relationship between cool ENSO events and dry conditions in the Andes discussed in the literature. Likewise, the wetter hydroclimatic conditions recorded in the Andes after 1977, concurrent with a 'warm' phase of the PDO, also resemble the warm–wet relationship discussed above in relation to the impacts of ENSO in this portion of the Andes (see, e.g., Rutlland and Fuenzalida 1991; Masiokas et al. 2006). Dettinger et al. (2000) found a similar, consistent pattern of positive correlations between streamflow data from the study area and interannual and decadal ENSO-like climatic variations across the Pacific. However, whether these cool–dry/warm–wet relationships are entirely valid at the longer timescales characteristic of the PDO remains uncertain, and further research is needed to clarify this interesting issue.

5.14.5 Reconstructing Andean Snowpack Variations from Multiple Proxies

Masiokas et al. (2012) developed two complementary reconstructions of Andean snow accumulation covering the past two to eight centuries. The evidence used to develop and validate these snowpack reconstructions includes instrumental rainfall

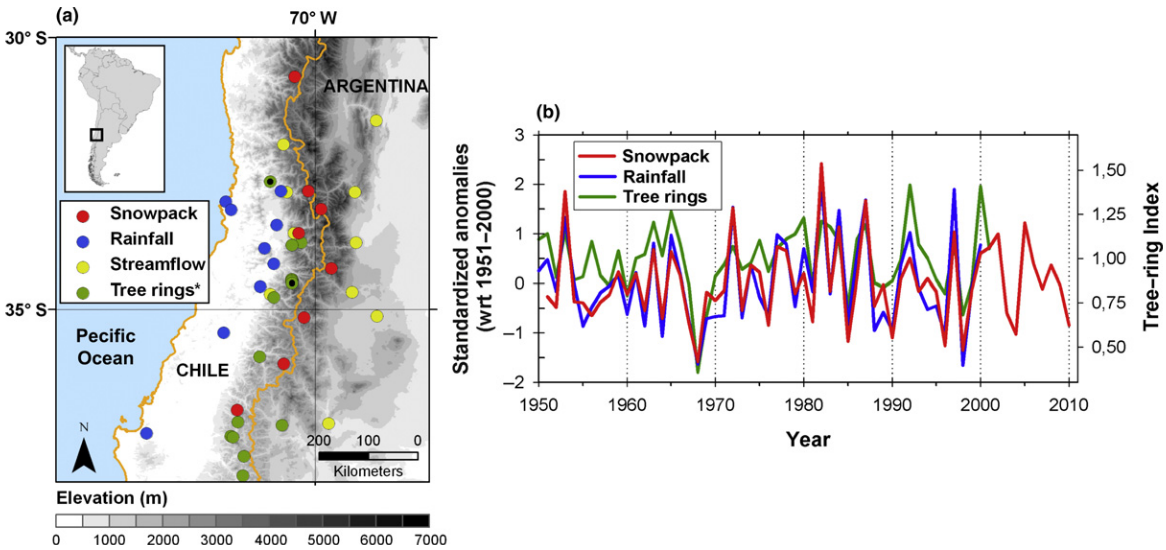

Figure 6 (a) Location of snowpack, rainfall, streamflow, and tree-ring sites used in the reconstruction of snowpack as described in Masiokas et al. (2012). Note (*): from the available network of tree-ring sites (green dots), the two tree-ring chronologies finally selected in the reconstruction model are marked with a black dot. (b) Comparison of the regional records of Andean snowpack and winter rainfall in central Chile, and the mean tree-ring index of the two selected chronologies as mentioned earlier. The resemblance between the snowpack and rainfall series is remarkable. The tree-ring series from these precipitation-sensitive trees also shows strong similarities with the instrumental records. The figure shows the 1951–2010 period covered by the snowpack series, but the regional central Chile rainfall series covers the period AD 1866–2000 and the tree-ring series goes back to AD 1150. The snowpack and rainfall series are expressed as standardized anomalies from the 1951–2000 period, whereas the tree-ring series is adimensional. See text for more details. Figure modified from Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

and streamflow data from adjacent lowlands, a variety of documentary records, and century-long tree-ring series of precipitation-sensitive species from the western side of the Andes. All these records share a common regional hydroclimatic signal (Figures 2 and 6) largely because of this region's particular and relatively simple hydroclimatic regime, with the moisture mainly coming from winter frontal systems of Pacific origin. Masiokas et al. (2012) argue that these different hydroclimate records can be used as snowpack 'proxies' for the development and independent validation of reliable snowpack reconstructions covering periods prior to 1951 when instrumental snowpack data are first available. Rainfall data from central Chile (very strongly correlated with snow accumulation values in the adjacent mountains) were used to extend the regional 1951–2010 snowpack record back to AD 1866. Subsequently, snow accumulation variations since AD 1150 were inferred from precipitation-sensitive tree-ring width series. The reconstructed snowpack values were validated with independent historical and instrumental information, including (1) documentary accounts of snow conditions over the main Andean pass between 1760 and 1890 (Prieto et al. 1999a), (2) newspaper-based records of snow depth along the main Andean pass between AD 1885 and 1996 (Prieto et al. 2000, 2001), (3) documentary accounts of the discharge of the Mendoza river (and other rivers) in the Argentinean piedmont between 1600 and 1960 (Prieto et al. 1999b), (4) the compilation of evidence for wet years in central Chile used by Ortlieb (1994) to infer the severity of El Niño events between AD 1535 and 1900, and (5) a record of total monthly hours of rain in the city of Santiago de Chile for the period 1824–1850 (Taulis 1934). Masiokas et al. (2012) assumed that the duration of the rainfall events during winter is very likely positively correlated with the amount of precipitation received in the lowlands of central Chile and in the adjacent mountains to the east. Thus, extended periods of rain in Santiago during the winters of 1824–1850 should correspond with higher-than-normal snow accumulations in the Andes, and vice versa.

According to Masiokas et al. (2012), the verification tests performed on the snowpack reconstructions offer some confidence in the reliability of these reconstructed time series. However, the authors indicate that because of the varying nature of the proxy data available, the resulting reconstructions contain certain characteristics that can be considered as either strengths or limitations depending on the needs of the end users of these data. For example, the first reconstruction approach, based on central Chile rainfall data, showed exceptional skill for modeling Andean snowpack variations (84% of variance accounted for by the model over the 1951–2000 calibration period; Masiokas et al. 2012). However, this reconstruction was restricted to the period after AD 1866 by the length of the instrumental records (Figure 7). The high quality of this first reconstruction could be very useful, however, for local water resource managers, decision makers, and stakeholders interested in long, highly reliable mountain snowpack data as a basis for infrastructure planning and for developing a better understanding of Andean hydroclimatic variability over the past 150 years. In contrast, the tree-ring based reconstruction model was less accurate in modeling the instrumental snowpack record over the calibration period (45% explained variance and higher associated uncertainties than the other model; (Masiokas et al. 2012)). Nevertheless, the resulting reconstruction offers the unique possibility of assessing in

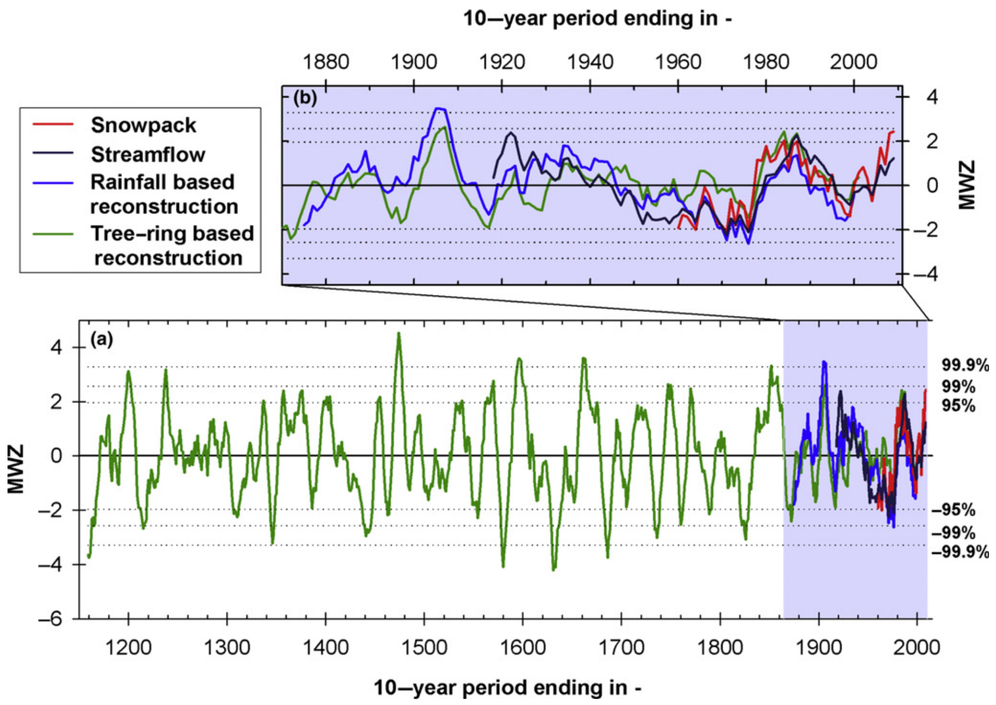

Figure 7 Comparison of the decadal patterns of variations in instrumental snowpack and streamflow records (red and dark blue lines, respectively), with those of the rainfall-based and tree ring-based snowpack reconstructions (blue and green lines, respectively) recently developed by Masiokas et al. (2012). As in **Figure 5(c)**, here, Mann–Whitney Z statistics for running 10-year samples of each original series are shown. (a) Period covered by the tree ring-based reconstruction (AD 1150–2001). (b) Period since AD 1866 covered by the rainfall-based reconstruction. Horizontal dotted lines indicate positive and negative significance at the 95, 99, and 99.9% confidence levels derived from Monte Carlo simulations. In this case, 10-year windows reaching these levels would be considered statistically wetter or drier than expected under essentially stationary conditions (see Mauget 2011 for details on the methodology). Note the overall similarities of decadal variations between the instrumental and reconstructed series. Reproduced from Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

a quantitative and objective manner the history of snowpack fluctuations over the past 850 years in this Andean region (Figure 7). This reconstruction represents the first annually resolved mountain snowpack reconstruction covering most of the past millennium in the Southern Hemisphere. According to Masiokas et al. (2012), the lower skill of the tree ring-based 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 (Fritts 1976).

Masiokas et al. (2012) used the same approach used in 2010 for assessing the main IMD modes of variability in the snowpack reconstructions. This technique had already been used in other instrumental hydroclimatic records (Mauget 2011) but is novel in paleoclimatic studies. The approach offers very promising perspectives for identifying the most extreme intervals in a given time series while testing their statistical significance in a simple and objective manner. The timing and significance of the intervals with the highest and lowest values detected by the running MWZ method (Mauget 2011) for each window length were recorded and tested collectively to identify the driest and snowiest periods in the reconstructed time series. The results provide a very useful reference for assessing the relative significance of recent conditions in a long-term context, and can also be used to evaluate the extent and magnitude of historic droughts and snowy periods in this region. Figure 7 shows that in general the instrumental and reconstructed time series show broad similarities using a 10-year period as a reference. This was somewhat expected in the rainfall-based reconstruction, but the similarities with the tree ring-based reconstruction are interesting and suggest that despite the inherent limitation of this reconstruction in capturing extreme high snowpack values (see earlier discussion), the overall decadal-scale regional patterns of snowpack variations are still represented relatively accurately in this time series. This information could be useful for both local water resource managers and ongoing modeling analyses intended to predict decadal climate patterns (Meehl et al. 2009; Keenlyside and Ba 2010), which are of more direct relevance to society than the more distant, highly uncertain centennial-scale climate projections generally discussed in the literature. However, it should be noted that only those models that accurately simulate (hindcast) the statistics and the inherent variability observed on the instrumental hydroclimatic records and on the most relevant atmospheric and ocean circulation features will provide a solid basis for the assessment of future vulnerabilities and the development of adaptive strategies to increase resilience.

These main temporal patterns identified in the reconstructions can also provide relevant, quantitative information for larger scale studies involving the main factors affecting the hydroclimate in this portion of the Andes. Besides the well-known influence of ENSO in this region, recent analyses have also identified a potential influence of the PDO on the low-frequency modes of variability in the snowpack and streamflow records of this region (Masiokas et al. 2010; see also Dettinger et al. 2001). The long Andean snowpack reconstructions presented by Masiokas et al. (2012) allow an assessment of the strength and time stability of the relationships with ENSO and the PDO over most of the past millennium and may complement the great number of studies (e.g., Stahle et al. 1998; Cobb et al. 2003; MacDonald and Case 2005; D'Arrigo et al. 2005; D'Arrigo and Wilson 2006; Gergis and Fowler 2009) that discuss the regional manifestations and long-term variability of these large-scale ocean–atmosphere features.

5.14.6 Climate and Hydrological Sciences Informing Vulnerability Reduction and Adaptation

The term 'vulnerability' can be defined as the degree to which a system, such as a rural community or agricultural producer, is susceptible to the adverse effects of stressors and change (Smit and Wandel 2006). Given the exposure of a community or agricultural producer to climatic hazards and their impacts, vulnerability results from an equation involving the sensitivity the degree to which a system is affected by climate-related stimuli and the adaptive capacity the ability of a system to adjust to climatic risks and opportunities by increasing its coping range. Both sensitivity and adaptation are related to variables such as natural, human, social and institutional capital, economic resources, and infrastructure. Climate exposures articulate with others from economic and social spheres, composing double exposures (Leichenko and O'Brien 2008). Vulnerabilities are also unequally distributed in space and in relation to different social groups or actors. They could come not only from these exposures but also from undesired effects of adaptive practices, as one's adaptation practices may cause increasing vulnerabilities in others (Montaña 2011).

The Río Mendoza basin is a very interesting case study because it expresses well the different vulnerabilities to sustained water deficits. Although all agricultural producers are vulnerable to droughts, the degree to which these producers will be affected by this natural phenomenon will depend on their productive system. For example, producers of crops that are relatively resistant to water stress, such as vine growers, are inherently less vulnerable to water deficits than horticulture producers, which are entirely dependent on a certain watering frequency. Likewise, large-scale capitalized producers from both vine and horticultural productive systems, who have access to high technology irrigation systems and who are able to drill wells and pump groundwater according to their needs, are obviously less vulnerable to fluctuations in surface runoff from mountain rivers than the smaller scale producers whose subsistence is entirely dependent on water distributed through surface irrigation. There are also double exposures, as the vulnerability of the smaller producers has already been increased by previous exposure to the dominant globalized agribusiness, in a vicious circle of increasing sensitivity to droughts and decreasing capacities to adapt to this phenomenon. Likewise, vulnerability to droughts depends on location. Producers located upstream or near the sources of water tend to be less sensitive to droughts than those located downstream from urban centers or at the far end of the irrigation network. The more favorable locations are accessible only to producers with enough capital to acquire these more expensive oases lands or to those able to start new farms in the natural dry shrublands along the Andean piedmonts that require significant investments in land cleaning, leveling, well construction, pressurized irrigation systems, etc.

Extreme hydroclimatic events such as extended droughts will only consolidate or accelerate the existing tendency toward a spatial and socioeconomic segregation of the agricultural producers of the oases in central-western Argentina, widening the gap between the dominant players of the local agri business and those who are barely able to survive as subsistence producers. In many cases, these small-scale producers will have to neglect their farms to work on a salary basis for large-scale companies or even be forced out from the agricultural sector and migrate to cities, where they will join the growing number of urban poor. Scenarios of increasing water deficits suggest an intensification of the current process of transformation of the socioeconomic and agricultural structure of these hydraulic societies along the eastern side of the Andes (Montaña, 2011).

Interestingly, the degree of vulnerability of the different players in this hydraulic society may change considerably based on specific adaptive practices. The flows of Río Mendoza have been recently regulated to reduce seasonal and interannual variability in the river discharge and to compensate for spring and autumn water deficits in crops. As several studies have projected an earlier onset of spring snowmelt in response to potentially future warmer conditions in high-elevation regions, this may result in reduced vulnerabilities to potential changes in the seasonal supply of water, ultimately producing only minor impacts on the local agricultural system. However, given the spatial distribution of agricultural lands and the less favorable, scattered location of goat breeders in the drylands downstream from the main users of the Río Mendoza waters, all positive effects that regulation provides to the agricultural oasis will work against the delivery of flows to the distal part of the basin. As these regulations do not ensure ecological flows, a more intense and regulated use of water upstream by the social groups with highest power clearly reduces the possibilities of water 'escaping' to the downstream part of the basin where desert communities are settled. This evident inequity constitutes an interesting case in which a particular set of adaptive practices benefit some sectors but considerably increase the vulnerability of other groups. Although their subordinate social position largely determines the sensitivity of these poor rural communities to various economic and environmental factors, extended droughts will ultimately be the trigger for increased conflicts in this hydraulic society.

The recent findings on the spatiotemporal patterns of mountain snowpack and streamflows provide a new perspective for a better understanding of vulnerabilities in these dryland, coupled human and natural systems. In a social research context, these findings offer the possibility of contextualizing contemporary droughts and their socioeconomic impacts in a long-term perspective. For example, the relative magnitude of the 2004–2005 drought, locally perceived as severe, can now be revaluated in the light of the existing snowpack and streamflow time series. This new evidence indicates that such extreme dry years are not as uncommon as initially believed. This may in turn help raise awareness of the possibility that harsher and longer droughts will occur in the future, and encourage appropriate adaptation measures.

A better understanding of the functioning of these coupled natural and social systems, and the possibility of linking the occurrence of dry and wet periods over the past century with the evolution of recent crises in local agricultural economies, may also offer the very interesting opportunity of exploring the balance between 'social' and 'natural' factors involved in these particular crises. This integrative assessment could be approached by focusing on the local economic effects of particularly dry or wet years and the ENSO impacts in this region, or by focusing on longer timescales where intra- to multidecadal dry or wet periods (which appear to be modulated by the PDO, see earlier) may have also affected the evolution of certain favorable or unfavorable economic cycles in these societies.

The existence of long, reliable hydroclimatic time series and strong, time-stable correlations between Andean snowpack and river discharges with central Chile rainfall and Pacific SSTs constitutes a possible early warning tool that may help anticipate the occurrence of droughts in the eastern foothills of the Andes. This information is also crucial for a detailed testing and validation of results from global and regional climate and hydrological models. Only models that accurately simulate (hindcast) the statistics and the inherent variability observed on the hydroclimatic records and on the most relevant atmospheric and ocean circulation features will provide a solid basis for the assessment of future vulnerabilities and the development of adaptive strategies to increase resilience. With these caveats in mind, various measures to rationalize the water resources and accommodate agricultural practices could be taken based on this information. Other strategies involving longer timescales for planning and development of major projects and investments (e.g., major hydraulic infrastructure such as dams) may in turn be decided taking into account robust modeling results and the inherent multidecadal patterns of fluctuations observed in Andean hydroclimatic records. For example, the construction of the Potrerillos dam in the Río Mendoza basin took almost a century from the first proposal of the project. Increased awareness of the recent past, present, and possible future behaviors of the Andean hydroclimatic system could help shorten the decision times and promote cost-effective measures for better management of the water resources. Whether in the case of purely empirical hydrological research or in a comprehensive socioeconomic vulnerability assessment, the mere existence of the long-term Andean snowpack and streamflow data for these river basins constitutes an important step toward reducing the inherent uncertainties associated with climate scenarios currently available from global climate models and opens the possibility of formulating adaptive strategies based on a more site-specific, 'bottom-up' approach.

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