Snowpack Variations in the Central Andes of Argentina and Chile, 1951–2005: Large-Scale Atmospheric Influences and Implications for Water Resources in the Region

MARIANO H. MASIOKAS

Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA-CRICYT-CONICET), Mendoza, Argentina, and Department of Geography, University of Western Ontario, London, Ontario, Canada

RICARDO VILLALBA

Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA-CRICYT-CONICET), Mendoza, Argentina

BRIAN H. LUCKMAN

Department of Geography, University of Western Ontario, London, Ontario, Canada

CARLOS LE QUESNE

Instituto de Silvicultura, Universidad Austral de Chile, Valdivia, Chile

JUAN CARLOS ARAVENA

Department of Geography, University of Western Ontario, London, Ontario, Canada, and Centro de Estudios Cuaternarios (CEQUA), Punta Arenas, Chile

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ABSTRACT

The snowpack in the central Andes (30°–37°S) is the primary source for streamflow in central Chile and central-western Argentina, but few published studies are available on snowpack variability in the region. This paper develops the first regional snowpack series (1951–2005) from Chilean and Argentinean snow course records. This series shows a strong regional signal, marked interannual variability, and a positive, though nonsignificant, linear trend. Correlations with local precipitation and temperature records reveal a marked association with conditions in central Chile. High snow accumulation is generally concurrent with El Niño events in the tropical Pacific, but only 5 of the 10 driest years coincided with La Niña events. Evaluation of 500-hPa geopotential height anomaly maps during extreme snow years highlights the crucial significance of tropospheric conditions in the subtropical and southeast Pacific in modulating snowfall. Correlations with gridded SST and SLP data and multiple regressions with large-scale climatic indices corroborate a Pacific ENSO-related influence largely concentrated during the austral winter months. This hampers the predictability of snowpack before the onset of the cold season. Annual and warm-season river discharges on both sides of the cordillera are significantly correlated with the regional snowpack record and show positive linear trends over the 1951–2004 common period, probably related to a greater frequency of above-average snowpacks during recent decades. Future demand and competition for water resources in these highly populated regions will require detailed information about temporal and spatial variations in snow accumulation over the Andes. The results indicate that the relationships between snowpack and atmospheric circulation patterns prior to the winter season are complex, and more detailed analyses are necessary to improve prediction of winter snowfall totals.

Corresponding author address: Mariano H. Masiokas, Department of Geography, University of Western Ontario, London ON N6A 5C2, Canada.
E-mail: mmasiok2@uwo.ca

1. Introduction

The snowpack accumulated in the central Andes[1] is the main water source of the major rivers in central Chile and central-western Argentina and therefore represents a critical resource for local domestic consumption, irrigation, industries, and hydroelectric generation. Since the main road connecting Santiago, Chile, with Mendoza and Buenos Aires in Argentina crosses the cordillera at these latitudes, snow accumulation also has significant economic impacts on surface transportation, trade, and winter tourism along this portion of the Andes. Thus, the analysis of recent snowpack variations and their relationships with large-scale atmospheric features is of fundamental socioeconomic importance in developing water management strategies and seasonal snowpack and snowmelt forecasts for the region.

Careful investigation of recent snowpack variability in the central Andes is also of particular interest in view of the potential climate changes predicted for this area. In an analysis of seven coupled atmosphere–ocean general circulation models especially targeted to investigate high-elevation sites, Bradley et al. (2004) showed that for the next 80 years the central Andes will probably experience significant temperature increases of ≥2°C. Independent general circulation model simulations also predict a significant decrease in precipitation over the region for the next five decades (Cubasch et al. 2001), with likely impacts on the hydrological cycle and long-term water resource availability. Basic knowledge about the causes and amount of recent snowpack variability and change in this mountainous area is probably one of the most important factors to consider in planning mitigation of possible future effects of climate change on the socioeconomic activities in this region.

Prior studies of observed snowpack records in the central Andes have mainly been restricted to the government agencies dealing with water resources in Chile and Argentina, and few results have been published in the scientific literature. Snowmelt–runoff simulation models for isolated basins on both sides of the Andes have been developed from some of these data by Peña and Nazarala (1987) and Maza et al. (1995). Escobar and Aceituno (1998) utilized data from 17 snow courses in central Chile to evaluate the influence of May–August sea surface temperatures (SSTs) from the tropical Pacific (Niño-3 region) on winter snow accumulation. They found a higher probability for increased (decreased) winter snowpack between 30° and 35°S during positive (negative) Niño-3 SST anomalies. Prieto et al. (2000, 2001) used a 100-yr record (1885–1996) from a local newspaper reporting the annual number of snow days and maximum snow depth for the high-elevation highway between Santiago and Mendoza to analyze the frequency domain and the influence of El Niño–Southern Oscillation (ENSO) on these records. They found significant periodicities centered around 28 and 5 yr, together with a positive trend over the twentieth century in the number of snow days per year. Prieto and coworkers also report a strong association between above-average winter snow accumulation and El Niño events. To our knowledge, no combined temporal and spatial assessment of snow course data integrated across the central Andes has been undertaken.

The main purposes of the present paper are 1) to develop a regional snowpack record for the central Andes utilizing updated snow-water equivalent (SWE) data from both Chile and Argentina, 2) to assess the spatial and temporal influence of large-scale atmospheric variables on snow accumulation in this region, 3) to investigate the possibility of predicting snowpack in the central Andes using climatic indices, and 4) to quantify the relationship between recent snowpack variations and water availability in the adjacent lowlands.

2. Study area

The central Andes separate the two key agricultural and industrial regions of central Chile and central-western Argentina (Fig. 1). The metropolitan region of Santiago and regions V and VI contain about 55% of the Chilean population (~8.4 million people; INE 2003) with a rapidly growing demand on water for urban, agricultural, and industrial uses (Brown and Saldivia 2000; Rosegrant et al. 2000; Ribbe and Gaese 2002; Cai et al. 2003). The average annual (1961–90) rainfall for Santiago is approximately 290 mm, and most water needs are met from river runoff from melting mountain snowpack. In the mid-1990s about 48% of the annual discharge of the Maipo River (the main water source for Santiago) was withdrawn to meet these needs (Cai et al. 2003). Central Chile also accounts for about 45% of the total irrigated area of the country (Brown and Saldivia 2000). On the drier Argentinean side of the central Andes the rivers originating in the mountains serve a population of ~2.2 million people in the provinces of San Juan and Mendoza (INDEC 2001). With less than 200 mm of precipitation per year the vast majority of the agriculture must rely on irrigation (Díaz Araujo and Bertranou 2004). Snow-

[1] The central Andes are here considered as the portion of the Andes between 30° and 37°S.

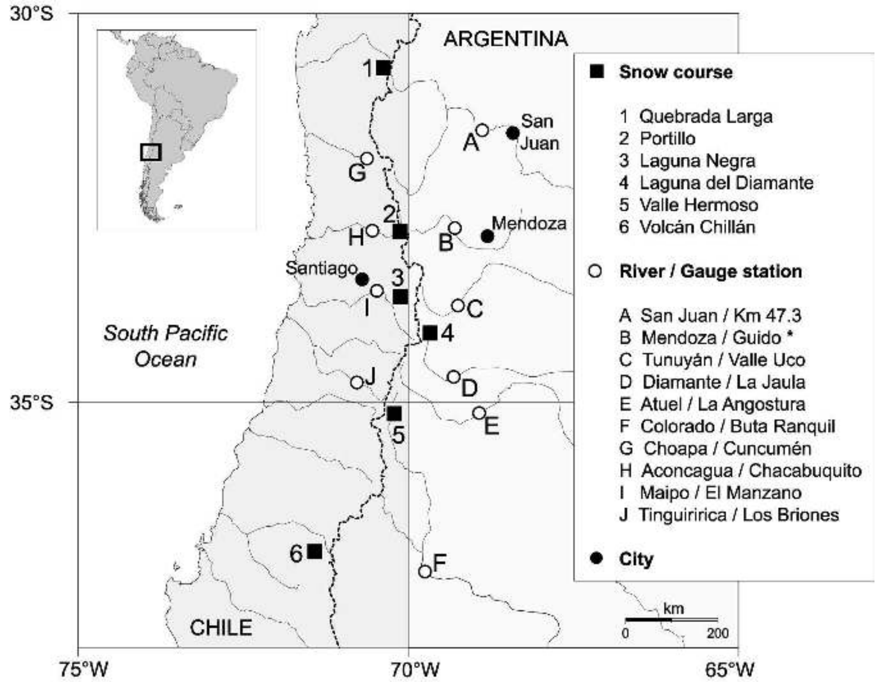

FIG. 1. Map of central Chile and central-western Argentina, showing the location of snow courses and gauge stations used in this study. The international boundary between Chile and Argentina runs along the drainage divide in the cordillera. Note: the Guido gauging station also provided precipitation records for this study (see text for details).

melt runoff is also the main source of water for hydroelectric power generation in the region. Between 1986 and 2003, hydropower plants fed by rivers coming from the cordillera generated, on average, 62% and 86% of the total domestic energy generation in the provinces of Mendoza and San Juan, respectively (Secretaría de Energía 2004; earlier reports available through http://energia.mecon.gov.ar).

The mean elevation of the central Andes is around 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 central Chile and over the mountains (Miller 1976; Aceituno 1988; Lliboutry 1998). The high elevation and north–south orientation of the cordillera are an effective topographic barrier for Pacific air masses, and little Pacific moisture reaches the easternmost slopes of the cordillera. In fact, cold season (March–September) precipitation on the easternmost slopes and adjacent lowlands in Argentina are not correlated with precipitation in Santiago during the same period (Compagnucci and Vargas 1998). The region east of the central Andes experiences a continental regime with a marked warm season precipitation peak associated with moist air masses from the northeast as well as nonfrontal convective processes (Prohaska 1976). Unfortunately, the lack of high-elevation climate stations in the mountains prevents a more detailed analysis of the spatial and temporal patterns of climate over the central Andes (Lliboutry 1998).

Numerous studies have analyzed rainfall variations in the lowlands of central Chile, and the significant influence of tropical Pacific atmospheric features associated with ENSO has been known for decades (Pittock 1980; Quinn and Neal 1983; Aceituno 1988; Rutlland and Fuenzalida 1991; Montecinos et al. 2000; Montecinos and Aceituno 2003; Quintana 2004). Above-average winter rainfall anomalies generally coincide with El Niño events, and below-average winter rainfall anomalies are more likely to occur during La Niña years. Rutlland and Fuenzalida (1991) and Montecinos and Aceituno (2003) further describe a strong relationship between above-average winter rainfall conditions in central Chile and enhanced blocking activity over the Amundsen–Bellingshausen Seas (Am–Be) in the southeast (SE) Pacific, a known ENSO-related atmospheric teleconnection occurring during El Niño events (Karoly 1989; Renwick 1998; Kiladis and Mo 1998).

During the twentieth century, annual and winter rainfall variations in central Chile between 30° and 33°S show strong interdecadal variability with an overall negative trend (Quintana 2004). However, within this period of general negative trend, increased rainfall anomalies occurred between about 1900–40 and 1970–2000, whereas negative anomalies were more frequent between 1940 and 1970. In general, studies of streamflow variations also show that ENSO-related features in the tropical Pacific play a predominant role in regulating the hydrological variability in the region with increased (decreased) summer and annual river discharges following El Niño (La Niña) events (Waylen and Caviedes 1990; Caviedes 1998; Compagnucci and Vargas 1998; Norte et al. 1998; Waylen et al. 2000). Temperature variations in the lowlands of central Chile and central-western Argentina show different trends over the 1960–92 interval (Rosenblüth et al. 1997). Mean annual, summer, and winter temperatures show significant positive trends (>0.3°C decade^{-1}) west of the cordillera centered at around 33°S. However, lowland stations east of the Andes show cooling (though nonsignificant) trends for the mean annual and seasonal temperatures (Rosenblüth et al. 1997).

Studies of recent glacier fluctuations in central Chile (Casassa 1995; Rivera et al. 2000, 2002) indicate a general reduction in glacier mass. Detailed analysis of seven glaciers between 32° and 35°S indicates that they lost approximately 16% of their area in the second half of the twentieth century, and ice thicknesses measured at four glaciers indicated an average thinning of −0.775 m yr^{-1} (Rivera et al. 2002). Generalized recession has also been reported from the small number of Argentinean glaciers that have been studied (Leiva 1999). These changes have been mainly linked to the observed rise in elevation of the 0°C isotherm and the equilibrium line altitude of glaciers in central Chile during the last quarter of the twentieth century (Casassa et al. 2003; Carrasco et al. 2005). Localized studies (Peña and Nazarala 1987; Milana 1998) indicate that glacier meltwater has been particularly critical to maintain minimum water flows during extreme dry years. However, the potential hydrological impacts of the observed ice mass loss in this region have not been studied in detail.

3. Data and methods

Since streamflow variability in this region is dominated by snowmelt runoff, snow data have been monitored to forecast spring and summer water supply for over five decades by Dirección General de Aguas (DGA) in Chile and Departamento General de Irrigacíon (DGI) in Mendoza, Argentina. Between 28° and 37°S, there are fewer than 30 available snow course records in Chile and Argentina, and they cover a large altitudinal range from 1380 to 3600 m. Generally, these data consist of measurements of snow depth, density, and SWE averaged over several samples per snow course. The longest snowpack records are from Portillo, Chile (1951–2004), and Valle Hermoso, Mendoza (1952–2005). However, the snow data available vary in quality and length, and the majority of snow courses have missing data for one or several years. During the cold season (early April to late November) most key stations have been monitored on a monthly to bimonthly basis (and, since 2000, daily snow pillow measurements are also available for a few Argentinean stations), but numerous circumstances (budget limitations, difficulty of access to the sites, etc.) have produced considerable variability in the frequency and timing of the snow measurements across the network. The analysis of records with four or more measurements per winter indicates that the timing of peak SWE values is variable, with 31.0% occurring in August, 43.4% in September, and 14.2% in October. Thus the use of a standard measuring date[2] to estimate the true SWE peak during the cold season could result in substantial error.

To overcome these limitations, the maximum value of SWE (MSWE) for each year was used as a surrogate of total snow accumulation at each site. This was deemed to be the best option available, but we acknowledge the likely existence of minor differences (probably not larger than 10%) between the true SWE winter peak and the MSWE values used in this study. The MSWE values for the six longest (>30 yr) and most complete (<10% missing years) snow course records were retained to develop a regional snowpack time series for the central Andes (Table 1). Following Jones and Hulme (1996), annual MSWE values for each snow course were converted to percentages of their 1966–2004 mean and subsequently averaged to create a regional MSWE record from 1951–2005.

The lack of a representative network of long, complete high-elevation climate records has hampered the assessment of long-term climatic variations in the central Andes and their impacts on mountain snow accumulation and the regional hydrological cycle. These issues were investigated by correlating the regional MSWE series with 4-month moving sums (January–April, . . . , September–December) and January–December annual precipitation totals (1961–90) from three stations lo-

[2] This is equivalent to the 1 April date extensively used in the western United States as a surrogate for winter snow accumulation (e.g., Cayan 1996; Bohr and Aguado 2001; McCabe and Dettinger 2002; Mote et al. 2005).

TABLE 1. Snow courses used to develop a regionally averaged series of annual MSWE record for the central Andes, 1951–2005. Data sources: DGA, Chile; DGI, Argentina.

Snow course	Lat (S)	Lon (W)	Elevation (m)	Period	Missing years (%)	MSWE mean (mm)	Data source
Quebrada Larga	30°43′S	70°22′W	3500	1956–2004	1970, 1971, 2002 (6.5%)	201	DGA
Portillo	32°50′S	70°07′W	3000	1951–2004	1980, 1981 (3.8%)	616	DGA
Laguna Negra	33°40′S	70°08′W	2768	1965–2004	None	573	DGA
Laguna del Diamante	34°15′S	69°42′W	3310	1956–2005*	None	463	DGI
Valle Hermoso	35°09′S	70°12′W	2275	1952–2005*	None	805	DGI
Volcán Chillán	36°50′S	71°25′W	2400	1966–2004	None	771	DGA

* 2000–05 MSWE values derived from daily snow pillow records available online at http://www.irrigacion.gov.ar.

cated at ~110 km west (Santiago–Pudahuel, 33°23′S, 70°47′W, 475 m), and ~110 km (Guido, 32°51′S, 69°16′W, 1550 m) and 200 km (Mendoza–Observatorio, 32°54′S, 68°54′W, 828 m) east of the continental divide (Fig. 1). Monthly total precipitation records for Santiago and Mendoza were downloaded from the Global Historical Climatology Network Web site (http://www.ncdc.noaa.gov/oa/climate/research/ghcn/ghcn.html) and data from Guido were provided by Subsecretaría de Recursos Hídricos, Argentina. MSWE data were also correlated with 5° × 5° gridded mean seasonal and annual temperature records for central Chile (30°–35°S, 70°–75°W) and central-western Argentina (30°–35°S, 65°–70°W) from the HadCRUT2v dataset [This dataset is the variance adjusted version of HadCRUT2, a combined land and marine grid-box temperature anomaly dataset developed by the Climatic Research Unit (CRU), University of East Anglia in conjunction with the Hadley Centre of the Met Office (see Jones and Moberg 2003; Rayner et al. 2003 for details)]. to examine relationships between regional temperature variations and winter snow accumulation in the mountains. The annual and seasonal time series (and in particular the temperature averages) are strongly autocorrelated. If unaccounted for, this would make the statistical tests of significance of correlations too liberal (i.e., too often rejection of the null hypothesis, $r = 0$). To ensure that all records are serially random prior to correlation, each series was prewhitened using an autoregressive (AR) model where the AR(p) order was estimated following the minimum Akaike information criterion (Akaike 1974). By prewhitening all series under analysis, the significance tests of the moving correlations do not require any degrees-of-freedom adjustment for the serial persistence seen in the original data (e.g., Dawdy and Matalas 1964).

Previous studies have reported a strong ENSO-related tropical and subtropical Pacific influence on snow accumulation in the central Andes (e.g., Escobar and Aceituno 1998) and rainfall variations in central Chile (e.g., Pittock 1980; Aceituno 1988; Montecinos and Aceituno 2003). In general, the warm (cold) phases of ENSO, usually associated with El Niño (La Niña) events in the tropical Pacific, have been related to wet (dry) years in central Chile. Enhanced blocking over the Am–Be area in the southeast Pacific during El Niño events has also been linked to increased winter rainfall in central Chile (Rutlland and Fuenzalida 1991; Montecinos and Aceituno 2003). However, the identification and timing of El Niño or La Niña events (i.e., the months covered by such events) varies depending on the parameters used to define those events (Trenberth 1997). In this analysis we define El Niño (La Niña) events as periods when the 5-month running means of SST anomalies in the Niño-3.4 region (5°N–5°S, 120°–170°W) were above 0.4°C (below −0.4°C) for six months or more (Trenberth 1997). These objectively defined events were used to examine the warm–wet/cold–dry hypothesis in the central Andes by comparing their occurrence with the 10 highest and lowest snowpack values in the 1951–2005 MSWE regional record. Subsequently, we used the 2.5° × 2.5° gridded monthly mean 500-hPa geopotential height dataset from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) to investigate the influence of tropospheric circulation anomalies during these extreme years. For each event year and grid point, mean peak winter (June–September) height anomalies from the 1968–96 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.

We also compared the regional MSWE record with seasonally averaged 2.5° × 2.5° gridded SST and sea level pressure (SLP) time series derived from the reanalysis global database (Kalnay et al. 1996). Mean monthly gridded SST and SLP data were composited into October–January (spring–early summer), February–May (summer–early winter), and June–September (midwinter) averages and correlated against the regional MSWE series using the linear correlation and

TABLE 2. Climatic indices used in this study. The data sources are the Climate Prediction Center (CPC); NOAA; NCEP; Climatic Research Unit (CRU), University of East Anglia; Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington; CDC; and Cooperative Institute for Research in Environmental Sciences (CIRES).

Climate index description	Period	Data source	Reference
N34: Mean monthly SST anomalies for the Niño-3.4 region, east-central tropical Pacific (5°N–5°S, 170°–120°W).	1950–2004	CPC, NOAA–NCEP http://www.cpc.ncep.noaa.gov/data/indices/	Trenberth (1997)
SOI: Normalized pressure difference between Tahiti and Darwin.	1866–2004	CRU http://www.cru.uea.ac.uk/cru/data/	Ropelewski and Jones (1987)
PDO: Leading PC of monthly SST anomalies in the North Pacific Ocean, poleward of 20°N.	1900–2004	JISAO http://jisao.washington.edu/pdo/	Mantua et al. (1997)
Atlantic Oscillation (AMO): Mean monthly Atlantic SST anomalies north of the equator, computed with respect to the 1951–2000 base period.	1948–2004	CDC, NOAA–CIRES http://www.cdc.noaa.gov/ClimateIndices/	Enfield et al. (2001)
Tropical southern Atlantic index (TSA): Mean monthly SST anomalies from the equator to 20°S, and 10°E to 30°W.	1948–2004	CDC, NOAA–CIRES http://www.cdc.noaa.gov/ClimateIndices/	Enfield et al. (1999)
Antarctic Oscillation (AAO): Leading PC of 850-hPa geopotential height anomalies south of 20°S.	1948–2002	JISAO http://www.jisao.washington.edu/data/aao/	Thompson and Wallace (2000)

mapping routines available at the Climate Diagnostics Center, National Oceanic and Atmospheric Administration (CDC, NOAA) Web site (http://www.cdc.noaa.gov/Correlation/).

Given the socioeconomic importance of mountain snow accumulation in central Chile and central-western Argentina, better management of water resources could be achieved with the development of reliable models for the prediction of winter snowpack from atmospheric variables or climatic indices (e.g., McCabe and Dettinger 2002). We performed exploratory multiple regression analyses using several climate indices as potential predictors of snow accumulation in the study area. These climate indices (see Table 2) have been widely used to characterize atmospheric conditions in the Pacific, Atlantic, and Antarctic regions and were thus possibly linked to interannual snowpack variations in the central Andes. As some of these candidate predictors are not statistically independent [the Niño-3.4 index (N34), Southern Oscillation index (SOI), and Pacific decadal oscillation (PDO), in particular, exhibit strong intercorrelation], a stepwise regression approach (F-to-enter 0.05, F-to-remove 0.10) was used to avoid multicollinearity among the predictors and develop a more reliable regression model. The analyses were performed separately for four 3-month seasons starting in November of the previous year and ending in October of the current year. Since most of the seasonal climatic index series exhibit strong serial correlations, we utilized the prewhitened versions of the seasonal climatic indices as predictors of the prewhitened MSWE snowpack record (see discussion above). While minimizing the impacts of serial persistence on the estimation of the regression models, this approach allowed us to isolate the partial seasonal influences of each candidate predictor on interannual snowpack variations during the 1953–2002 interval common to all series.

Mean monthly streamflow data for the main rivers in central-western Argentina and central Chile were used to examine the influence of the regional MSWE records on runoff (Fig. 1 and Table 3). Gauge station records were selected for maximum overlap with the MSWE regional series and to avoid major anthropogenic influences on river discharge. Earlier and overlapping monthly records from discontinued stream gauges in the same basin were used to extend (through simple linear regression) the records from active gauge stations on the Mendoza and Diamante Rivers and provide a set of complete and updated (up to June 2004) monthly streamflow series for the most important rivers in central-western Argentina. Missing monthly values in the Chilean records were estimated using a reference series created from the remaining streamflow records in the region. Mean annual values were calculated using the July–June water year, and each year is identified by the year of the earliest month (i.e., the 2003 water year extends from July 2003 to June 2004). Mean monthly and annual streamflow series were prewhitened prior to correlation with the regional snowpack record.

Finally, linear trends in the MSWE regional record and the mean annual and seasonal temperatures from the HadCRUT2v grid cells on both sides of the cordillera were analyzed to explore relationships with river discharges and glaciers over the twentieth century. Annual (July–June) and warm season (November–February) river discharges for the region were calculated as the average of the individual streamflow series expressed as percentages from their 1966–2004 mean.

TABLE 3. Argentinean and Chilean streamflow records used in this study. Annual data refer to a July–June water year. The statistical significance of least squares linear trends during the common period was estimated after accounting for the lag-1 autocorrelation in the regression residuals of each series (Santer et al. 2000). Data sources: Subsecretaría de Recursos Hídricos (SSRH 2004), Argentina; Dirección General de Aguas (DGA), Chile.

River (basin area)	Gauge station	Lat (S), Lon (W)	Elevation (m)	Period of record (% missing)	Mean annual discharge ($m^3 s^{-1}$)	1954–2003 linear trend ($m^3 s^{-1} yr^{-1}$)	Nov–Feb contribution to annual runoff (%)
San Juan ($25670 km^2$)	km 47.3	31°32′S, 68°53′W	945	Jul 1909–Jun 2004	65.2	+0.54 NS[a]	53.5
Mendoza ($9040 km^2$)	Guido[b]	32°51′S, 69°16′W	1550	Jul 1909–Jun 2004	48.9	+0.37 NS	58.7
Tunuyán ($2380 km^2$)	Valle de Uco	33°47′S, 69°15′W	1200	Jul 1954–Jun 2004	28.6	+0.12 NS	59.7
Diamante ($2753 km^2$)	La Jaula[c]	34°40′S, 69°19′W	1500	Jul 1938–Jun 2004	30.9	+0.23 NS	57.0
Atuel ($3800 km^2$)	La Angostura	35°06′S, 68°52′W	1200	Jul 1906–Jun 2004	35.2	+0.24 NS	51.3
Colorado ($15300 km^2$)	Buta Ranquil	37°05′S, 69°44′W	850	Apr 1940–Jun 2004	148.3	+0.77 NS	55.8
Choapa ($1172 km^2$)	Cuncumén	31°58′S, 70°35′W	955	Jan 1941–Jun 2005 (3.0%)	9.6	+0.08 NS	56.5
Aconcagua ($2059 km^2$)	Chacabuquito	32°51′S, 70°31′W	1030	Oct 1913–Jun 2005 (0.8%)	33.0	+0.18 NS	61.0
Maipo ($4769 km^2$)	El Manzano	33°36′S, 70°23′W	890	Nov 1946–Jun 2005 (1.6%)	107.8	+0.93[d]	55.8
Tinguiririca ($1424 km^2$)	Bajo Los Briones	34°43′S, 70°49′W	518	Jan 1942–Jun 2005 (9.3%)	50.7	+0.38[e]	55.3

[a] NS means that linear trend is not significant ($P > 0.05$).
[b] July 1909–June 1956 estimated from Cacheuta (33°01′S, 69°07′W, 1238 m).
[c] July 1938–June 1977 estimated from Los Reyunos (34°35′S, 68°39′W, 850 m).
[d] Significant at the 0.05 level.
[e] Significant at the 0.01 level.

Linear trends were computed for the 1951–2004 interval common to all series, and for the 1906–2004 interval common to the gridded temperature and regional runoff records. The statistical significance of trends was assessed following a conservative approach that accounts for the temporal autocorrelation in the regression residuals of each time series (the AdjSE + AdjDF approach: Santer et al. 2000).

4. Results

a. Regional snowpack record, 1951–2005

In this paper we have developed the first regional snowpack series (expressed as annual maximum snow-water equivalent) using snow course data from both sides of the central Andes in Chile and Argentina. This series covers the 1951–2005 period and is derived from the six longest and most complete snow course records in the region (Table 1). Despite the large latitudinal range (~30°–37°S) of these six snow courses and other data limitations discussed above, the individual MSWE records show similar year-to-year variability and share a high percentage of common variance (Figs. 2a–f). The mean correlation coefficient from all possible paired combinations is 0.697, and only one significant principal component explains 77% of the total variance in these records over the 1966–2004 period. The regional MSWE record (Fig. 2g) is approximately normally distributed and shows a nonsignificant positive linear trend (+3.95% $decade^{-1}$, $P = 0.543$) over the 1951–2005 interval. The negative first-order autocorrelation coefficient for this series is not statistically significant (-0.258, $P > 0.05$) but reflects the strong year-to-year variability present in both individual snow course records and the regional MSWE series. Regional MSWE annual values can vary widely from 6% (1968) to 257% (1982) of the 1966–2004 mean (Fig. 2g).

b. Relationship with local climate conditions

Lagged correlation analysis of the regional MSWE series with seasonal and annual precipitation and temperature records from both sides of the cordillera re-

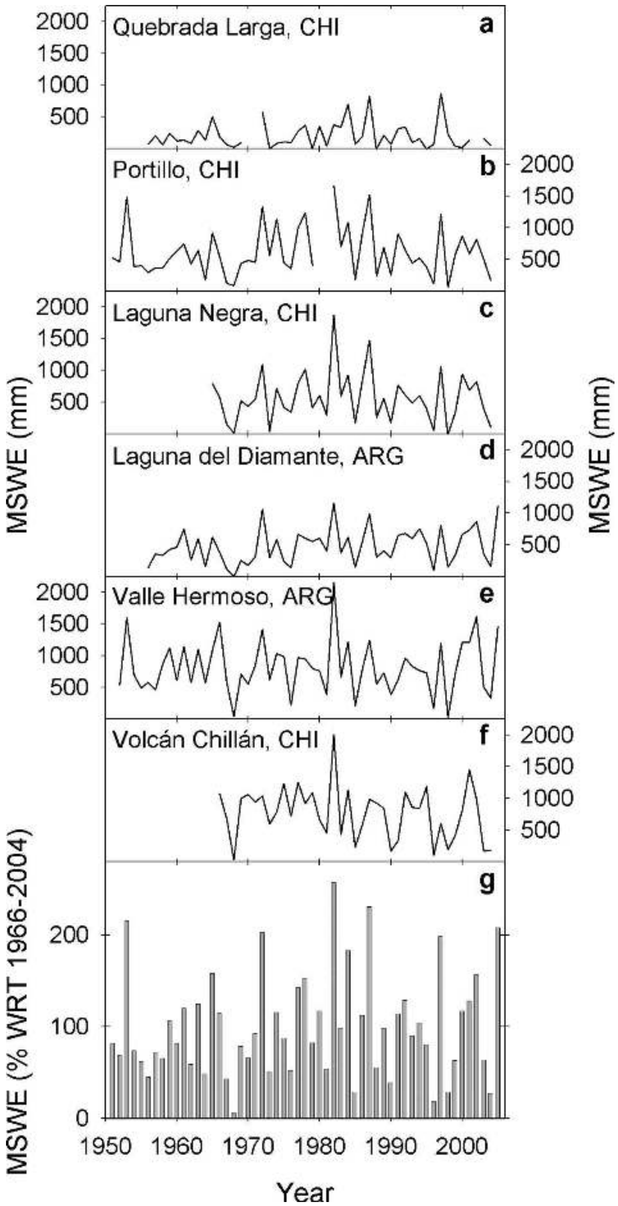

FIG. 2. (a)–(f) Plot of the annual maximum snow water equivalent (MSWE) records for the six snow courses used in this study. CHI: Chile; ARG: Argentina. (g) Regional snowpack series (1951–2005) developed by averaging the above six series expressed as percentages of their 1966–2004 common period mean.

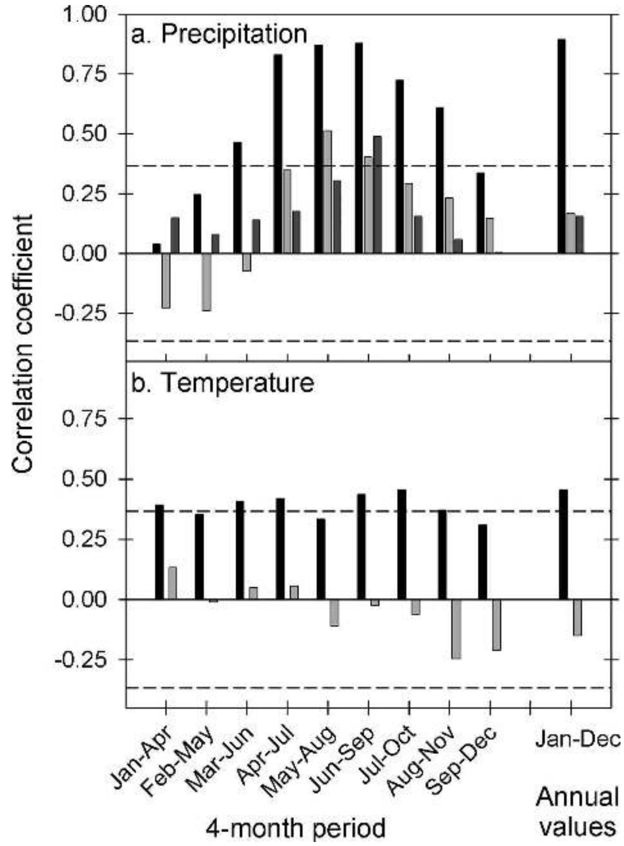

FIG. 3. (a) Correlations over the 1961–90 period between the prewhitened MSWE regional series and 4-month seasonal and annual precipitation totals. The stations are Santiago (black bars) west of the Andes, and Guido (light gray bars) and Mendoza (dark gray bars) east of the water divide. (b) Correlations between the prewhitened MSWE regional series and 5° × 5° gridded mean seasonal and annual temperature data for central Chile (30°–35°S, 70°–75°W, black bars) and central-western Argentina (30°–35°S, 65°–70°W, gray bars). The 95% confidence level is depicted by horizontal dashed lines.

vealed the much stronger influence of western (Pacific) conditions on winter snow accumulation at high-elevation sites (Fig. 3). Using the prewhitened versions of each series, the MSWE series showed highly significant positive correlations with Santiago precipitation for several four-month periods during winter (e.g., r = 0.878 with June–September totals, Fig. 3a) and also with the annual total (r = 0.893). Correlations with winter precipitation east of the mountains at Guido were lower but still significant (at the 0.05 level) for the May–August and June–September periods. However, only June–September precipitation totals in Mendoza (farther east of the continental divide) were significantly correlated with the regional snowpack record (Fig. 3a).

The gridded temperature record for central Chile was significantly positively correlated at the 0.05 level with the regional snowpack record for most of the four-month periods analyzed and the mean annual values (Fig. 3b). However, none of the gridded temperature data from east of the mountains were significantly correlated with snowpack, further demonstrating that, at these latitudes, conditions in the Andes are much more strongly related to climate variations west of the continental divide. The significant positive correlations with

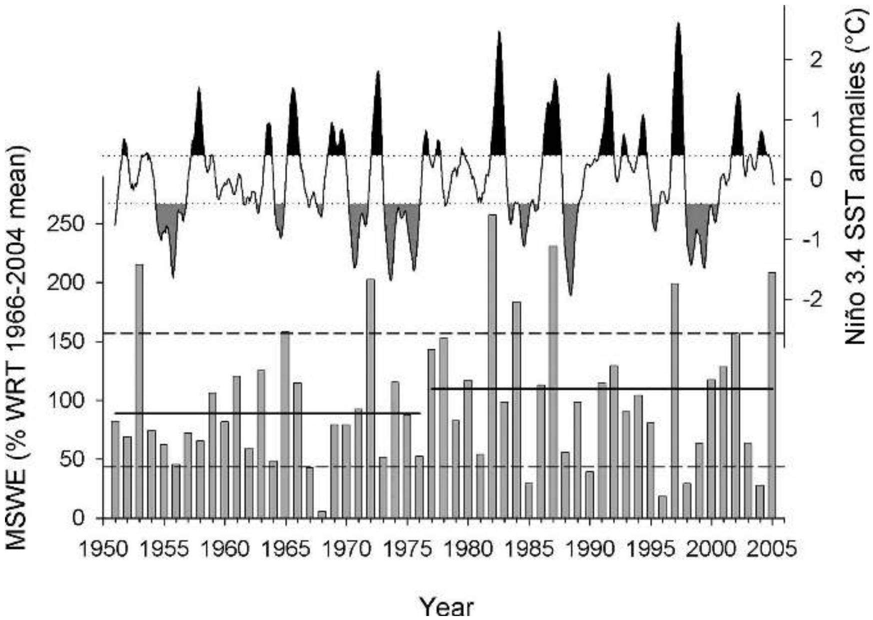

FIG. 4. Comparison between (top) 5-month moving averages of monthly SST anomalies for the Niño-3.4 region and (bottom) the regional snowpack series from the central Andes. MSWE (SST) records are expressed as percentages (anomalies) from the 1966–2004 (1971–2000) base period. El Niño (La Niña) events are identified following Trenberth (1997) and are shaded black (gray) in the upper diagram. The dashed lines indicate ±1 standard deviations in the 1951–2005 regional snowpack record. MSWE means for the 1951–76 and 1977–2005 periods are shown as thick horizontal lines.

temperature variations in central Chile are surprising, as we would expect mountain snowpack records to be positively correlated with nearby precipitation data (e.g., Selkowitz et al. 2002) but mostly negatively correlated with temperature records (e.g., Mote et al. 2005). However, this could partially be explained if the variables involved are not fully independent, where, for example, increases in precipitation may result from warmer air masses with potentially higher water vapor contents (Barry 1990). The 1961–90 annual total precipitation values in Santiago and the mean annual gridded temperature series in central Chile are significantly positively correlated ($r = 0.463$, $P < 0.01$).

c. Influence of ENSO events and relationship with 500-hPa geopotential height anomalies

Figure 4 shows that above-average snow accumulation in the central Andes is generally associated with the warm phases of ENSO (El Niño events), as was earlier reported by Escobar and Aceituno (1998) and Prieto et al. (2000, 2001). However, comparison of the 10 highest and 10 lowest MSWE years with El Niño and La Niña events (Table 4) revealed that this relationship is complex: two of the 10 snowiest years on record did not correspond to El Niño events (as defined by positive SST anomalies in the Niño-3.4 region). In fact, 1984 and 1978 (7th and 10th snowiest years, respectively) actually occurred during extended negative SST anomalies in the Niño-3.4 region (Table 4). Extremely low snowfall years in the central Andes show a weaker association with the cold phase of ENSO, and 5 of the 10 driest years (1968, 1996, 2004, 1990, and 1967) did not correspond with concurrent La Niña events in the tropical Pacific (Table 4).

Numerous studies have analyzed the 1976–77 climatic shift throughout the Pacific basin and the changes in ENSO activity toward more warm phases after 1976 (e.g., Mantua et al. 1997; Zhang et al. 1997; Trenberth et al. 2002). This large-scale atmospheric shift and the associated higher frequency and intensity of El Niño events seem to have impacted the snowpack records in the central Andes. During the 1951–76 interval, only 8 years are above the long-term mean, compared with 15 years during the 1977–2005 period. The average snowfall is higher during this latter part of the record, although the means are not significantly different due to the high interannual variability (Fig. 4). This agrees with the positive trend in central Chile rainfall records between 1970 and 2000 (Quintana 2004) and is likely

TABLE 4. The 10 highest and lowest snow accumulation years in the central Andes (1951–2005), expressed as percentages from the 1966–2004 base period. El Niño and La Niña events (as defined by Trenberth 1997) that overlap at least two of the snow season months (April–October) are also listed. Note that not all highest (lowest) ranked annual MSWE values coincide with El Niño (La Niña) events.

	10 snowiest years			10 driest years		
Rank	Year	Averaged MSWE (%)	El Niño?	Year	Averaged MSWE (%)	La Niña?
1	1982	257.2	Yes	1968	5.6	No[a]
2	1987	230.7	Yes	1996	18.5	No[b]
3	1953	215.1	Yes	2004	27.6	No[c]
4	2005	208.2	Yes	1985	29.1	Yes
5	1972	202.6	Yes	1998	29.2	Yes
6	1997	198.9	Yes	1990	39.1	No[d]
7	1984	183.4	No[e]	1967	42.8	No[f]
8	1965	158.2	Yes	1956	45.3	Yes
9	2002	156.9	Yes	1964	48.6	Yes
10	1978	152.8	No[g]	1973	51.6	Yes

[a] La Niña event from October 1967 to April 1968 (early winter). Niño-3.4 region SST anomalies remained negative until June 1968, turned positive in July 1968, and an El Niño event started in September 1968 (late winter).

[b] Strictly, an 8-month La Niña event ended in April 1996. Nevertheless, SST anomalies remained negative throughout the winter of that year.

[c] Positive Niño-3.4 SST anomalies were observed during 2004, with values above +0.4°C between June 2004 and May 2005.

[d] Positive SST anomalies (between 0° and 0.4°C) were observed during 1990.

[e] Niño-3.4 SST anomalies remained negative from August 1983 through May 1986. A La Niña event occurred between August 1984 and August 1985.

[f] Strictly, a La Niña event only started in October 1967, but SST anomalies had remained negative throughout that year.

[g] Negative Niño-3.4 SST anomalies occurred between April and December 1978.

responsible for the positive trend observed in the regional MSWE series.

The 500-hPa geopotential height anomaly maps (Fig. 5) suggest a clear association between peak winter large-scale tropospheric circulation anomalies in the mid- to high latitudes of the Southern Hemisphere and extreme snowfall years in the central Andes. The most noticeable features associated with the 10 snowiest years on record are the extensive and well-defined regions of averaged positive and negative height anomalies concentrated between 60° and 70°S, 90° and 120°W (Am–Be area) and 30° and 40°S, 130° and 150°W in the subtropical South Pacific (Fig. 5a). These patterns confirm the results from previous studies (e.g., Rutlland and Fuenzalida 1991; Montecinos and Aceituno 2003) and indicate that enhanced blocking activity around the Am–Be area and the concurrent weakening of the subtropical Pacific anticyclone are key features influencing above-average snow accumulation in the study area. Interestingly, the 10 driest years on record corresponded with almost an 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 (Fig. 5b). High snow years also corresponded with generalized positive height anomalies between New Zealand and the southern tip of South Africa, whereas negative anomalies occurred over the Southern Ocean between the date line and 90°E and the eastern Antarctic sector around 70°–80°S, 105°–120°E (Fig. 5a). A similar, opposite, anomaly pattern in these remote regions is apparent for the 10 driest years (Fig. 5b), providing evidence of the large-scale, relatively time-stable nature of these atmospheric relationships.

d. Relationships with gridded SST, SLP, and climate indices

In addition to the results described above, correlations of the regional MSWE series with mean seasonal gridded global SST and SLP data (Fig. 6) revealed interesting spatial patterns that may help to understand the relative temporal and spatial significance of these variables on snow accumulation in the central Andes. In general, the seasonally averaged spring–early summer (October–January) gridded SST values showed nonsignificant correlations with the regional MSWE series (Fig. 6a). The February–May (late summer–early winter) SST gridded records show some negative correlation fields centered south and east of Australia and in the southeast Pacific, whereas positive correlations were found over most of the tropical and subtropical eastern Pacific and the southwest Atlantic (Fig. 6b). The highest correlations occurred during the June–September (peak winter) period showing the strong and well-known ENSO-like wedge pattern over the tropical and subtropical Pacific (e.g., Trenberth and Caron 2000; Trenberth et al. 2002: Fig. 6c). Strong positive correlations were found during this four-month period especially over the Niño-3 and -4 regions in the tropical Pacific. Conversely, negative correlations occurred mostly over the subtropical western Pacific. Negative correlations were also found on the eastern Pacific off the coast of central Chile. This correlation pattern resembles that obtained by Montecinos and Aceituno (2003) for June–August central Chile rainfall variations and SST gridded fields over the tropical and subtropical Pacific.

Field correlations between the MSWE series and SLP gridded seasonal averages (Figs. 6d–f) also showed a temporal pattern with a noticeable ENSO-related

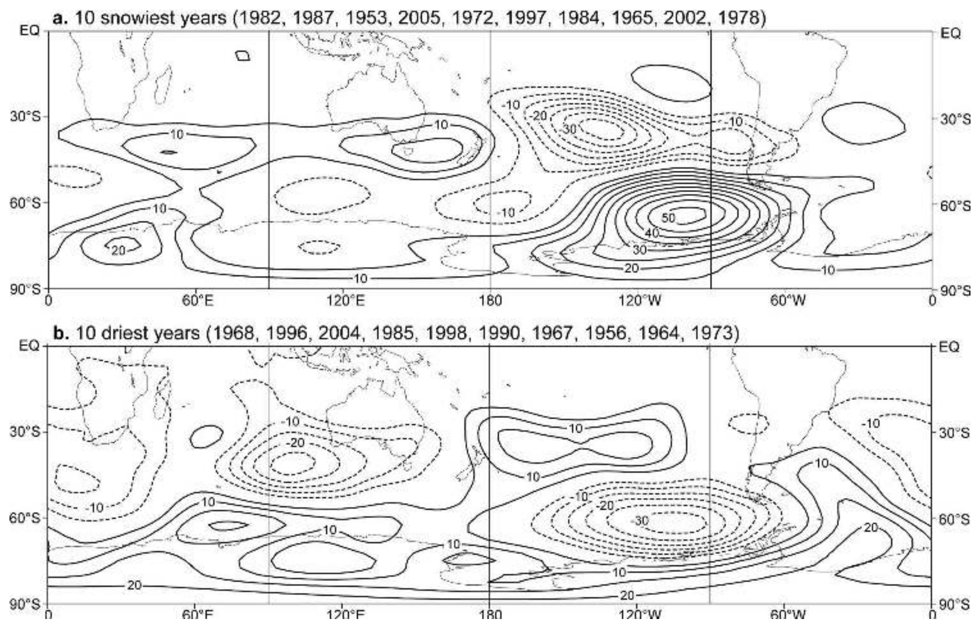

FIG. 5. June–September mean 500-hPa geopotential height anomalies for (a) the 10 snowiest years and (b) the 10 driest years in the central Andes. Mean monthly gridded data were obtained from the NCEP–NCAR reanalysis global dataset (Kalnay et al. 1996). Contours are in meters with a 5-m contour interval, and zero lines are omitted. Positive (negative) contour anomalies are shown as solid (dashed) lines.

structure (Trenberth and Caron 2000). In general, low or nonsignificant field correlations were found with gridded SLP October–January seasonal averages. Negative correlations, concentrated over the subtropical South Pacific, were found with February–May SLP averages, while the grid cells over the northern Indian Ocean and around Australia were positively correlated with the snowpack series. The strongest gridded SLP–MSWE correlations also occurred in the June–September period during the current winter season (Fig. 6f) with negative correlations over the subtropical Pacific and southeast Atlantic Oceans. Figure 6f also shows positive correlations concentrated around northern Australia and over the Am–Be area in the southeast Pacific, closely resembling the Pacific SLP–central Chile winter rainfall correlation pattern obtained by Montecinos and Aceituno (2003). As expected, the pattern in Fig. 6f is also roughly similar to the 500-hPa geopotential height anomaly map shown in Fig. 5a.

The analysis of the anomaly maps and correlation fields depicted in Figs. 5 and 6 suggests that, in addition to the strong ENSO-related influence in the Pacific basin, snowpack variations in the central Andes might also be related to large-scale atmospheric features that extend beyond the tropical and subtropical Pacific. If physically and statistically meaningful, these relationships could be used to develop winter snowpack forecasts for the study region. Our multivariate regression trials revealed that none of the climatic indices for the November–April period is significantly correlated with the snowpack record and, therefore, they are not useful predictors of winter snow accumulation in the central Andes (Table 5). However, significant correlations were found between the MSWE record and May–July (early–midwinter) averages of the N34, SOI, and the Antarctic Oscillation (AAO) but due to intercorrelation among these variables only the SOI was included in a regression model, which explains about 44% of the variance in the snowpack record (Table 5). The predictive skill of these candidate variables decreases later in the winter season. Although the August–October (late winter) averages for the N34, SOI, and PDO showed statistically significant correlations with the regional snowpack record, only the N34 series was selected in the stepwise regression procedure to explain about 31% of the variance in the MSWE regional series (Table 5).

e. Relationships between regional streamflow records and winter snowpack

All of the rivers studied display typical unimodal annual hydrographs with a November to February (late spring–early summer) snowmelt peak that represents about 57% of the annual discharge (Table 3). Over the 1954–2003 common period, only one significant princi-

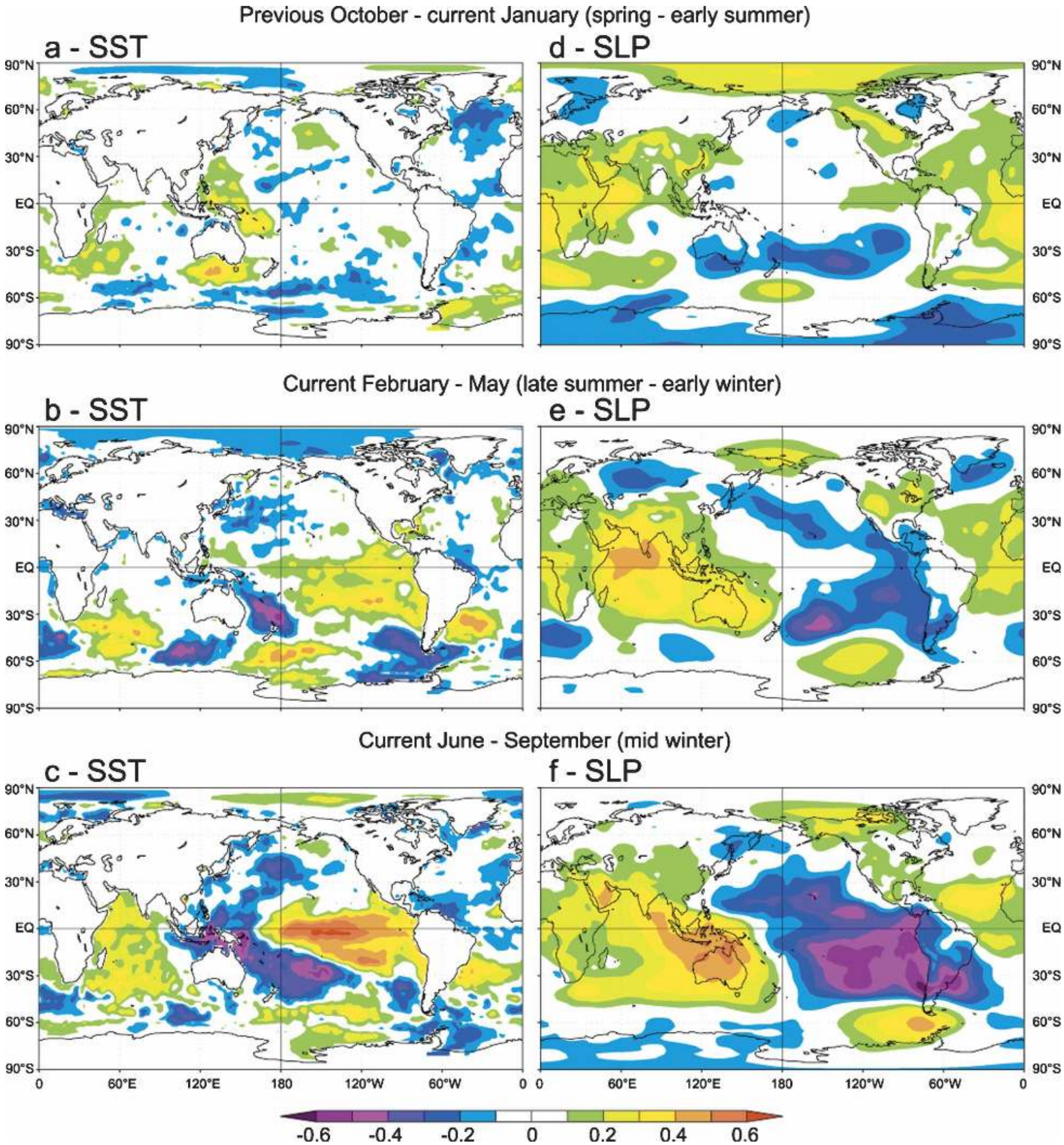

FIG. 6. Correlation maps showing the changing seasonal strength in the relationships between the regional MSWE series and seasonally averaged NCEP–NCAR reanalysis 2.5° × 2.5° (a)–(c) SST and (d)–(f) SLP gridded data over the 1952–2003 interval.

pal component (PC1) explains 85.5% of the total variance in mean annual discharge of these rivers, indicating a strong similarity in flow regimes on both sides of the cordillera. A similar coherent pattern is shown by a principal component analysis of the mean summer (November–February) flows with PC1 explaining 86.1% of the total variance. All 10 rivers showed positive linear trends in annual runoff over the 1954–2003 period (Table 3). However, after accounting for the serial correlation in the regression residuals of each series (Santer et al. 2000), only the Maipo and Tinguiririca Rivers in Chile showed positive linear trends that are statistically significant at the 0.05 level. Positive linear trends were also observed in the November–

TABLE 5. Multivariate regression trials between 1953–2002 prewhitened versions of the regional snowpack record and seasonally averaged estimates for the six climatic indices described in Table 2. Four 3-month seasons starting in November of the previous year were used, and candidate predictors were selected following a stepwise regression approach (F-to-enter 0.05, F-to-remove 0.10). Here *r* denotes the correlation coefficient between the snowpack series and seasonal averages for each climatic index; Beta denotes the standardized regression coefficients used to compare the relative strength of the various predictors within each model; Adj R^2 denotes the coefficient of determination adjusted for the number of predictors in the model; and # indicates that none of the predictors passed the threshold value for F-to-enter.

Climate	NDJ			FMA			MJJ			ASO		
index	*r*	Beta	Adj R^2	*r*	Beta	Adj R^2	*r*	Beta	Adj R^2	*r*	Beta	Adj R^2
N34	0.091	−0.147	#	0.273	0.368	#	0.526*	0.038	0.437	0.567*	0.567*	.307
SOI	−0.154	−0.163		−0.240	0.153		−0.670*	−0.670*		−0.509*	−0.079	
PDO	0.235	0.253		0.170	0.083		0.105	−0.108		0.299**	-0.101	
AMO	−0.017	0.080		0.074	−0.076		−0.073	−0.138		−0.065	−0.096	
TSA	−0.189	−0.198		−0.141	−0.130		−0.087	0.075		0.105	0.071	
AAO	−0.109	−0.055		−0.195	−0.152		−0.247**	−0.045		0.050	0.085	

* Coefficient is significant at the 0.01 level.
** Coefficient is significant at the 0.05 level.

February mean seasonal values, but none of these trends reached statistical significance at the 0.05 level.

The strong, positive association between winter snowpack and spring–summer river discharges is a well-known hydrometeorological relationship in the study area. However, to our knowledge no published studies have actually quantified this relationship. In Fig. 7 we show that highly significant correlations (particularly for the warm season peak flows) exist between the regional MSWE series and mean monthly streamflow records from both sides of the cordillera, even after accounting for serial persistence in the individual series. Extremely high correlation values (ranging between 0.778 and 0.908) were also found with the annualized July–June river discharges. Over the 1951–2004 period, the correlation between the MSWE record and the regionally averaged November–February (July–June) river discharges were as high as 0.945 (0.926) (Fig. 8), reflecting the crucial influence of mountain snowpack on freshwater availability in the adjacent lowland areas in Chile and Argentina. However, month-by-month correlation analysis (Fig. 7) revealed some interesting differences in the relationship between the western and eastern sides of the cordillera. Although the hydrographs of these rivers have a simple unimodal warm season peak centered around December–January, correlations with the Chilean (western) rivers (light bars, Fig. 7) were statistically significant approximately two months prior (even including June, in the middle of the snow season) to the Argentinean (eastern) rivers (dark

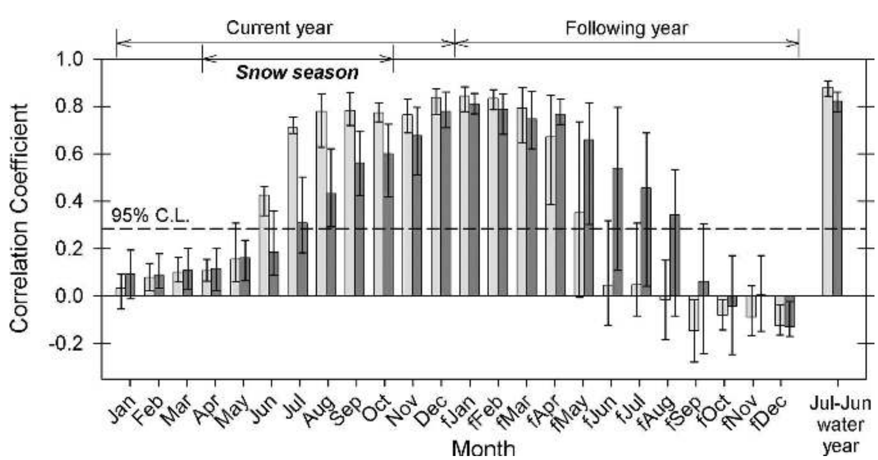

FIG. 7. Correlations between the prewhitened regional snowfall MSWE record and streamflow over the 1955–2002 period. The mean and range of the correlations coefficients for the four Chilean (light bars) and six Argentinean (dark bars) rivers are shown for each month and the July–June water year. The 95% confidence level is depicted by the dashed line.

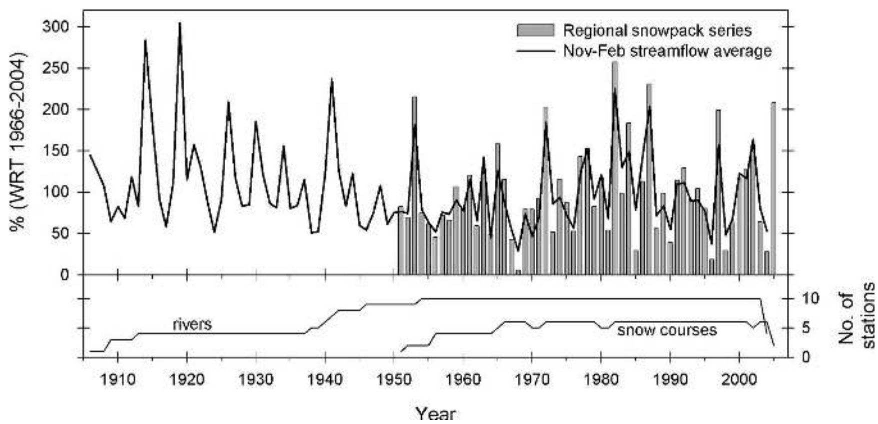

FIG. 8. Relationship between the 1951–2005 MSWE series (bars) and the 1906–2004 regionally averaged November–February discharge from central Chile and central-western Argentina (solid line). Both series are expressed as percentages with respect to the 1966–2004 base period. The correlation between these raw series is extremely high ($r = 0.945$, $P < 0.001$). Correlations with the prewhitened data showed similar results.

bars, Fig. 7). Significant correlations with the Chilean rivers also ended earlier in the following year than the Argentinean rivers (Fig. 7).

All winter snowpack and annual and seasonal streamflow and temperature series showed positive trends over the 1951–2004 period, but only the trends for mean annual and warm season temperatures from central-western Argentina were significant at the 0.05 level when the conservative approach of Santer et al. (2000) was used (Table 6). Temperature trends on both sides of the Andes remained positive for all seasons when the extended 1906–2004 period was considered, but in this case only the central Chile records reached statistical significance at the 0.05 level or higher. In contrast, mean annual regional and warm season runoff series showed negative (though nonsignificant) linear trends over this interval (Table 6).

5. Discussion and conclusions

Either directly or indirectly, over 10 million people in central Chile and central-western Argentina depend on the freshwater originating from the winter snowpack in the central Andes to meet water demands for drinking, domestic consumption, irrigation, industry, and hydroelectric generation. Winter snow accumulation has been systematically monitored for over 50 years for spring–summer snowmelt discharges on both sides of the mountain range, but few published studies are available and little is known about winter snowpack variability in the region. In this paper we present the first attempt to integrate snowpack data from the Andes in Chile and Argentina (Fig. 1). Our results generally agree 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, using updated snow course data our analyses provide further insight into 1) the main temporal and spatial patterns in the snowpack records; 2)

TABLE 6. Linear trends over the 1951–2004 and 1906–2004 periods for several hydroclimatic parameters. Moisture-related variables are the regional MSWE series and averaged annual (July–June) and warm season (November–February) regional streamflow records, expressed as percentages from the 1966–2004 common period. Temperature data (°C anomalies from the 1961–90 period) are from the 5° × 5° HadCRUT2v gridded dataset averaged over the year (January–December), and six-month warm (October–March) and cold (April–September) seasons. The grid cells used are CRU A = 30°–35°S, 70°–75°W (central Chile) and CRU B = 30°–35°S, 65°–70°W (central-western Argentina). The statistical significance (t test) of the least squares linear trends was estimated after accounting for the lag-1 autocorrelation in the regression residuals of each series (Santer et al. 2000).

Variable	Slope (values per decade)	
	1951–2004	1906–2004
MSWE	+1.9%	N/A
Streamflow Jul–Jun	+4.4%	−2.3%
Streamflow Nov–Feb	+3.7%	−2.8%
CRU A Jan–Dec	+0.068°C	+0.081°C*
CRU A Apr–Sep	+0.065°C	+0.057°C**
CRU A Oct–Mar	+0.066°C	+0.104°C*
CRU B Jan–Dec	+0.122°C**	+0.023°C
CRU B Apr–Sep	+0.101°C	+0.033°C
CRU B Oct–Mar	+0.139°C**	+0.017°C

* Coefficient is significant at the 0.01 level.
** Coefficient is significant at the 0.05 level.

their relationships with local climate, ENSO events, large-scale atmospheric variables (500-hPa geopotential height, SST, and SLP), and climatic indices indicative of conditions in the Pacific, Atlantic, and Antarctic regions; 3) the temporal importance of the winter snow records on river discharges in the region; and 4) possible causes for the observed streamflow and glacier trends over the second half of the twentieth century.

Unlike western North America or the European Alps, the snow course data available in the southern South American Andes are very limited in temporal and spatial extent. Between ~30° and 37°S only two snow course records exceed 50 years, and only six stations with >30 years of records and <10% of missing data were deemed appropriate for this study (Table 1). However, these records demonstrate a strong regional signal, indicating that they are reliable indicators of interannual and interdecadal snowpack variations in the central Andes over the 1951–2005 period. In contrast to the decreasing trends observed in snowpack records across western North America (Mote et al. 2005), the averaged regional MSWE series displays a positive (though nonsignificant) trend with marked interannual variability ranging from 6% to 257% of the 1966–2004 mean.

The most noticeable feature evidenced by the correlation analyses between the regional snowpack series and climate records from both sides of the cordillera is the highly significant positive correlations with winter and annual rainfall totals in central Chile, which reflect the importance of moist westerly air masses in regulating snowfall over the mountains. Lower (though marginally significant) positive correlations were also found with central Chile gridded temperature records. Precipitation and gridded temperature data east of the continental divide showed a much weaker association with the MSWE series. While highlighting the predominant influence of western conditions on snowpack accumulation in the central Andes, these results revealed an intriguing positive association between temperature and snowpack variations that agrees with a theoretical model of possible effects of warming trends in mountain regions (see Barry 1990). According to this model, warmer air masses with a potentially higher specific humidity may lead to a temporary increase in snowfall at high-elevation sites. The positive trends observed in our snowpack series and in surface and tropospheric temperature records in central Chile during winter (Aceituno et al. 1993; Rosenblüth et al. 1997) are in line with this hypothesis. However, the limited empirical information available and the complex nature of the atmospheric processes and feedbacks involved (Allen and Ingram 2002) hamper our ability to assess the possible implications of this positive snowpack–temperature association in the near future. Nonetheless, the analysis of several climate and hydrologic models (Jacobs et al. 2001) suggests that substantial increases in temperature will ultimately result in a reduction of the mountain snowpack, with potential impacts on the hydrological cycle and water supply for the region.

We found a clear correspondence between the warm phases of ENSO (El Niño events) and above-average snow accumulation in the central Andes, but two of the snowiest years on record did not correspond with concurrent positive SST anomalies in the Niño-3.4 region. Moreover, only 50% of the driest years in the central Andes coincided with La Niña events in the tropical Pacific, suggesting the existence of additional factors outside the tropical Pacific that contribute to explain snowfall variability in the central Andes. The analysis of 500-hPa geopotential height anomaly maps associated with the extreme years in the study region revealed that tropospheric conditions in the mid- to high latitudes in the Pacific are key factors modulating extreme snowpack variations in the study region. Enhanced blocking activity (associated with positive height anomalies) 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 snow accumulation in the study area. A remarkably similar height anomaly pattern of opposite sign for the driest years suggests that a stronger Pacific anticyclone and depleted height anomalies in the SE Pacific during winter determine a southward displacement of westerly air masses with a marked reduction in snowfall in the central Andes. These results coincide with previous related studies in the region (e.g., Rutlland and Fuenzalida 1991).

Lagged correlations between the regional MSWE series and global gridded SST and SLP data averaged over previous and current seasons showed the well-known association between central Chile precipitation and ENSO conditions in the tropical and subtropical Pacific (see, e.g., Montecinos and Aceituno 2003). Interestingly, the higher correlations with the SST and SLP records were mostly observed during the austral winter season (June–September), suggesting that conditions preceding the cold season have little or no influence on winter snow accumulation in this region (see Fig. 6). This was further corroborated by multivariate regression trials between the MSWE series and 3-month moving averages of large-scale climatic indices (Tables 2 and 5), which revealed serious limitations in predicting snow accumulation before the onset of the winter season using these candidate predictor variables alone. These results also confirmed that the predominant Pacific, ENSO-related influence on snowpack in the central Andes is mainly concentrated during the cold season months, but even during this period the variance explained by the stepwise regression models was relatively modest (44%–31%). Given the socioeconomic importance of the central Andes snowpack, improved predictive skills are desirable and more research is needed to identify better predictors of snowpack records from the period prior to the austral winter. Since the most serious challenges in managing the mountain water supply will likely occur during below-average snowfall years, special attention should be paid to those large-scale atmospheric linkages associated with (or leading to) extreme dry years in the central Andes. One possibility is the development of 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 Am–Be area in the southeast Pacific (see Figs. 5 and 6f). Although blocking activity in this area is strongly associated with ENSO variability (see, e.g., Renwick 1998), a better understanding of additional atmospheric teleconnections affecting conditions in the southeast Pacific (e.g., Jacobs and Comiso 1997; Marques and Rao 1999) may in turn lead to improved predictive skills for snowpack in this region.

River discharges on both sides of the central Andes are strongly correlated with the snowpack record and show remarkably similar interannual variability and trends, highlighting the existence of a marked regional hydrologic signal between 31° and 37°S. The correlation between the MSWE record and regionally averaged river discharges suggests that over the past 55 years >85% of the streamflow variance could be explained by the snowpack record alone (Fig. 8). As expected from a snowmelt-dominated streamflow regime, the late spring–early summer months (November–February) account for almost 60% of the annual total flows and show the highest correlations with the snowpack record (Table 3 and Fig. 7). However, the Chilean rivers also showed highly significant correlations during July–September in the middle of the snow season. Although additional work is needed to elucidate these previously undocumented differences in the snowpack–streamflow relationships between Chilean and Argentinean rivers, we hypothesize that, as winter rainfall in central Chile and snow accumulation in the central Andes are strongly correlated (see Fig. 3a), the higher correlations of the Chilean rivers during the snow season probably reflect the influence of winter rainfall over the gauge stations located west of the cordillera.

Linear trend analyses of snowpack, streamflow, and local climate records during the 1951–2004 period showed a consistent pattern of positive trends for all these variables. However, conservative estimates revealed that most of these trends are not statistically significant and therefore should be interpreted with caution. During the extended 1906–2004 period, trends in annual and warm season streamflow records changed in sign but remained within the 95% confidence levels, whereas temperatures on both sides of the central Andes showed a sustained warming tendency, especially in the annual and warm season series from central Chile. This consistent pattern of positive trends found in the temperature records, together with the generalized recession of glaciers observed in the central Andes (Casassa 1995; Rivera et al. 2000), suggest that significant changes in climate have already impacted glacier mass balances in the region. The higher average in snow accumulation during recent decades [which has likely been influenced by the higher frequency and intensity of the warm phases of ENSO after 1976 (Trenberth et al. 2002)] does not seem to have counteracted the negative impacts of increased glacier ablation associated with higher temperatures across the region. Although largely speculative, these analyses also suggest that the positive trends observed in river discharges during this most recent period (Tables 3 and 6) may be related to both the higher snow inputs and increasing snow and ice ablation due to higher temperatures during the snowmelt season. Even when increased glacier recession may result in higher runoff in the short term, the observed and predicted climate tendencies for this region indicate that ultimately the glacier melt contribution to streamflow will diminish, with substantial and widespread socioeconomic impacts especially during extreme dry years.

Higher temperatures are also expected to influence the amount of precipitation that falls as rain rather than snow and produce earlier snowmelt peaks, which will change the seasonal availability of water supply (Jacobs et al. 2001; Stewart et al. 2005). If such projections are correct, local water management authorities will likely face increasing challenges to allocate the scarce mountain water among the rapidly growing urban, industrial, and agricultural sectors. Further work is needed to quantify the relative influences of rainfall, snowmelt, and glacier ablation on the rivers west and east of the continental divide and properly evaluate the potential hydrological and socioeconomic impacts of the predicted climate changes in this region. This will also require detailed information about the inherent long-term variability and change in snow accumulation over the central Andes. The remarkably strong association between winter snowpack and summer runoff suggests that streamflow records could be used as surrogates of snowpack variations for most of the past century (see Fig. 8). However, this interval may still be inadequate to capture the full range of decade- to century-long fluctuations in the snowpack record. Examination of the long and well-replicated moisture-sensitive tree-ring width chronologies, available from the Chilean side of the central Andes (Boninsegna 1988; Le Quesne et al. 2006), indicates that these proxy records could provide a much longer (and thus more appropriate) perspective to assess the low-frequency snowpack variability and improve our understanding of past changes and possible future scenarios for winter snow accumulation in this mountainous region.

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REFERENCES

Aceituno, P., 1988: On the functioning of the Southern Oscillation in the South American sector. Part I: Surface climate. *Mon. Wea. Rev.,* **116,** 505–524.

——, H. Fuenzalida, and B. Rosenblüth, 1993: Climate along the extratropical west coast of South America. *Earth System Responses to Global Change—Contrasts between North and South America,* H. A. Mooney, E. R. Fuentes, and B. I. Kronberg, Eds., Academic Press, 61–69.

Akaike, H., 1974: A new look at the statistical model identification. *IEEE Trans. Autom. Control,* **AC19,** 716–723.

Allen, M. R., and W. J. Ingram, 2002: Constraints on future changes in climate and the hydrologic cycle. *Nature,* **419,** 224–232.

Barry, R. G., 1990: Changes in mountain climate and glacio-hydrological responses. *Mountain Res. Dev.,* **10,** 161–170.

Bohr, G. S., and E. Aguado, 2001: Use of April 1 SWE measurements as estimates of peak seasonal snowpack and total cold-season precipitation. *Water Resour. Res.,* **37,** 51–60.

Boninsegna, J. A., 1988: Santiago de Chile winter rainfall since 1220 as being reconstructed by tree rings. *Quat. South Amer. Antarct. Pen.,* **6,** 67–87.

Bradley, R. S., F. T. Keimig, and H. F. Diaz, 2004: Projected temperature changes along the American cordillera and the planned GCOS network. *Geophys. Res. Lett.,* **31,** L16210, doi:10.1029/2004GL020229.

Brown, E., and J. E. Saldivia, 2000: Water management in Chile (in Spanish). Comité Asesor Técnico de América del Sur (SAMTAC), Asociación Mundial del Agua (GWP). [Available online at http://www.eclac.cl/DRNI/proyectos/samtac/InCh01100.pdf.]

Cai, X., M. W. Rosegrant, and C. Ringler, 2003: Physical and economic efficiency of water use in the river basin: Implications for efficient water management. *Water Resour. Res.,* **39,** 1013, doi:10.1029/2001WR000748.

Carrasco, J. F., G. Casassa, and J. Quintana, 2005: Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. *Hydrol. Sci. J.,* **50,** 933–948.

Casassa, G., 1995: Glacier inventory in Chile: Current status and recent glacier variations. *Ann. Glaciol.,* **21,** 317–322.

——, A. Rivera, F. Escobar, C. Acuña, J. Carrasco, and J. Quintana, 2003: Snow line rise in central Chile in recent decades and its correlation with climate. *Geophys. Res. Abs.,* **5,** 14 395.

Caviedes, C.N., 1998: ENSO influences on the interanual variations of South American rivers (in Spanish). *Bull. Inst. fr. étud. Andines,* **27,** 627–641.

Cayan, D., 1996: Interannual climate variability and snowpack in the western United States. *J. Climate,* **9,** 928–948.

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.

Cubasch, U., and Coauthors, 2001: Projections of future climate change. *Climate Change 2001: The Scientific Basis,* J. T. Houghton et al., Eds., Cambridge University Press, 525–582.

Dawdy, D. R., and N. C. Matalas, 1964: Statistical and probability analysis of hydrologic data. Part III. Analysis of variance, covariance, and time series, *Handbook of Applied Hydrology: A Compendium of Water-Resources Technology,* V. T. Chow, Ed., McGraw-Hill, 8.68–8.90.

Díaz Araujo, E., and A. Bertranou, 2004: Systemic study of water management regimes, Mendoza, Argentina. Comité Asesor Técnico de América del Sur (SAMTAC), Asociación Mundial del Agua (GWP). [Available online at http://www.eclac.cl/DRNI/proyectos/samtac/InAr00404.pdf.]

Enfield, D. B., A. M. Mestas-Nuñez, D. A. Mayer, and L. Cid-Serrano, 1999: How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures? *J. Geophys. Res.,* **104,** 7841–7848.

——, ——, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.,* **28,** 2077–2080.

Escobar, F., and P. Aceituno, 1998: ENSO influence on Andean winter snowfall in central Chile (in Spanish). *Bull. Inst. fr. étud. Andines,* **27,** 753–759.

INDEC, 2001: National census, 2001 (in Spanish). Instituto Nacional de Estadística y Censos, Argentina. [Available online at http://www.indec.mecon.gov.ar.]

INE, 2003: National census, 2002 (in Spanish). Instituto Nacional de Estadísticas, Chile. [Available online at http://www.ine.cl.]

Jacobs, K., D. B. Adams, and P. Gleick, 2001: Potential consequences of climate variability and change for the water resources of the United States. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change,* J. M. Melillo et al., Eds., Cambridge University Press, 405–435.

Jacobs, S. S., and J. C. Comiso, 1997: Climate variability in the Amundsen and Bellingshausen Seas. *J. Climate,* **10,** 697–709.

Jones, P. D., and M. Hulme, 1996: Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *Int. J. Climatol.,* **16,** 361–377.

——, and A. Moberg, 2003: Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Climate,* **16,** 206–223.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Karoly, D. J., 1989: Southern Hemisphere circulation features associated with El Niño–Southern Oscillation events. *J. Climate,* **2,** 1239–1252.

Kiladis, G. N., and K. C. Mo, 1998: Interannual and intraseasonal variability in the Southern Hemisphere. *Meteorology of the Southern Hemisphere, Meteor. Monogr.,* No. 49, Amer. Meteor. Soc., 307–336.

Leiva, J. C., 1999: Recent fluctuations of the Argentinian glaciers. *Global Planet. Change,* **22,** 169–177.

Le Quesne, C., D. W. Stahle, M. K. Cleaveland, M. D. Therrell, J. C. Aravena, and J. Barichivich, 2006: Ancient *Austrocedrus* tree-ring chronologies used to reconstruct central Chile precipitation variability from A.D. 1200 to 2000. *J. Climate,* **19,** 5731–5744.

Lliboutry, L., 1998: Glaciers of the dry Andes. Satellite Image Atlas of Glaciers of the World: South America, R. S. Williams and J. G. Ferrigno, Eds., USGS Professional Paper 1386-I. [Available online at http://pubs.usgs.gov/prof/p1386i/index.html.]

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

Marques, R. F. C., and V. B. Rao, 1999: A diagnosis for a long-lasting blocking event over the southeast Pacific Ocean. *Mon. Wea. Rev.,* **127,** 1761–1776.

Maza, J., L. Fornero, and H. Yañez, 1995: Simulating and forecasting snowmelt (in Spanish). *Bull. Inst. fr. étud. Andines,* **24,** 651–659.

McCabe, G. J., and M. D. Dettinger, 2002: Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate. *J. Hydrometeor.,* **3,** 13–25.

Milana, J. P., 1998: Forecasting river discharges in glacierized basins using energy balance models in the Andes Centrales, Argentina (in Spanish). *Rev. Asoc. Arg. Sedimentol.,* **5** (2), 53–69.

Miller, A., 1976: The climate of Chile. *World Survey of Climatology,* W. Schwerdtfeger, Ed., Vol. 12, Elsevier, 113–218.

Montecinos, A., and P. Aceituno, 2003: Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies. *J. Climate,* **16,** 281–296.

——, A. Diaz, and P. Aceituno, 2000: Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical Pacific SST. *J. Climate,* **13,** 746–758.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.,* **86,** 39–49.

Norte, F., S. Simonelli, and N. Heredia, 1998: Impacts of ENSO on the hydrometeorological regime in Mendoza, Argentina (in Spanish). *Bull. Inst. fr. étud. Andines,* **27,** 761–770.

Peña, H., and B. Nazarala, 1987: Snowmelt-runoff simulation model of a central Chile Andean basin with relevant orographic effects. *Large Scale Effects of Seasonal Snow Cover,* B. E. Goodison, R. G. Barry, and J. Dozier, Eds., IAHS Publication 166, IAHS Press, 161–172.

Pittock, A. B., 1980: Patterns of climatic variation in Argentina and Chile—I. Precipitation, 1931–60. *Mon. Wea. Rev.,* **108,** 1347–1361.

Prieto, M. R., H. G. Herrera, T. Castrillejo, and P. I. Dussel, 2000: Recent climatic variations and water availability in the central Andes of Argentina and Chile (1885–1996). The use of historical records to reconstruct climate (in Spanish). *Meteorologica,* **25** (1–2), 27–43.

——, ——, P. Doussel, L. Gimeno, and P. Ribera, 2001: Interanual oscillations and trend of snow occurrence in the Andes region since 1885. *Aust. Meteor. Mag.,* **50,** 164–168.

Prohaska, F., 1976: The climate of Argentina, Paraguay and Uruguay. *World Survey of Climatology,* W. Schwerdtfeger, Ed., Vol. 12, Elsevier, 13–112.

Quinn, W. H., and V. T. Neal, 1983: Long-term variations in the Southern Oscillation, El Niño, and the Chilean subtropical rainfall. *Fish. Bull.,* **81,** 363–374.

Quintana, J. M., 2004: Factors affecting Central Chile rainfall variations at interdecadal scales (in Spanish). M.S. thesis, Departamento de Geofísica, Universidad de Chile, 88 pp.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Globally complete analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Renwick, J. A., 1998: ENSO-related variability in the frequency of South Pacific blocking. *Mon. Wea. Rev.,* **126,** 3117–3123.

Ribbe, L., and H. Gaese, 2002: Water management issues of the Aconcagua watershed, Chile. *Technology Resource Management and Development: Water Management,* Vol. 2, Institute of Technology in the Tropics, Eds., University of Applied Sciences Cologne, 86–108. [Available online at http://www.th.fh-koeln.de/publications/ittpub301202_6.pdf.]

Rivera, A., G. Casassa, C. Acuña, and H. Lange, 2000: Recent glacier variations in Chile (in Spanish). *Invest. Geogr.,* **34,** 29–60.

——, C. Acuña, G. Casassa, and F. Bown, 2002: Use of remotely sensed and field data to estimate the contribution of Chilean glaciers to eustatic sea-level rise. *Ann. Glaciol.,* **34,** 367–372.

Ropelewski, C. F., and P. D. Jones, 1987: An extension of the Tahiti–Darwin Southern Oscillation Index. *Mon. Wea. Rev.,* **115,** 2161–2165.

Rosegrant, M. W., C. Ringler, D. C. McKinney, X. Cai, A. Keller, and G. Donoso, 2000: Integrated economic–hydrologic water modeling at the basin scale: The Maipo river basin. *Agric. Econ.,* **24,** 33–46.

Rosenblüth, B., H. Fuenzalida, and P. Aceituno, 1997: Recent temperature variations in southern South America. *Int. J. Climatol.,* **17,** 67–85.

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.

Santer, B. D., and Coauthors, 2000: Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. *J. Geophys. Res.,* **105** (D6), 7337–7356.

Secretaría de Energía, 2004: Electric sector annual report, 2003 (in Spanish). Ministerio de Planificación Federal, Inversión Pública y Servicios, Secretaría de Energía, Argentina. [Available online at http://energia.mecon.gov.ar/Publicaciones/Informe%202003.pdf.]

Selkowitz, D. J., D. B. Fagre, and B. A. Reardon, 2002: Interannual variations in snowpack in the Crown of the Continent Ecosystem. *Hydrol. Processes,* **16,** 3651–3665.

SSRH, 2004: *Hydrological Statistics of Argentina* (in Spanish). Subsecretaría de Recursos Hídricos, Buenos Aires, Argentina, CD-ROM, 1st ed.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate,* **18,** 1136–1155.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate,* **13,** 1000–1016.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.,* **78,** 2771–2777.

——, and J. M. Caron, 2000: The Southern Oscillation revisited: Sea level pressures, surface temperatures, and precipitation. *J. Climate,* **13,** 4358–4365.

——, ——, D. P. Stepaniak, and S. Worley, 2002: Evolution of El Niño–Southern Oscillation and global atmospheric surface temperatures. *J. Geophys. Res.,* **107,** 4065, doi:10.1029/2000JD000298.

Waylen, P. R., and C. N. Caviedes, 1990: Annual and seasonal fluctuations of precipitation and streamflow in the Aconcagua River basin. *J. Hydrol.,* **120,** 79–102.

——, R. Compagnucci, and R. M. Caffera, 2000: Interannual and interdecadal variability in streamflow from the Argentine Andes. *Phys. Geogr.,* **21,** 452–465.

Zhang, Y., J. M. Wallace, and D. S. Battisti, 1997: ENSO-like interdecadal variability: 1900–93. *J. Climate,* **10,** 1004–1020.