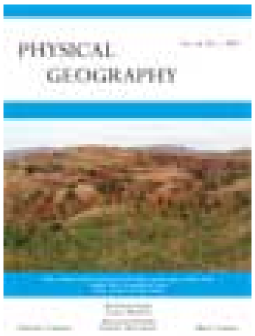

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ARTICLE

Water, agriculture, and climate dynamics in central Chile's Aconcagua River Basin

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ABSTRACT

Agriculture in the Aconcagua Basin is both vital to Chile's economy and critically dependent on water resources from snow and glaciers. Expanding croplands, a growing population, and a changing climate are all expected to exacerbate water scarcity in this arid region where agriculture requires 7.1×10^8 m^3 of water for irrigation annually. We investigate agricultural water resources in the Aconcagua Basin by examining the drivers of and trends in river discharge, calculating approximate crop water demand, and assessing the potential for future water scarcity given discharge rates and agricultural demand. We find that growing-season (October to March) discharge is significantly correlated with austral winter precipitation and the El Niño-Southern Oscillation. Austral winter precipitation provides snow that melts during the growing season, supplying water for agricultural irrigation. Time series analysis shows that temperature increased by 0.23°C per decade between 1965 and 2017, and snow cover frequency decreased 2.7% per decade over the relatively short time period of 2000 to 2017. Based on historical discharge data and our assessment of current agricultural water demand, we show that the Aconcagua Basin is already water-scarce, experiencing demand exceeding supply approximately three out of every 10 years.

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Water resources; glaciers; irrigation; Chile; Aconcagua

Introduction

Access to freshwater resources is a defining challenge of the 21st century, with a majority of the global population already vulnerable to water scarcity (Mekonnen & Hoekstra, 2016; Oki & Kanae, 2006). An estimated 17% of the world's population relies on water resources located in mountainous snow and glacier regimes, which are highly sensitive to changes in climate (Barnett et al., 2005; Viviroli et al., 2007). One such mountainous regime is Chile's Aconcagua Basin, which supports half a million residents and a water-intensive economy dominated by agriculture and mining (Valdés-Pineda et al., 2014; Clarvis & Allan, 2014).

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The Aconcagua Basin is located between 32.3° and 33°S, 50 km north of the Chilean capital of Santiago. The Río Aconcagua and its tributaries stretch 215 km in length and span an elevation range of 6,100 m from sea level to the glaciated Andean peaks (Figure 1). This arid basin covers an area of 7,333 km^2 and supports 12% of Chile's national agriculture, livestock, and forestry production. Here, we focus on large-scale irrigated agriculture, which is dependent on seasonal meltwater from the Andes.

The climate of the Aconcagua Basin is subject to high intra- and inter-annual variability (Janke et al., 2017; Martínez et al., 2012). Precipitation is concentrated in the austral winter months of June, July, and August (hereafter winter months), with extremely limited precipitation in the austral summer months of December, January, and February (hereafter summer months; Valdés-Pineda et al., 2014). As a result, during the summer months, which comprise the majority of the growing season, the basin relies on meltwater originating from the Andes (Valdés-Pineda et al., 2014; Clarvis & Allan, 2014; Viviroli et al., 2007).

Nationwide, Chile faces increasing sociopolitical and climatological stress on its water resources. Between 1980 and 2016, Chile experienced a 751% increase in GDP and a 58% increase in population, leading to greater water consumption (Valdés-Pineda et al., 2014; World Bank, 2016). In 2011, Chilean leaders announced plans to increase irrigated land

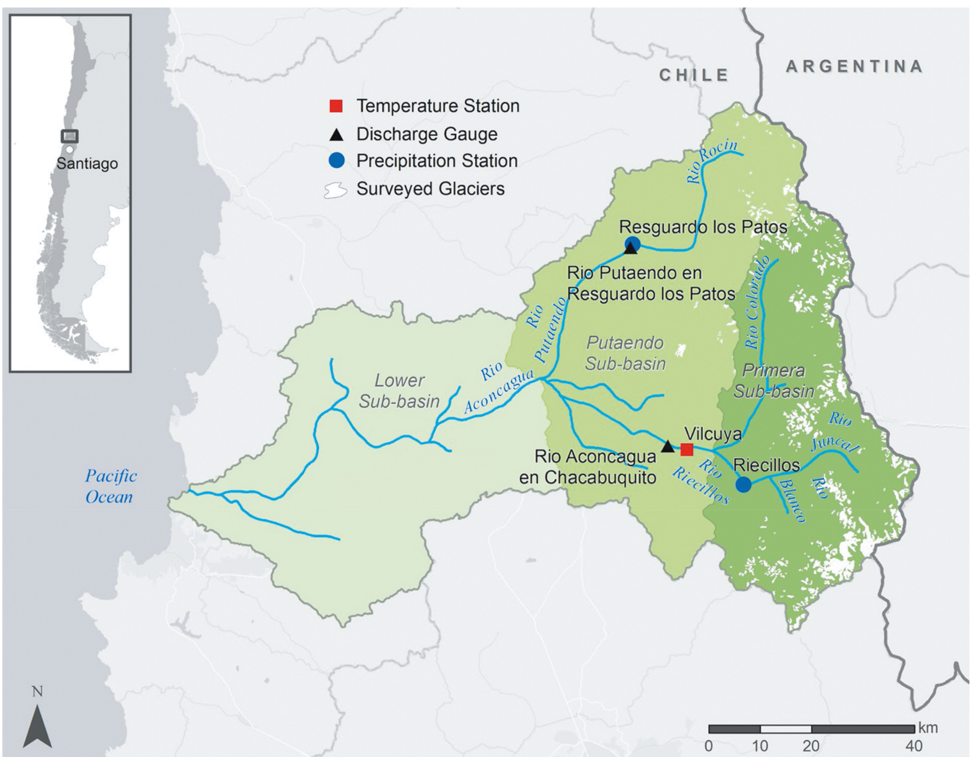

Figure 1. Map of the Aconcagua Basin and sub-basins (indicated with green shading), Río Aconcagua and its tributaries, and the temperature (red squares), precipitation (blue circles), and river discharge (black triangles) stations used in this study. Previously surveyed glaciers are also highlighted in white.

by 57% by 2022, further heightening the water demands of the agricultural sector, which currently accounts for 78% of the country's total consumptive water usage (Comisión Nacional de Riego, 2011; McPhee et al., 2012). Complicating matters further, Chile privatized water rights in 1981, which has led to disputes over water resource usage and distribution while eliminating centralized control (Valdés-Pineda et al., 2014; Clarvis & Allan, 2014). Moreover, coupled atmosphere-ocean general circulation models (CGCMs) project that Chile will experience a median 2.5°C rise in temperature and a 20% decrease in precipitation by the end of the twenty-first century due to the poleward expansion of the South Pacific subtropical high and an increase in moisture divergence (Christensen & Hewitson, 2007; Collins et al., 2013). Rising temperatures will cause a greater proportion of precipitation to fall as rain instead of snow, potentially decreasing the amount of freshwater available during the summer growing season (Viviroli et al., 2007). Combined, the sociopolitical and climatological factors described above present a challenging future for Chile, and motivate the ongoing study of water resources and sustainable water management (Clarvis & Allan, 2014; Oficina de Estudios y Políticas Agrarias, 2012).

Previous studies in the Aconcagua Basin have inventoried glaciers (Bown et al., 2008; Janke et al., 2017; Pellicciotti et al., 2014), estimated snow cover area (Masiokas et al., 2006), and investigated regional precipitation and river discharge trends, especially those related to El Niño-Southern Oscillation (ENSO) variation (Cai et al., 2014; Martínez et al., 2012; Montecinos & Aceituno, 2003; Pellicciotti et al., 2007; Waylen & Caviedes, 1990). Some studies have suggested that perennial glaciers are the essential drivers of growing-season river discharge (Ohlanders et al., 2013; Peña & Nazarala, 1987; Ragettli & Pellicciotti, 2012), while others have pointed to the important role of annual snow cover (Masiokas et al., 2006; Stehr & Aguayo, 2017). However, the long-term effects of climate trends on the sustainability of regional mountain water resources, and by extension, irrigated agricultural productivity, are to date poorly constrained. Further, the lack of consensus on the snow or glacial origins of discharge during the growing-season leads to uncertainty about current and future water availability across the Aconcagua Basin.

Here, we add to the literature on the Aconcagua Basin by (1) identifying the key drivers of and trends in growing-season river discharge; (2) examining the role of snow and glaciers in regional mountain water resources; and (3) assessing the implications of the recent expansion in irrigated agriculture on water scarcity. To accomplish this, we analyze the climate variables associated with water availability for irrigation, develop a time series of snow cover and glacier area, and estimate irrigation requirements for the Aconcagua Basin. We provide new insight into how snow cover and glaciers are related to growing season discharge used for irrigation and the longevity and sustainability of the Aconcagua Basin's water resources given agricultural irrigation requirements, climate trends, and climate variability.

Materials and methods

Agriculture

We used the 2007 Chilean National Agricultural Census to determine the prevalence, distribution, and water needs of crops throughout the Aconcagua Basin (Ministerio de

Agricultura, 2007). The census data report the acreage of individual crops within 111 community units in the Aconcagua Basin, and we used them to determine the most prevalent crops and the overall spatial distribution of agriculture within the basin. We derived crop irrigation requirements from a 2007 report commissioned by the Chilean Ministry of Public Works (Dirección General de Aguas, 2007), and determined total agricultural water consumption by multiplying the acreage of individual crops by their crop irrigation requirement.

Glacier and snow cover

We examined the time series of glacier area from 1986 to 2017 top-of-atmosphere (TOA) Landsat 5 (1986–2011) and Landsat 8 (2013–2017) imagery in Google Earth Engine. We defined glacier area as the minimum snow and ice extent in the austral summer. We measured snow and ice extent in Landsat imagery using an elaboration on the Normalized Difference Snow and Ice Index (NDSI), incorporating cloudiness, the Normalized Difference Water Index (NDWI), slope, and spectral reflectance in the blue band (Figure 2).

Although Burns and Nolin (2014) successfully used only an NDSI threshold to classify snow and ice, we incorporated auxiliary data into the NDSI classification to improve accuracy given the Aconcagua Basin's complex topography and numerous water bodies, which could be misclassified as snow and ice.

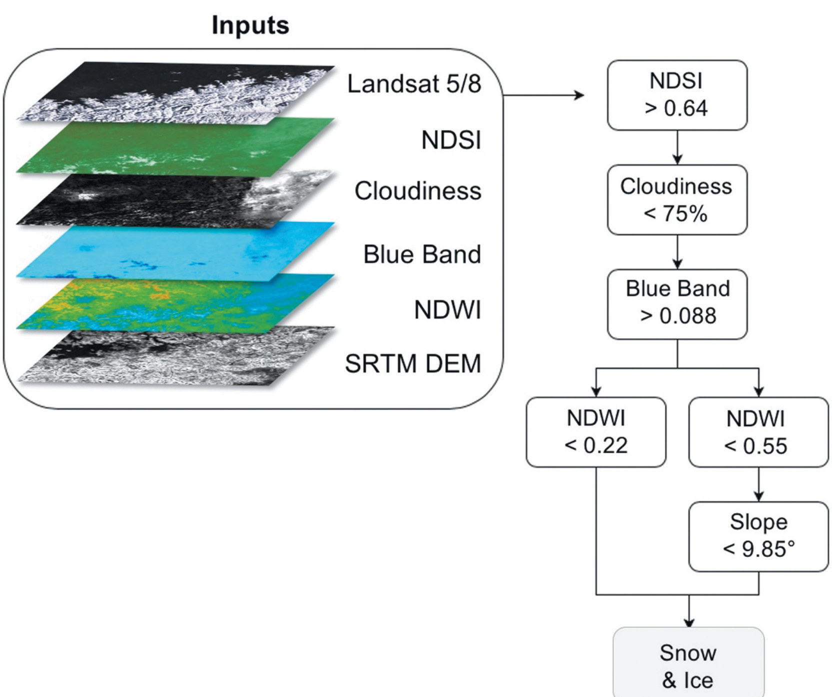

Figure 2. Google earth engine decision tree classifier representing the algorithm used to identify snow and ice pixels in Landsat 5 and 8 imagery over the study area.

NDSI uses the normalized difference of the green and short-wave infrared (SWIR) bands to detect the presence of snow and ice, relying on the high reflectance of snow and ice in the green wavelengths and the lower reflectance of snow and ice in the SWIR wavelengths (Burns & Nolin, 2014). An NDSI threshold of 0.64 classified snow and ice best in the study area. To remove clouded pixels, composite and pixel cloudiness were calculated using the Google Earth Engine Landsat Simple Cloud Score algorithm. Pixels with a cloud score greater than 75% were excluded from the analysis. We used a blue band threshold of 0.088 to distinguish between bare earth in shadow and snow and ice in shadow, as shaded snow and ice have significantly higher reflectance in the blue wavelengths compared to shaded bare earth (Paul & Kääb, 2005).

To avoid the NDSI falsely classifying bodies of water as snow and ice, we incorporated a water mask using NDWI and slope. NDWI uses the normalized difference between the green and near-infrared (NIR) bands to detect the presence of water. NDWI can distinguish liquid water from snow and ice because of the greater reflectance of snow and ice in the NIR wavelengths (McFeeters, 1996). To avoid the misclassification of shadowed areas as water pixels, we also included a slope threshold of 9.85° derived from the 2000 SRTM DEM (Ji et al., 2015; Sun et al., 2012). Thus, to be classified as water and not shadowed snow or ice, a pixel required either an NDWI greater than 0.55 or an NDWI greater than 0.22 and a slope of less than 9.85°. We performed a visual inspection of the glacier imagery to remove dates containing persistent snow cover, resulting in eight glacier area data points over the 26-year period between 1989 and 2015.

We used Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Snow Cover Daily Global imagery to evaluate changes in snow cover. While the minimum snow and ice area from Landsat worked well for determining glacier area, which has less intra- and interannual variability, Landsat did not have sufficient regularity in the 1980s and 1990s to analyze snow cover frequency, which quantifies the varying coverage of snow in both space and time. Therefore, we calculated snow cover from 2000 to 2017 using the MODIS product in Google Earth Engine. Similar to our Landsat classification of snow and ice described above, the MODIS snow cover product is derived from a snow mapping algorithm combining NDSI with other criteria tests (Hall et al., 2016). We created 8-day snow cover composite images from the snow cover products, and then calculated annual snow cover frequency to capture the relative extent and longevity of snow cover within the basin in a given year (Sproles et al., 2018).

We constructed annual time series of glacier area and snow cover frequency within the study area boundaries, and trends were assessed using a nonparametric Theil–Sen robust linear regression to ensure insensitivity to outliers (Sen, 1968; Theil, 1950). The significance of Theil-Sen monotonic trends was evaluated using the Mann–Kendall test (Kendall, 1948; Mann, 1945). Using Janke et al.'s (2017) average Aconcagua Basin glacier thickness of 24.4 m, the volume of water stored in the Aconcagua Basin glaciers was estimated by multiplying the average glacier thickness by the total glacier area and 0.92, representing the ratio of the density of water to the density of ice.

Discharge, precipitation, temperature, and ENSO

We analyzed monthly local datasets for river discharge, precipitation, and temperature, as well as global ENSO indices, to assess relationships between glacial extent, snow cover, and climate. For each station in Figure 1, annual time series and seasonal cycles were calculated.

We used monthly mean discharge data published by the General Water Directorate (DGA) from Chile's Climate Data Library (Ministerio de Agricultura, 2015) and the DGA website (Dirección de General de Aguas, 2017). We selected the Río Putaendo en Resguardo los Patos and Río Aconcagua en Chacabuquito gauges because of their location on the two main tributaries of the Río Aconcagua above the majority of agricultural areas (Figure 1) and because both stations have observations dating back to 1950, with 94.6% and 99.0% complete data coverage, respectively. Río Putaendo en Resguardo los Patos is located at 1218 m above sea level (a.s.l.) in the Putaendo sub-basin, below the Río Rocin tributary (Figure 1). Río Aconcagua en Chacabuquito is located at 950 m a.s.l. on the Putaendo sub-basin, below the Río Blanco, Río Colorado, and Río Juncal tributaries (Figure 1). The summed discharge from Río Putaendo en Resguardo los Patos and Río Aconcagua en Chacabuquito, therefore, provides an estimate of the total amount of discharge available to downstream agriculture. To construct the discharge time series, we calculated average monthly mean discharge for each gauge between 1950 and 2017. We also calculated and analyzed the time series of discharge for the growing season of October to March (O-M) from each station.

Monthly precipitation data were acquired from the Center for Climate Resilience Research (Centro de Ciencia del Clima y la Resiliencia, 2018), which combines nationwide datasets from the Chilean Meteorological Directorate and DGA. Eleven precipitation stations were available in our study area, and we analyzed both seasonal and annual precipitation data for 1950–2017. We used two precipitation stations representative of the mountain precipitation regimes on the Aconcagua Basin's two main tributaries, Riecillos (1100 m a.s.l) and Resguardo los Patos (1258 m a.s.l; Figure 1). Both datasets are 93% complete over the 1950–2017 study period. Riecillos is located in the Primera sub-basin, above Río Aconcagua en Chacabuquito discharge gauge and below the Río Blanco and Río Juncal tributaries (Figure 1). Resguardo los Patos is located in the Putaendo sub-basin, in proximity to the Río Putaendo en Resguardo los Patos gauge (Figure 1). We used average precipitation between Riecillos and Resguardo los Patos to estimate alpine precipitation within the Aconcagua Basin.

Because Chile has relatively sparse and discontinuous temperature records in the Aconcagua Basin, we used a single temperature station at Vilcuya, located above the Río Aconcagua en Chacabuquito discharge gauge and just below where Río Colorado joins Río Riecillos (Figure 1). Vilcuya has 97% complete monthly temperature data from 1965 to 2017. We used NOAA's Bivariate ENSO Time Series (BEST) Index (Smith & Sardeshmukh, 2000) to represent El Niño and La Niña conditions on an annual and seasonal basis from 1965 to 2017.

Analysis of climate drivers of discharge

We calculated correlations between detrended discharge, precipitation, temperature, and ENSO time series to determine the climate variables related to growing season water availability. Specifically, we removed the linear trend from each time series and correlated growing season (DJF) discharge with DJF, MAM, JJA, SON, and annual time series of precipitation, temperature, and ENSO, for the period 1965–2017. Initial analyses indicated that DJF discharge was closely associated with JJA precipitation, so we also correlated DJF, MAM, JJA, SON, and annual time series of temperature and ENSO with JJA precipitation to explore potential drivers of JJA precipitation. Further, we determined long-term trends for O-M discharge, JJA precipitation, and annual temperature. As with snow cover frequency and glacier area trends, we used a Theil–Sen robust linear regression (Sen, 1968; Theil, 1950) and the Mann–Kendall significance test (Kendall, 1948; Mann, 1945).

To evaluate whether there have been changes in the seasonality of meltwater, we calculated the centroid of timing (CT; Cortés et al., 2011; Stewart et al., 2005), which represents the timing of peak discharge in each year based on daily mean discharge values (Equation 1):

$$CT = \frac{\sum_{i=1}^{12} Q_i t_i}{\sum_{i=1}^{12} Q_i} \quad (1)$$

where Q_i is the daily mean discharge value and t_i is the number of months since the start of the water year, which in Chile begins on April 1st. We then used the time series of CT values to explore trends and correlations of discharge timing with seasonal precipitation, temperature, or ENSO events.

Finally, we compared our calculated contemporary irrigation water consumption to measured discharge in the Aconcagua Basin to evaluate the sustainability of irrigated croplands. Disparities in water supply and demand were of particular interest given the expected decrease in precipitation over the next century in this region (Boisier et al., 2016; Christensen & Hewitson, 2007). We scaled our estimates of discharge available for agricultural irrigation by the proportion of irrigation sourced from surface water and the relative water demands of agriculture compared to other consumptive uses. The Food and Agriculture Organization of the United Nations (FAO) estimates that regionally, 74% of agriculture is equipped for irrigation with surface water (FAO, 2000) and agriculture makes up 78% of Chilean consumptive water usage (McPhee et al., 2012). We determined the difference between the 1950–2017 discharge time series and our estimate of agricultural water consumption. We then calculated the probability of water scarcity for the lowest, median, and highest discharge years.

Results

Aconcagua Basin climate and discharge drivers

Averaged across the Aconcagua Basin for 1965–2017, precipitation disproportionately occurs outside the growing season. With a Mediterranean climate of wet, cool winters and dry, hot summers, 64% of annual precipitation in the basin falls during the winter months of JJA (244.7 mm ± 154.2), while only 2% of annual precipitation occurs during the summer months of DJF (Figure 3(a)). The two stations used to assess precipitation, Riecillos and Resguardo los Patos (Figure 1), both exhibit the same strong seasonal variation. However, Riecillos, located at a higher altitude and farther south, experiences 17.7 mm/month more precipitation on average than Resguardo los Patos. This difference

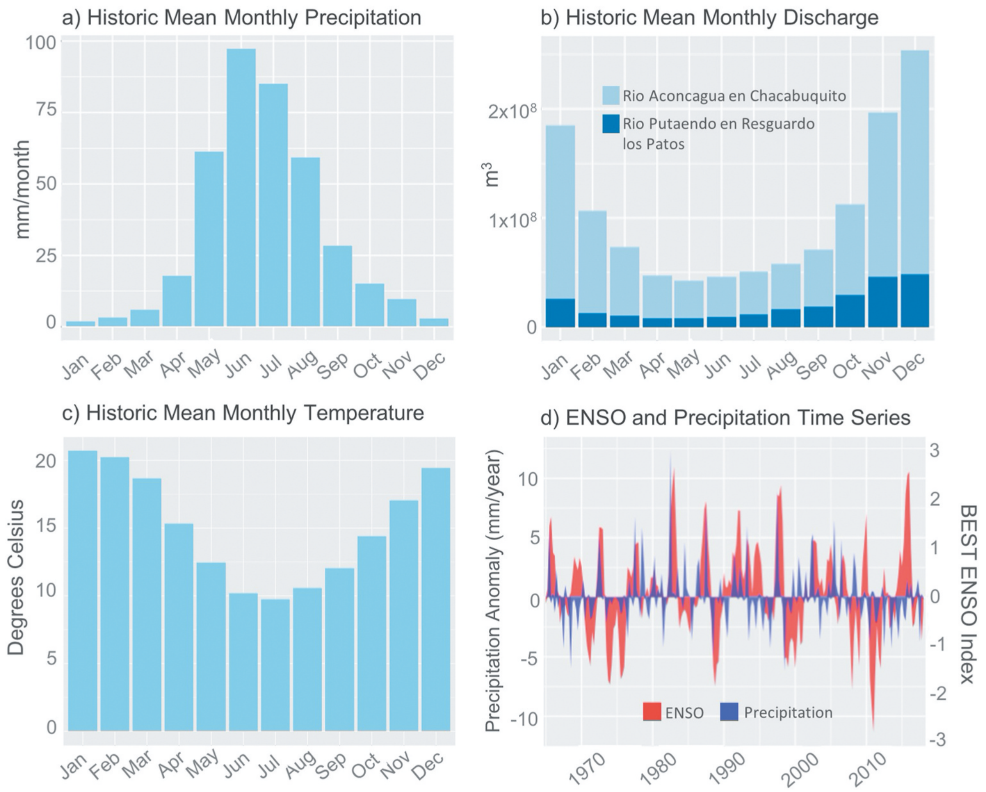

Figure 3. Seasonal cycles of (a) precipitation, (b) discharge, and (c) temperature, and (d) time series of ENSO and precipitation, in the Aconcagua Basin for 1965–2017.

is amplified during the winter months when Riecillos receives almost twice as much precipitation (102.1 mm/month) as Resguardo los Patos (62.1 mm/month).

Monthly mean discharge is greatest during the October through March growing season (1.5 x 10^8 m^3/month; Figure 3(b)), accounting for a disproportionate 75% of annual discharge. Monthly mean temperatures fluctuate 11.0°C seasonally, from a low of 9.7°C in July to a high of 20.7°C in January (Figure 3(c)). Thus, precipitation that falls as snow during the cold wet season melts out during the warm dry season (Figure 3(b,c)). Río Aconcagua en Chacabuquito (Figure 3(b), light blue) contributes the majority of the O-M discharge available for downstream use by agriculture (82%), whereas Río Putaendo en Resguardo los Patos (Figure 3(b), dark blue) contributes significantly less (18%).

Analyses of the climate and hydrologic data reveal several seasonal relationships. Cold season (JJA) precipitation is strongly and positively correlated with the subsequent warm season (O-M) runoff (R^2 = 0.93, $\alpha < 0.001$; Table 1) for 1965–2017. ENSO also has a strong influence on summer runoff with JJA ENSO accounting for 49% of the variation in the following O-M discharge and DJF ENSO accounting for 46% of O-M discharge. However, ENSO and precipitation in the Aconcagua Basin are themselves correlated (Montecinos & Aceituno, 2003; Pellicciotti et al., 2007; Waylen & Caviedes, 1990). SON (late winter/early spring) precipitation also modulates warm season runoff, explaining

47% of O-M discharge. Again, enhanced SON precipitation correlates with ENSO and other large-scale atmospheric patterns that would also produce increased JJA precipitation. There are also positive, though weaker, correlations between O-M discharge and MAM precipitation, O-M temperature, and SON temperature (Table 1). Cryosphere variability is strongly linked to warm season runoff, with O-M discharge significantly correlated with snow cover frequency ($R^2 = 0.93$, $\alpha < 0.001$) for 2000–2017. Off-season temperatures have little influence on summer runoff: O-M discharge is not significantly correlated with DJF temperature, MAM temperature, or JJA temperature. O-M temperature is significantly correlated with O-M discharge, but the correlations are much weaker than precipitation, snow cover, and ENSO correlations (Table 1). Summer runoff is also insensitive to seasonal variations in the very small contribution of summer (DJF) precipitation, and the influence of SON ENSO.

Given the strong correlation between O-M discharge and JJA precipitation, we further analyzed potential drivers of JJA precipitation. Not surprisingly, cold season precipitation is linked to snow cover frequency (2000–2017) and glacier area (8 years 1989–2015), DJF and JJA ENSO (1965–2017), and to a lesser extent, annual ENSO (1965–2017; Table 2). Figure 3(d) shows the 3-month composite time series for both ENSO and precipitation. Some, but not all, precipitation anomalies are associated with ENSO warm or cool phases, likely reflecting the atmospheric response to seasonal sea surface temperature anomalies.

We find that the timing of peak runoff covaries as a function of total wintertime precipitation, causing earlier melt-season runoff in years of low JJA precipitation and later runoff in years of high JJA precipitation (Table 3). Peak runoff is assessed using the

Table 1. Correlation of climate variables (2000–2017 for snow cover, 1965–2017 for all other variables) with O-M discharge in the Aconcagua Basin.

Climate Variable	R^2	P-Value	Direction of Correlation
JJA Precipitation	0.93	< 0.001	+
Snow Cover	0.93	< 0.001	+
JJA ENSO	0.49	< 0.001	+
SON Precipitation	0.47	< 0.001	+
DJF ENSO	0.46	0.001	+
MAM ENSO	0.40	0.004	-
MAM Precipitation	0.36	0.009	+
Annual ENSO	0.29	0.04	+
O-M Temperature	0.28	0.05	+
SON Temperature	0.24	0.08	+

Table 2. Correlation of climate variables with JJA precipitation (2000–2017 for snow cover, 1989–2015 for glacier area, 1965–2017 for all other variables) in the Aconcagua Basin.

Climate Variable	R^2	P-Value	Direction of Correlation
Snow Cover	0.86	< 0.001	+
Glacier Area	0.70	0.05	+
DJF ENSO	0.51	< 0.001	+
JJA ENSO	0.47	< 0.001	+
Annual ENSO	0.30	0.03	+
MAM ENSO	0.24	0.08	+
O-M Temperature	0.24	0.09	+

Table 3. Correlation of climate variables with centroid of timing (2000–2017 for snow cover, 1965–2017 for all other variables) in the Aconcagua Basin.

Climate Variable	R^2	P-Value	Direction of Correlation
JJA Precipitation	0.64	< 0.001	+
JJA ENSO	0.50	< 0.001	+
DJF ENSO	0.46	< 0.001	+
SON Precipitation	0.44	0.001	+
Snow Cover	0.42	0.09	+
Annual ENSO	0.35	0.01	-
MAM ENSO	0.25	0.07	-

average CT value, which between 1965 and 2017 was 8.2, corresponding to an average peak discharge occurring on November 6. CT is most strongly correlated with JJA precipitation (R^2 = 0.64, $p < 0.001$), JJA ENSO (R^2 = 0.50, $p < 0.001$), DJF ENSO (R^2 = 0.46, $p < 0.001$), and SON precipitation (R^2 = 0.44, $p = 0.01$). As noted above, there are correlations between ENSO and precipitation.

Climate trends

O-M discharge between 1950 and 2017 has no statistically significant trend (Figure 4(a)). However, there have been highly negative O-M discharge anomalies since 2010. Similarly, JJA precipitation between 1950 and 2017 has no statistically significant trend, although it declines starting in 2010 (Figure 4(b)). From 1965 to 2017, annual temperature increased by 0.23°C per decade ($\alpha < 0.001$; Figure 4(c)) while JJA temperature increased at a rate of 0.24°C per decade ($\alpha = 0.009$; Figure 4(d)). The timing of peak discharge (CT) has no discernable trend (not shown) despite positive trends in temperature (Figure 4).

Representative average winter snow cover and summer glacial area from Landsat are shown in Figure 5. Annual snow cover frequency between 2000 and 2017 has an average value of 13.3%. Between 2000 and 2017 snow cover frequency decreased a total of 4.5% or 2.7% per decade ($\alpha = 0.03$; Figure 4(e)), although we caveat that this trend is observed over a short, 17-year time period and could be the result of decadal variability. The lowest values of snow cover frequency from 2000 to 2017 were recorded in 2010 and 2014.

Glacier area averaged 32.8 km^2 during our study period, covering less than 1% of the basin. Based on our calculated glacier area, we estimate that the Aconcagua Basin glaciers contained 0.73 km^3 of water, on average, over the 1989–2015 period. We find no significant trend in glacier area for 1989–2015, but note that for the most recent year examined (2015) the estimate of water contained in basin glaciers is 0.55 km^3.

Agricultural water demands and scarcity in the Aconcagua Basin

Within the Aconcagua Basin, 557 km^2, or 7.6% of the total area, is dedicated to agricultural cultivation. More than 90% of croplands are concentrated in the two westernmost sub-basins, the Lower and Putaendo sub-basins, with grapes primarily grown in the Putaendo sub-basin and avocados primarily grown in the Lower sub-basin (Figure 6).

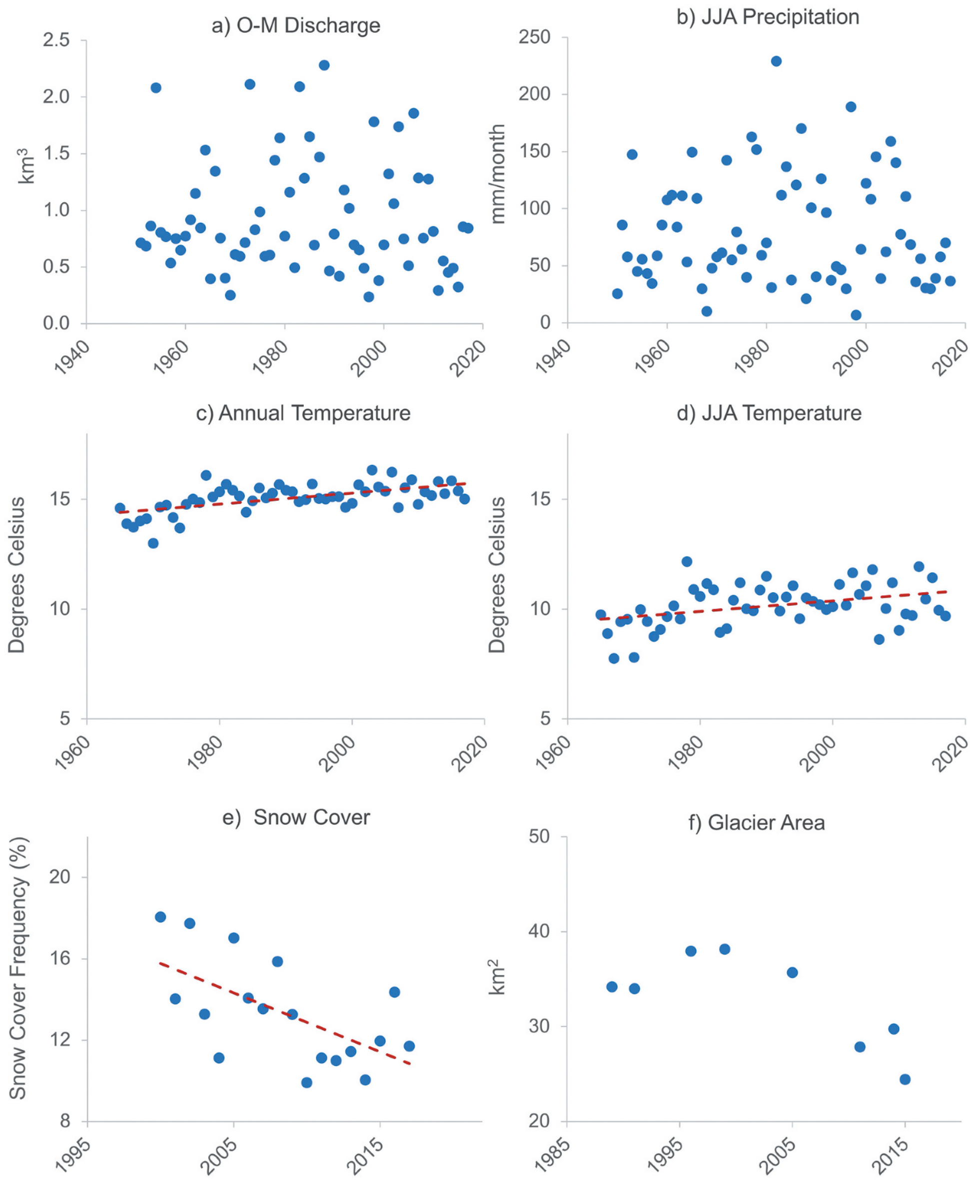

Figure 4. Time series of (a) JJA precipitation, (b) O-M discharge, (c) annual temperature, (d) JJA temperature, (e) snow cover frequency, and (f) glacier area in the Aconcagua Basin. Glacier area time series are the minimum value for three-year periods and plotted in the occurrence year. Red lines denote linear trends.

Based on the 2007 Chilean agriculture census and water demands of individual crop species, agricultural practices in the Aconcagua Basin require 7.10×10^8 m^3 water annually (Table 4), of which surface water supplies 74%, or 5.25×10^8 m^3. Fruit constitutes 70.7% of irrigated crops, followed by vegetables (14.6%), irrigated pasture (9.8%), cereals (2.4%), and legumes (2.2%). Alfalfa requires the most water per unit area (30,299 m^3/ha), more than double the water demands per unit area of grapes or avocado,

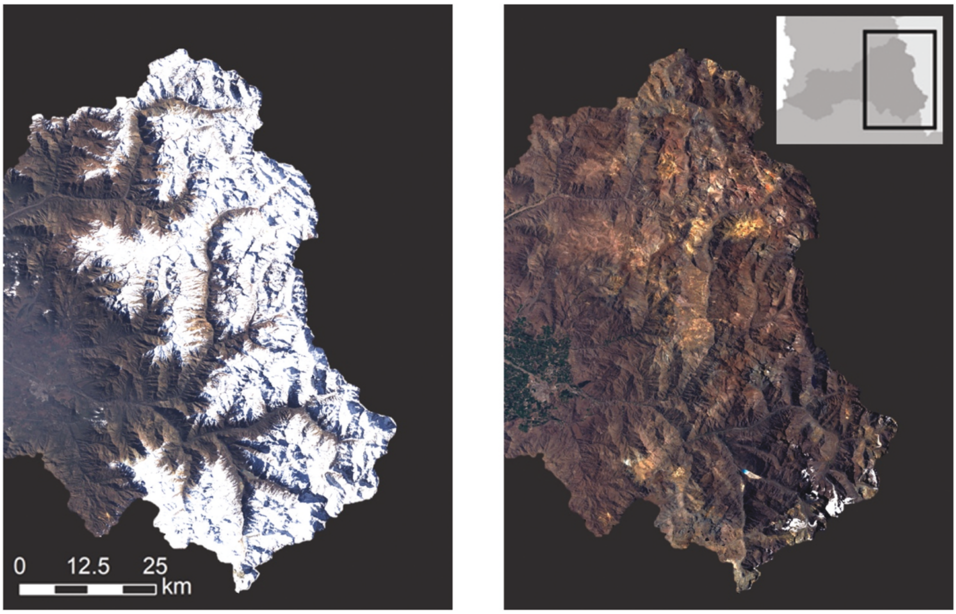

Figure 5. Representative wintertime snow cover in 2003 (left) compared to representative summertime glacier area in 2014 (right).

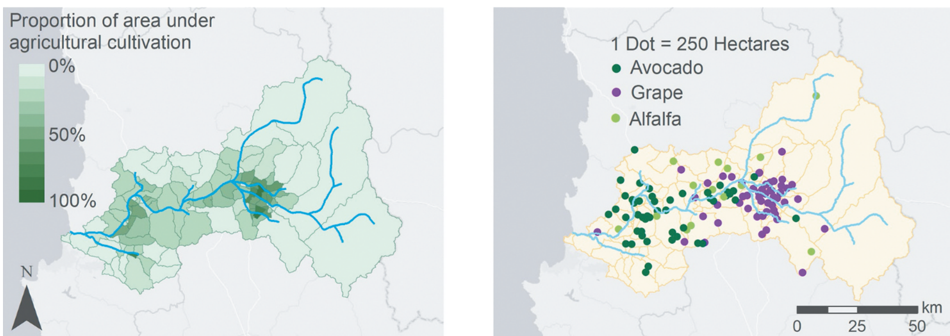

Figure 6. Distribution of agriculture across the Aconcagua Basin by percentage of cultivated area per agricultural community (left) and number of hectares in production for the top three crops by percentage area (right).

and accounts for 23.3% of total annual agricultural water consumption, followed by avocados (19.9%) and grapes (17.5%; Table 4).

Water scarcity in the Aconcagua Basin

Given the lack of trends in discharge and the relatively short time series available of snow cover frequency and glacier area, we rely on current agricultural surface water demand (5.25 x 10^8 m^3) and observations of discharge from 1950 to 2017 multiplied by the fraction of consumptive agricultural water use (0.78) to analyze the likelihood of contemporary

Table 4. Cultivated area and water demand for the most prevalent crop types in the Aconcagua Basin.

	Grape	Avocado	Alfalfa	Peach	Walnut	Orange	Tomato	Artichoke	Potato	Lemon	Other
Crop Area (ha)	14,112	13,021	5,461	3,972	2,451	1,174	1,114	1,097	1,072	1,045	11,255
Crop Area (%)	25.3%	23.3%	9.8%	7.1%	4.4%	2.1%	2.0%	2.0%	1.9%	1.9%	20.2%
Water Requirement (m^3/ha/year)	8,788	10,860	30,299	12,918	14,757	6,889	12,358	14,856	4,775	6,854	12,546
Total Water Demand (m^3/year)	1.24×10^8	1.41×10^8	1.65×10^8	5.13×10^7	3.62×10^7	8.08×10^6	1.38×10^7	1.63×10^7	5.12×10^6	7.16×10^6	1.41×10^8
Total Water Demand (%)	17.5%	19.9%	23.3%	7.2%	5.1%	1.1%	2.0%	2.3%	0.7%	1.0%	19.9%

water scarcity in the Aconcagua Basin (Figure 4(b)). We define a water-scarce year as one where agricultural water demand exceeds discharge. Using contemporary water demand, 34% of years 1950–2017 would have been water-scarce, with a notable water surplus period in 2000–2010, and a water deficit period in 2010–2015 corresponding with the Chilean megadrought (Figure 7; Boisier et al., 2016; Garreaud et al., 2017). We find that the percentage of high (top third), middle (middle third), and low (bottom third) discharge years with water scarcity is 0%, 2%, and 100%, respectively (Table 5). Expressed in percentage of agricultural water demand, the average surplus for the high and median discharge years is 126% and 15%, while the low discharge years have a deficit of 29%.

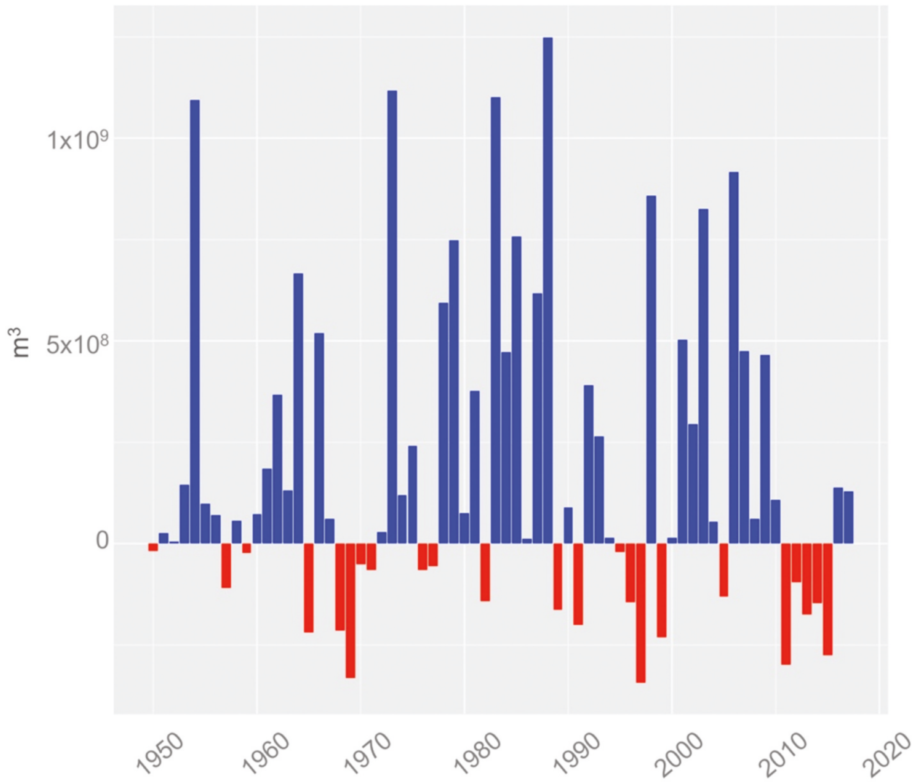

Figure 7. Time series of differences between historical discharge and current calculated agricultural surface water demand (5.25 x 10^8 m^3) for the Aconcagua Basin. Water surplus and scarcity are denoted in blue and red, respectively.

Table 5. Percentage of years experiencing water scarcity and the average surplus or deficit for the highest, median, and lowest Aconcagua Basin discharge years.

Aconcagua Discharge	Water-Scarce Years *(%)*	Average Surplus/Deficit *(m^3)*
Top 1/3 years	0	6.59 x 10^8
Middle 1/3 years	2	8.13 x 10^7
Bottom 1/3 years	100	−1.52 x 10^8
Total	34	1.96 x 10^8

Discussion

Aconcagua Basin climate and discharge drivers

Our results support the overwhelming importance of snow cover to Aconcagua Basin growing season discharge. Aconcagua Basin water resources are stored in seasonal snow cover, glaciers, and permafrost. While glaciers and permafrost tend to serve as long-term (annual to millennial scale) storage for water (Jones et al., 2019), seasonal snow cover contains by far the greatest volume of readily available water (Janke et al., 2017). O-M discharge is significantly correlated with snow cover but not with glacier area. We calculated that in 2015, glaciers in the Aconcagua Basin contained 5.5×10^8 m^3 of water, which translates to less than 1 year of O-M discharge. We caveat that our estimate of glacial water storage does not account for water resources stored in rock and debris-covered glaciers. While these water resources have been estimated to comprise 67% of water stored in glacier landforms in the Aconcagua Basin (Janke et al., 2017), the current hydrological contributions of rock and debris-covered glaciers to the active water budget are minimal (Duguay et al., 2015; Jones et al., 2019). Moreover, even if the water stored in glaciers is four times greater than our estimate, snow cover still dominates.

We find that O-M discharge is most closely related to JJA precipitation. JJA Precipitation critically influences the snow cover that is established in the winter months and melts out during the summer. Our relationships are consistent with Pellicciotti et al. (2007), who noted positive correlations between ENSO and discharge, and ENSO and precipitation. We also find significant correlations between JJA precipitation and both both DJF ENSO (R^2 = 0.51 $\alpha < 0.001$) and JJA ENSO (R^2 = 0.47, $\alpha < 0.001$). The link between ENSO and JJA precipitation in the Aconcagua Basin is further supported by Masiokas et al. (2006), who found that snow cover is primarily driven by ENSO and tropospheric conditions.

We focus our analysis on observations, which reveal correlations but limit our assessment of the processes driving and changing discharge within the Aconcagua Basin. Potential future work includes the deployment of a hydrologic model inclusive of robust snow and glacier representations, which could help explain these processes and better assess the impact of climate change on water fluxes in the Aconcagua Basin. Additional future work includes the use of remote sensing methods (e.g. passive and active microwave systems) to estimate snow water equivalent and better understand snow cover contributions to stream flow (Durand et al., 2008; Tedesco et al., 2014).

Aconcagua Basin trends

We find the Aconcagua Basin is warming by 0.23°C per decade from 1965 to 2017, a rate slightly faster than the global increase of 0.20°C per decade reported by the IPCC (Allen et al., 2018). Increased temperatures are expected to decrease the amount of precipitation that falls as snow, which would deplete the water stored in snow essential to summer discharge and change the timing of snow and glacier melt (Masiokas et al., 2006). Despite this expectation, we find that the timing of peak discharge (CT) has no discernible trend.

Our results contain no statistically significant trends in JJA precipitation or O-M discharge, consistent with Pellicciotti et al. (2007). However, both precipitation and discharge have decreased in the past 25 years, coinciding with major drought events that occurred in 1996–1997, 2002, 2008, and 2010–2015 (Boisier et al., 2016; Clarvis & Allan, 2014; Garreaud et al., 2017). The 2010–2015 megadrought, in particular, stands out for its longevity and magnitude. This drought is the warmest – annual temperature 0.31°C above the 1965–2017 average – and driest – JJA precipitation 38.5 mm/month below the 1950–2017 average and O-M discharge 4.4 × 10^8 m^3 below the 1950–2017 average – 6-year period on record in Central Chile, and is partially attributed to anthropogenic climate change (Garreaud et al., 2017).

Masiokas et al. (2006) found a positive, though insignificant, trend in snow cover over Central Chile from 1951 to 2005 using a different methodology of interpolating discrete measurements of snow water equivalent (SWE). This is in contrast to the negative trend we found from 2000 to 2017, though we reiterate that the record we evaluate is short and could be strongly influenced by decadal variability. Prior glacier inventories in the Aconcagua Basin have reported a wide range of areal extents. Janke et al. (2017) used high-resolution 2009–2011 remotely sensed imagery to identify 61 glaciers occupying a total area of 39.9 km^2, 12 km^2 greater than the average 27.9 km^2 found by this study in 2011. Previous work has provided evidence for decreasing glacier area. Using aerial photographs taken in 1955 and 1956, Valdivia (1984) completed one of the first inventories of glaciers in the Aconcagua Basin and determined a glaciated area of 151.3 km^2. A follow-up glacier inventory using 2003 ASTER 15 m imagery estimated the glacier area to be 121.2 km^2, indicating a negative trend of 6.3 km^2 per decade, or a 20% decrease in the 48 years since the initial survey (Bown et al., 2008). We find no significant decrease in glacier area, but note that the observed record of glacier area (8 days 1989–2015) is short and sparse in part due to persistent snow cover.

Agricultural water demands and scarcity in the Aconcagua Basin

Over the past two decades, record droughts and increased climate variability have placed added strain on Chile's water resources (Bown et al., 2008; Janke et al., 2017; Martínez et al., 2012; Pellicciotti et al., 2007; Waylen & Caviedes, 1990). The 2010–2015 megadrought in Central Chile, in particular, included 25–45% deficits in rainfall that led to diminished snowpack and up to 90% declines in river flow and groundwater levels (Garreaud et al., 2017).

Our results indicate that the Aconcagua Basin could experience water scarcity in 34% of years moving forward if agricultural water demand remains constant and future discharge is similar to historical. We note that our analysis of water scarcity is simplistic, neglecting the full complexity of water sourcing (surface water versus groundwater), other water uses within the basin, environmental flows, and the spatial and temporal distributions of discharge. However, our analysis is also likely a conservative estimate of future water scarcity in the Aconcagua Basin, as there are several other factors that will presumably amplify water scarcity. The Chilean Ministry of Agriculture has set ambitious goals to increase the national land area under cultivation by 57% between 2011 and 2022 (Valdés-Pineda et al., 2014). Assuming the current water requirements and proportions of crop types in the basin, a 57% increase in the land area under cultivation would require an estimated additional 4.05 × 10^8 m^3 (surface and subsurface) of water annually. Furthermore, water demand from agriculture and other sectors will likely increase in future years due to the growing Chilean population, which increased by 59% between 1980 and 2016 (World Bank, 2016).

Climate change is also likely to amplify future water scarcity in the Aconcagua Basin. While there is substantial disagreement among the CGCM projections of 2081–2100 winter precipitation in the Aconcagua Basin, changes in temperature are robust (Collins et al., 2013). Annual temperature in the Aconcagua Basin has increased by 1.2°C between 1965 and 2017 and is expected to increase another 1–3°C by 2081–2100 (Collins et al., 2013). While JJA and O-M temperature are not highly correlated with JJA precipitation or O-M discharge, higher temperatures are expected to decrease the proportion of precipitation falling as snow, diminish glaciers, change the timing of snowmelt, and alter evapotranspiration (Valdés-Pineda et al., 2014; Fisher et al., 2017; Masiokas et al., 2006), all of which would have major implications for agricultural water resources.

In addition to changes in precipitation and temperature, climate change is expected to increase the frequency of extreme ENSO events, potentially driven by enhanced surface warming in the equatorial Pacific Ocean (Cai et al., 2014). More extreme ENSO events would amplify the climate variability in the Aconcagua Basin, making it more difficult to sustain agricultural practices. Greater occurrence and intensity of El Niño events associated with warm and wet conditions would bring excess precipitation to the basin resulting in flooding, while higher frequency and amplitude La Niña events would reduce rainfall causing more intense and elongated droughts in the Aconcagua Basin (Masiokas et al., 2006).

Conclusions

Examining the relationship between climate trends and mountain water resources essential to irrigated agricultural productivity is an important step toward sustainable water resource management in the Aconcagua Basin.We find recent decreases in snow cover, which is the primary driver of river discharge during the summer growing season, as well as increases in temperature. Water scarcity already occurs during an estimated 34% of years when low winter precipitation and snow cover reduce discharge. Combined with growing water demand, a continuation of observed declines in snow cover is likely to have a significant impact on future water security and agricultural productivity in the Aconcagua River Basin, and could also have broader socioeconomic impacts in Chile..

Disclosure statement

No potential conflict of interest was reported by the authors.

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