



# Projected hydroclimate changes over Andean basins in central Chile from downscaled CMIP5 models under the low and high emission scenarios

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**Abstract** This study examines the projections of hydroclimatic regimes and extremes over Andean basins in central Chile ( $\sim 30\text{--}40^\circ$  S) under a low and high emission scenarios (RCP2.6 and RCP8.5, respectively). A gridded daily precipitation and temperature dataset based on observations is used to drive and validate the VIC macro-scale hydrological model in the region of interest. Historical and future simulations from 19 climate models participating in CMIP5 have been adjusted with the observational dataset and then used to make hydrological projections. By the end of the century, there is a large difference between the scenarios, with projected warming of  $\sim +1.2^\circ\text{C}$  (RCP2.6),  $\sim +3.5^\circ\text{C}$  (RCP8.5) and drying of  $\sim -3\%$  (RCP2.6),  $\sim -30\%$  (RCP8.5). Following the strong drying and warming projected in this region under the RCP8.5 scenario, the VIC model simulates decreases in annual runoff of about 40% by the end of the century. Such strong regional effect of climate change may have large implications for the water resources of this region. Even under the low emission scenario, the Andes snowpack is projected to decrease by 35–45% by mid-century. In more snowmelt-dominated areas, the projected hydrological changes under RCP8.5 go together with more loss in the snowpack (75–85%) and a temporal shift in the center timing of runoff to earlier dates (up to 5 weeks by the end of the century). The

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severity and frequency of extreme hydroclimatic events are also projected to increase in the future. The occurrence of extended droughts, such as the recently experienced megadrought (2010–2015), increases from one to up to five events per 100 years under RCP8.5. Concurrently, probability density function of 3-day peak runoff indicates an increase in the frequency of flood events. The estimated return periods of 3-day peak runoff events depict more drastic changes and increase in the flood risk as higher recurrence intervals are considered by mid-century under RCP2.6 and RCP8.5, and by the end of the century under RCP8.5.

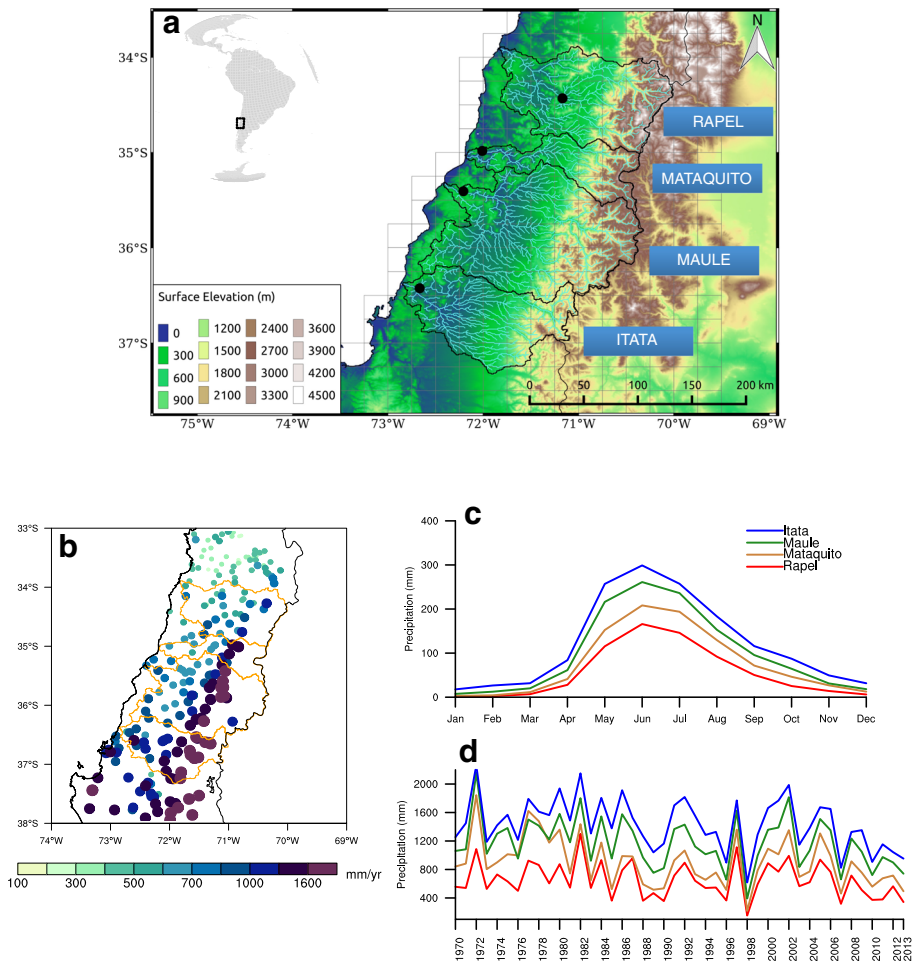
## 1 Introduction

Central Chile (hereafter CC), a narrow strip of land between the subtropical southeast Pacific and the Andes cordillera (30°–38° S, Fig. 1a), is the heartland of Chile with most of the country's population (around 15 million) and economic activities. The region harbors more than 75% of the country's total irrigated agriculture and the majority of the water reservoirs. Moreover, the winter Andes snowpack within the region provides a wide variety of socioeconomic and environmental benefits, notably the freshwater supply for human consumption, irrigation, and hydropower production (Masiokas et al. 2006).

CC features a semi-arid Mediterranean climate and its inhabitants are very much dependent on the 200–1000 mm or so of annual rainfall (Ruttlant and Fuenzalida 1991). The region has been facing a rainfall decline during the last decades and a persistent drought has recently (2010–2015) parched CC with a precipitation deficit of approximately 30% (CR2 2015; Boisier et al. 2016). Falvey and Garreaud (2009) highlighted that there is a clear warming trend in the Andes cordillera of CC for the period 1979–2006. As temperature-related effects are expected to yield changes in snow cover and seasonality of runoff over snowmelt dominated basins (e.g., Stewart et al. 2005; Adam et al. 2009), the observed temperature trend also plays a key role in determining regional hydroclimate variability in CC. Cortés et al. (2011) stated that a negative center time trend (i.e., shifting towards earlier dates) was detected for rivers south of 33° S in the western Andes. On the other hand, the same study highlighted that there has been no significant change in center time for high-elevated basins (between 30° S and 33° S), despite documented warming trends at high elevation sites.

Very likely, CC is being greatly affected by the anthropogenic climate drift, in a similar fashion in other Mediterranean climate-type regions such as California, western Australia, southern France, Spain, Greece, and Turkey (e.g., Giorgi and Lionello 2008; Hannah et al. 2013; Onol et al. 2014). Indeed, the last report of the Intergovernmental Panel on Climate Change (IPCC 2014) based on an ensemble of Global Climate Models (GCMs) shows that the observed decreasing trend in precipitation and increasing trend in surface air temperature over the central Andes of Chile are projected to continue into the twenty-first century.

Although GCMs are commonly used for large-scale climate change impacts studies and their data are easily accessible for a wide variety of usage, they provide limited information about climate change impacts on hydroclimatology and water resources at basin scales, especially over complex terrains such as in CC (e.g., Hansen et al. 2006). The construction and analysis of high-resolution meteorological information, as well as the application of hydrological models, are common tools to do a proper regional-scale hydroclimatic assessment (e.g., Vicuña et al. 2011; Demaria et al. 2013b). One common method to overcome the difficulties arising from the usage of coarse resolution GCMs is to downscale the GCM



**Fig. 1** **a** Central Chile basins on a digital elevation map derived from global hydrological data and maps based on shuttle elevation derivatives at multiple scales (HydroSHEDS) (Lehner et al. 2008). Grid boxes correspond to  $0.25 \times 0.25$  degree resolution VIC grids. Circles indicate the location of the four stream gauges used in VIC model runoff comparison. Also shown are **b** 1970–2013 mean annual observed precipitation (mm/yr), **c** mean annual cycle of precipitation (mm), and **d** interannual variation precipitation for each basin

fields to high-resolution grids by using statistical bias correction techniques based on a gridded observational dataset (e.g., Piani et al. 2010).

An observation-based gridded ( $0.25^\circ \times 0.25^\circ$ ) dataset of precipitation and temperature (1948–2008) was recently produced for CC (Demaria et al. 2013a). To evaluate their dataset, (Demaria et al. 2013a) used the Variable Infiltration Capacity hydrological model (VIC) and contrasted simulated streamflows against observations. Demaria et al. (2013b) then used the validated VIC model to assess the climate change impacts on the hydrology of the Mataquito basin in CC based on 12 CMIP3 and CMIP5 GCM outputs. They highlighted that a drier

and warmer future will shift the snow line upward (from 2000 m to 2700 m) and reduce the number of days with precipitation.

Given the general lack of assessments of future hydroclimate changes in CC, the main goal of this study is to make use of the VIC model capabilities to get future basin-wide projections in key hydroclimatic variables. The present study builds on Demaria et al. (2013b) and extends the hydroclimatological assessment to four basins in CC: Rapel, Mataquito, Maule, and Itata with the use of 19 GCM outputs under two emission scenarios: high-mitigation, Paris Agreement compatible (RCP2.6), and business-as-usual (RCP8.5). This extension allows contrasting the changes in hydroclimatic regimes and extremes in basins with different characteristics (e.g., snowmelt-dominated and rainfed) as well as the comparison of the different emission scenarios. Our approach makes use of the observational meteorological dataset of Demaria et al. (2013a) as a reference to downscale and bias correct 19 GCM outputs from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al. 2012) (see Table S1).

In Section 2, we describe study area and data. In Section 3, we provide bias correction method and hydrologic model description as well as model validation. Section 4 presents the projected hydroclimate changes. We summarize and discuss the results in Section 5 and Section 6, respectively.

## 2 Study area and data

The region of interest is located on the western slope of the Andes Cordillera in CC (33–38° S, see Fig. 1a) and includes four main basins namely (from north to south) Rapel, Mataquito, Maule, and Itata. These basins are characterized by a sharp increase in west-east topographic gradient varying between sea level and up to 4000 m for Rapel, and 2500–3000 m for the other basins. The Maule basin has the largest river system, with a drainage area covering approximately 21100 km<sup>2</sup>. Rapel, Mataquito, and Itata basins drain an area of approximately 13700, 6300, and 11500 km<sup>2</sup>, respectively. These four basins, holding a major fraction of Chile's population, provide water for consumption and irrigation and, therefore, play a key role in the country's socioeconomic activities. Rapel and Maule watershed feed also one of the largest hydropower plants in CC. The study area is characterized by mosaic croplands/vegetation land cover type in the central parts and sparse vegetation and Andean shrubland in the mountainous parts of the basins (Fig. S1a). The central valley and mountainous region is separated by a forested area including mixed deciduous and evergreen forests. Soils are mostly grouped in chromic luvisols in the central valley and lithosols and andosols along the cordillera (Fig. S1b).

In CC, a marked precipitation gradient increasing from north to south follows the relative influences of the South Pacific Subtropical dry regime and the wet climate prevailing at mid-latitudes (e.g., Falvey and Garreaud 2009; Falvey and Garreaud 2007). Most of annual precipitation accumulates during austral winter (JJA), when the mid-latitude frontal systems reach CC, whereas a large interannual precipitation variability in the region is partially controlled by El Niño-Southern Oscillation (ENSO) (Ruttlant and Fuenzalida 1991; Falvey and Garreaud 2009).

An observation-based gridded (0.25° × 0.25°) dataset of daily precipitation, maximum and minimum temperatures developed by Demaria et al. (2013a) is used as a reference to downscale 19 GCM outputs via the bias correction technique based on Piani et al. (2010).

In order to validate the hydrologic model, we have considered local streamflow records (Fig. 1a) from four stations maintained by Chilean Water Agency (Dirección General de

Aguas, DGA). The river discharge data are used to characterize the hydrology of the basins assessed. This data is compared with the simulated runoff integrated over the corresponding watershed. Therefore, the four stations adopted were chosen following their location (near the outlet of the corresponding watershed) but also based on the record length. The stations used to evaluate the Mataquito, Maule, and Itata basins indeed account for the whole catchment area. In contrast, due to a lack of long-term streamflow data at the outlet point of Rapel river, one of the sub-catchment outlet gauges is used in this basin (Fig. 1a). Monthly discharge data obtained from the stream gauges have been converted to an equivalent monthly unit runoff from the catchment area. In addition, daily discharge data obtained from the Mataquito, Maule, and Itata basins are used to evaluate simulated runoff in these basins.

Rain-gauge information from the Chilean National Weather Service (Dirección Meteorología de Chile) is also used to illustrate the precipitation variability in the region (see Fig. 1b). A quality control and gap-filling procedures were applied to monthly station data (see Boisier et al. 2016). For the hydrologic model validation, we have used also MODIS/TERRA snow cover data with a spatial resolution of 0.05° (Hall et al. 2006). Furthermore, given the difficulty of obtaining accurate evapotranspiration measurement, we have used GLEAM v3.0 (Martens et al. 2016) evapotranspiration product as a reference to evaluate the simulated evapotranspiration.

Rain-gauge data shows that the annual accumulation of precipitation is about 300–500 mm, increasing to up to 1500 mm in the southern part of CC and in the western slope of the Andes range (Fig. 1b). The annual cycle in each basin is characterized by very little summer precipitation (Fig. 1c). Figure 1d shows the basin averaged time-series of annual precipitation illustrating the above mentioned interannual variability and a long-term dry trend. The persistent dry period between 2010 and 2015 has been termed mega-drought because of its spatial and temporal extension (CR2 2015; Boisier et al. 2016). In terms of snow extension, MODIS/TERRA snow cover (Hall et al. 2006) areal fraction (2001–2005 period) in each basin indicates that the Maule basin has the highest snow coverage fraction (~ 31%) while Itata basin, with the lowest snow coverage fraction (~ 18%) during JJA, is a more rainfall-dominated basin (see Fig. S3a).

### 3 Bias correction, hydrologic model description, and validation

#### 3.1 Bias correction

The use of large ensembles of climate simulations has the advantage of providing an uncertainty range for the chosen emission scenario and hence, more robust information of climate change. However, because of the coarse spatial resolution of the GCMs, we downscaled the climate variables first.

Daily precipitation has been downscaled to a rectangular 0.25° grid by using the statistical bias correction technique based on Piani et al. (2010). A transfer function is obtained by fitting (polynomial fit) the curve of sorted observed time series by intensity versus the modeled one. This method imposes the observed intensity distribution onto the modeled variable. The fitting is done by season. In a first step, the model data were interpolated to the 0.25° grid of the observation-based dataset. Then, at each grid point, an empirical transfer function for precipitation has been computed by fitting the curve of the sorted observed versus sorted modeled daily distribution by season.

Figure S2 shows the mean (1986–2005) annual precipitation derived from the observation-based dataset (Fig. S2a), from CMIP5 models (Fig. S2b) and from the bias

corrected data (Fig. S2c). The mean and the spatial pattern of precipitation in the  $0.25^\circ$  grids are well captured with the bias correction. The raw CMIP5 model mean climatology shows to some degree the north to south precipitation gradient, but misses the east-west gradient imposed by the topography, and therefore greatly underestimates the precipitation over the Andes. Other important biases in the modeled precipitation are also corrected, such as the underestimation of dry days and extreme rainfall, overestimation of drizzle and biases in the mean (Fig. S2d). We tested the procedure by obtaining the transfer function for the 1960–1980 period (calibration period), corrected the 1986–2005 period (validation period) with the transfer function, and compared those to observations. Satisfactory results of the validation procedure are apparent in all the aspects of the abovementioned modeled precipitation. We have then used the same transfer functions to bias correct the simulated precipitation over the 21<sup>st</sup> century.

A simpler approach was followed to adjust the temperature data. In this case, the model data was corrected considering the climatological biases of each month separately. That is, the temperature correction considers the mean, but not any other aspect of the distribution. Figure S2e, f show the distribution of the daily temperatures both from the observational dataset and the models. In particular, the simulation of extreme events such as days with temperatures above  $30^\circ\text{C}$  or below  $0^\circ\text{C}$  are partially improved. For example, considering only the summer temperatures, the CMIP5 overestimate days with temperatures above  $30^\circ\text{C}$  (12% compared with 5% in the models), with the correction this index decreases to 8% (not shown).

### 3.2 Hydrologic model description and validation

We make use of the VIC model capacities (Liang et al. 1994) to assess the hydrological impacts of projected climate change in four basins of CC. Details of the model description and setup are given in the supplementary materials (Text S1). A gridded dataset of daily precipitation, maximum and minimum temperature developed by Demaria et al. (2013a) has been used to drive the model and to make an evaluation (VIC-OBS, see Table S2). Then, the hydrologic model has been forced by the adjusted daily precipitation, maximum and minimum temperature time series from 19 GCMs, including an historical (1960–2005, VIC-CMIP5-HIST) and projected (2006–2099, VIC-CMIP5-RCP2.6 and VIC-CMIP5-RCP8.5) periods.

A more detailed model validation in the same basins assessed here was carried out by Demaria et al. (2013a), concluding that the VIC model can realistically capture the hydrological regimes albeit with some biases for high and low flows. We also performed a model validation based on statistics of monthly runoff anomalies for the period 1970–2005 (see Table S3), as well as by simulated and observation-based information of snow cover and evapotranspiration. Furthermore, we provide additional metrics that show the performance of the VIC model for extreme events. Details of this evaluation are given in the supplementary material (Table S4, Figs. S3, S4, and S5).

Based on the evaluation metrics provided in Table S3, the VIC model performance is very good in Itata basin, and adequate for Maule and Mataquito basins. Furthermore, evaluation metrics for daily flow in these basins show that the model gives close estimations of return periods of 3-day peak runoff (2, 10, 50, and 100 years) as well as of center timing with those in the observations (Table S4 and Fig. S5). A comparison of density function of 3-day peak runoff from the VIC model simulations with that in the stream gauges shows that the model tends to have more variance in Mataquito basin, whereas it reproduces similar variance to the observation in Maule and Itata basins (Fig. S5).

On the other hand, the model simulation for Rapel basin shows a poor performance. This can be associated with the catchment characteristics as it is characterized by a snowmelt dominated basin. Furthermore, sparse observation network prevents an extensive calibration process for this basin. Therefore, results presented for Rapel basin should be considered with caution, given that the weaknesses of the model are high for this basin.

Here, we show the interannual variability and mean annual cycle of observed flow together with the results obtained with VIC-OBS and VIC-CMIP5-HIST for each basin. The observed streamflow indicates a large interannual variability in Mataquito, Maule, and Itata (Fig. 2c, e, g). Following the rainfall variability, the streamflow tends to increase during El-Niño years and to decrease during La-Niña years. Overall, VIC-OBS captures the temporal variability as well as ENSO related interannual runoff variability reasonably well. Yet, it should be noted that VIC-OBS systematically underestimates low flows and overestimates peak flows in Mataquito and Maule basins (Fig. 2c, e).

Figure 2b, d, f, and h present the mean annual cycle of observed streamflow together with the integrated runoff obtained with VIC-OBS and VIC-CMIP5-HIST for each basin. The observed annual cycle indicates that the four basins are mainly rainfed with 50–70% of annual discharge occurring during austral winter (JJA). The VIC-OBS and VIC-CMIP5-HIST runs reproduce the mean annual cycle and give close estimates in Mataquito and Itata basins (Fig. 2d, h), whereas runoff is overestimated for the Maule basin in both VIC-OBS and VIC-CMIP5-HIST (Fig. 2f) in the wet season (May to September). Furthermore, a systematic underestimation of low flows during the dry season (October to April) is seen in Mataquito and Maule basins.

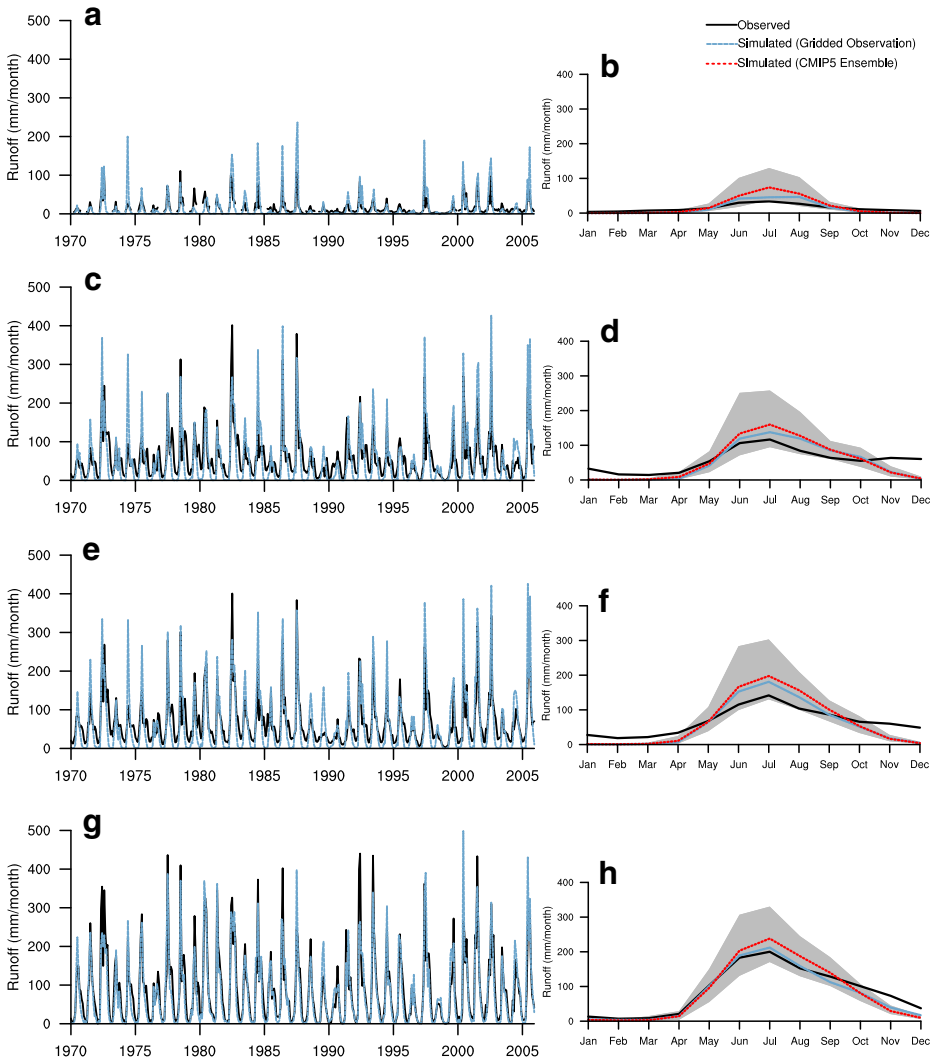
A lack of dry season snowmelt contribution to the flows can be considered a principal reason for the underestimation of low flows in these basins. Indeed, mean annual cycle of snow cover indicates a systematic underestimation in dry months with respect to MODIS/TERRA snow cover data (not shown). On the other hand, overestimation of the peak flows can be related to the precipitation dynamics that is influenced by local features of the basins (i.e., orography). A comparison of observed and simulated precipitation over the lowlands and highlands of Mataquito and Maule basins illustrates a tendency of increase in peak precipitation exceeding observation over the highlands (not shown).

## 4 Hydroclimate projections

In this section, we present projected changes in the meteorological forcing fields (extreme temperatures and precipitation) as well as changes in simulated variables, particularly runoff, snow water equivalent (SWE), evapotranspiration (ET). In addition, we show projected changes in runoff extremes. Future projections are computed for three 30-year periods (2010–2039, 2040–2069, and 2070–2099) from the VIC-CMIP5-RCP2.6 and VIC-CMIP5-RCP8.5 ensembles, which are contrasted with the reference period (1976–2005) simulated in VIC-CMIP5-HIST.

### 4.1 Changes in the mean hydroclimate regime

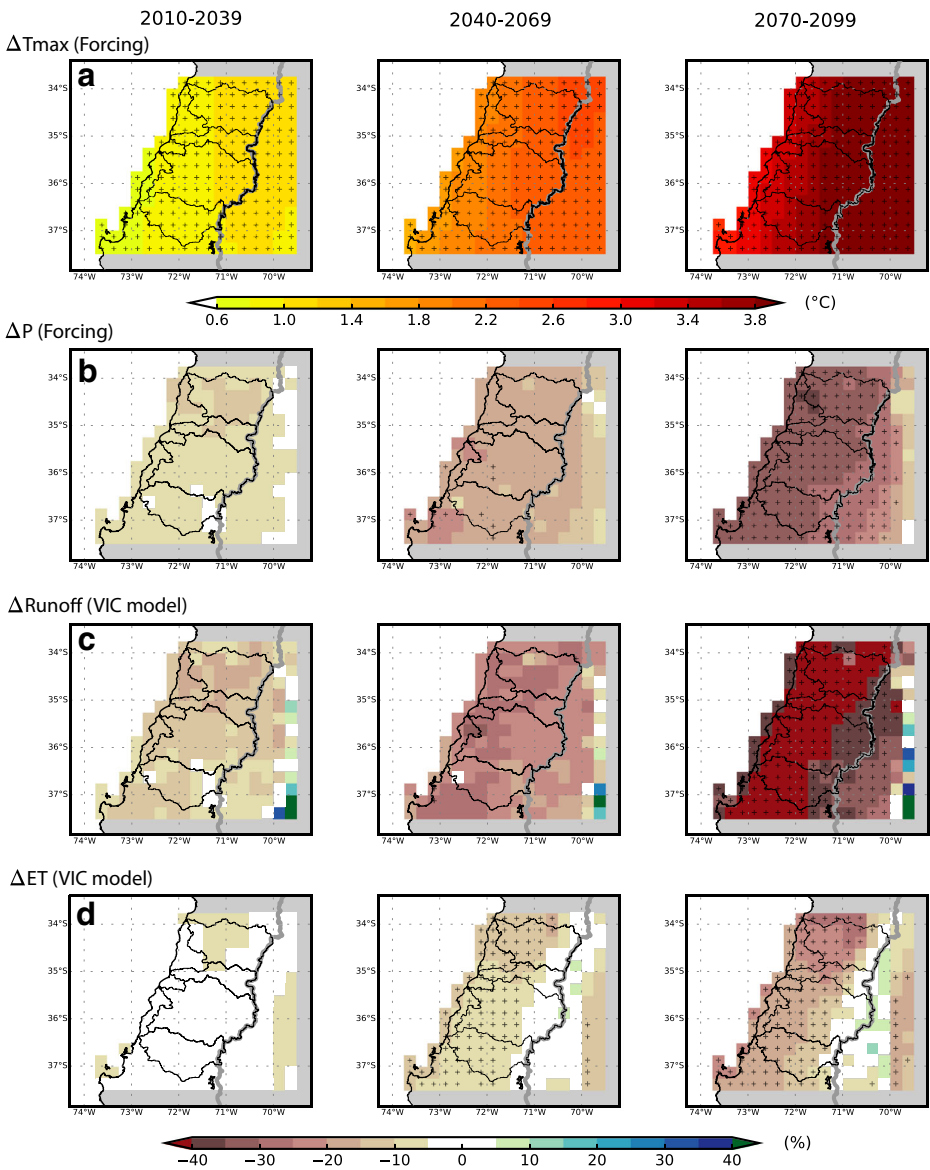
Figure 3a, b shows the absolute changes in annual mean maximum temperature and the relative differences in annual mean precipitation between the target future periods and the present, as derived with the adjusted RCP8.5 CMIP5 simulations in CC. The average daily maximum temperature indicates a warming above 1.0, 2.0, and 3.0 °C projected in the near (2010–2039), middle (2040–2069), and long (2070–2099) term, respectively. The



**Fig. 2** **a, c, e, g** Observed long-term (1970–2005) monthly runoff (black) and the VIC model simulation result forced with gridded observation (blue) for Rapel, Mataquito, Maule, and Itata basins from top to bottom, respectively. **b, d, f, h** Also shown are annual cycle of observed runoff (black) the VIC model simulation results forced with gridded observation (blue) and CMIP5 models (red for multimodel ensemble mean, gray shading for range of individual models) for Rapel, Mataquito, Maule, and Itata basins from top to bottom, respectively

temperature changes show geographical variations, with a stronger impact over the Andes compared to coastal areas (a difference of about 1.0 °C). A similar pattern of change is projected for daily minimum temperature, albeit the amplitude of change in this variable is generally weaker than those in the maximum temperature (not shown). Towards the same three periods in the 21st century, precipitation is projected to decrease by up to 10, 20, and





**Fig. 3** a, b CMIP5 ensemble mean bias corrected annual mean maximum temperature and annual mean precipitation differences ( $^{\circ}\text{C}$  for temperature, % for precipitation), respectively for 2010–2039 (left panels), 2040–2069 (middle panels), and 2070–2099 (right panels) periods (under RCP8.5) with respect to 1976–2005 reference period. Also shown are the ensemble VIC model projections for c runoff and d evapotranspiration (%) for the same periods (under RCP8.5) with respect to 1976–2005 reference period. Markers indicate where most of the models (> 50%) have statistically significant differences at 95% confident level based on Student’s *t* test

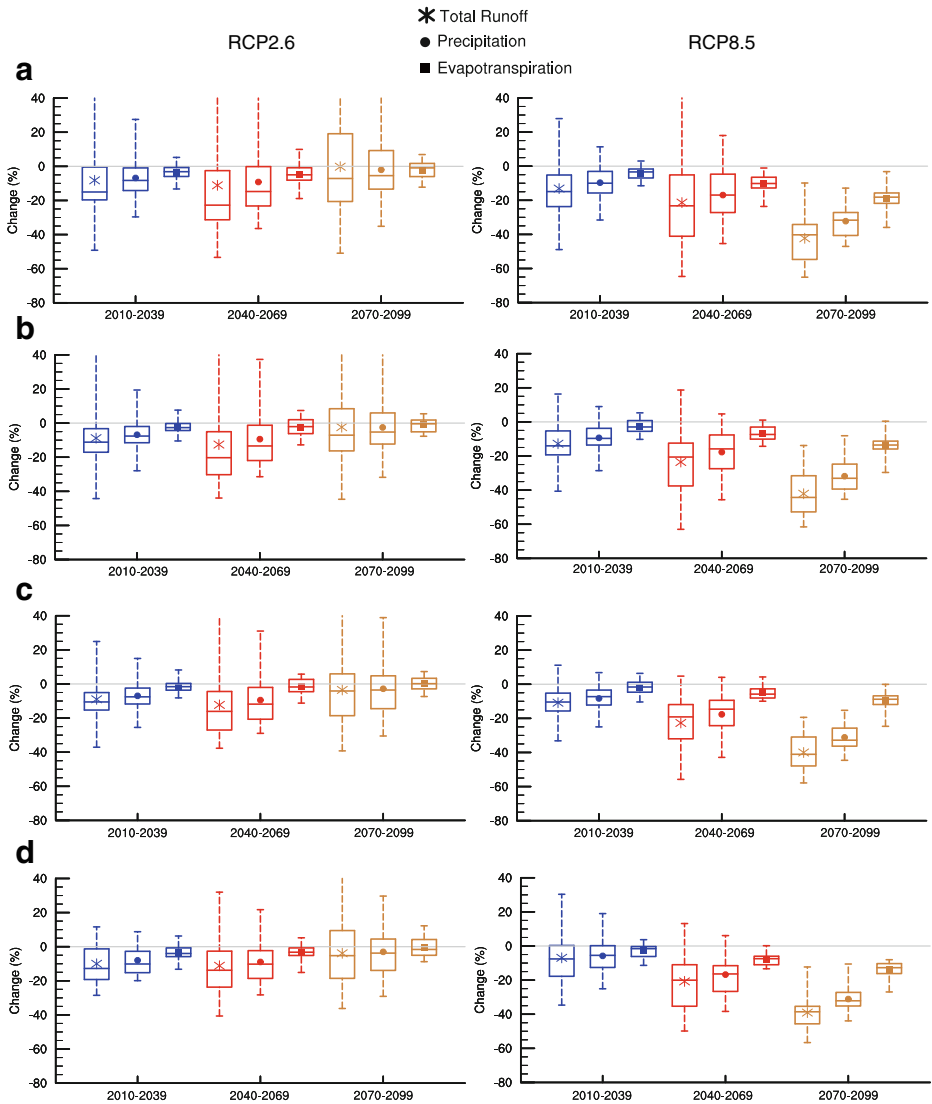
30%, respectively. The adjusted CMIP5 simulations under RCP2.6 show less changes compare to those under RCP2.6 (e.g., up to  $\sim 1.0$   $^{\circ}\text{C}$  mean temperature increase and  $\sim 10\%$  precipitation decrease by mid-century, not shown).

Figure 3c and d shows the simulated (ensemble mean) changes in annual runoff and ET, as obtained with the ensemble simulations of VIC-CMIP5-RCP8.5 for the periods of 2010–2039, 2040–2069, and 2070–2099 relative to historical period (VIC-CMIP5-HIST). Runoff is projected to decrease in each successive period with respect to the reference period, a result broadly consistent with the overall decrease in precipitation. Yet, in relative terms, the amplitude of the simulated runoff decline is particularly large, with anomalies of up to 10% in 2010–2039 and more than 40% by the end of the century. On the other hand, VIC-CMIP5-RCP2.6 shows very little or no change in precipitation by the end of the century ( $\sim -3\%$ , not shown). Larger decrease in precipitation and runoff is projected under RCP2.6 by mid-century than that projected by the end of the century (not shown). Very little or no change in ET is simulated in the first period (Fig. 3d) under RCP8.5, however, towards 2040–2069 and 2070–2099 ET is projected to decrease up to 10 and 20% in Mataquito, Maule, and Itata basins, while a slightly stronger effect is simulated in the Rapel basin. The annual mean ET responses to changes in meteorological forcing are constrained to lowlands, while a weak increase in ET is shown in some areas of the Andes. VIC-CMIP5-RCP2.6 illustrates very little or no change in ET in each period (not shown).

Figure 4 shows the changes in the water balance components. VIC-CMIP5-RCP2.6 foresees very low changes by the end of the century (e.g., a 2–3% decrease in basin-wide mean precipitation and runoff) with larger uncertainty range than that of the VIC-CMIP5-RCP8.5 for precipitation and runoff. During the same period, VIC-CMIP5-RCP8.5 projects a 30% decrease in basin-wide mean precipitation and a 40% decrease in basin-wide runoff. The basin-wide projections indicate that ET declines between 10% (Maule) and 18% (Rapel) under RCP8.5 by the end of the century. Decrease in precipitation and runoff ( $\sim -10\%$ ,  $\sim -12\%$ ) under RCP2.6 by mid-century is larger than that projected by the end of the century with similar range of variability. Table S5 summarizes the changes in the water balance components.

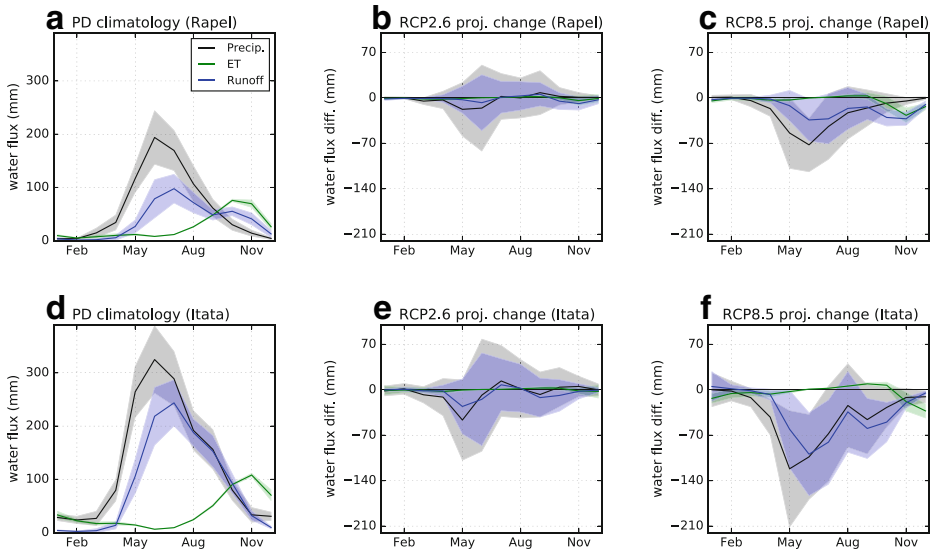
An increase in temperature over snowmelt dominated basins is expected to lead to a reduction of SWE as well as to temporal shifts in the peak flow (e.g., Immerzeel et al. 2010; Bozkurt et al. 2015). To further investigate the warming effect on snowpack and runoff, we look at the changes in the runoff timing. To do this, we have adopted a center time metric (CT), which defines the date marking the timing of the center of mass of annual flow (Stewart et al. 2005). The fraction of accumulated runoff over the highlands in each basin from the ensemble mean of VIC-CMIP5-HIST, VIC-CMIP5-RCP2.6, and VIC-CMIP5-RCP8.5 is given in Fig. S6. The CT of the reference period for the basins corresponds to 30<sup>th</sup> September for the Rapel basin, 14<sup>th</sup> August for the Mataquito basin, 4<sup>th</sup> August for the Maule basin, and 27<sup>th</sup> July for Itata basin (see Table S5). A bias of four to ten days exists with compared to VIC-OBS. Overall, VIC-CMIP5-RCP8.5 gives larger shifts in CT towards earlier dates in each basin compared to that in VIC-CMIP5-RCP2.6. As the increase in temperature is more pronounced by the end of the century, larger shifts in CT towards earlier dates for Rapel and Mataquito basins are projected to occur by the end of the century under RCP8.5 ( $\sim 5$  weeks for Rapel and  $\sim 2$  weeks for Mataquito, see Table S5). It is important to note that earlier snow-melting under RCP8.5 leads to increase in winter runoff in some parts of the Andes (see Fig. S7). By the end of the century, VIC-CMIP5-RCP2.6 shows less shifts in CT for Rapel and Mataquito basins ( $\sim 2$  weeks for Rapel and  $\sim 5$  days for Mataquito, see Table S5). Accordingly, the Itata basin, which has the lowest snow coverage fraction and is therefore mainly a rainfed basin, has no or very little CT shift under both scenarios (Fig. S6d).

The shifts in CT towards earlier dates, as well as the decrease in projected runoff, are consistent with SWE changes. Projected SWE changes show that the Andes snowpack



**Fig. 4** a Box plots of mean annual runoff (asterisk), precipitation (dot) and evapotranspiration (square) changes (%) from the ensemble mean of the VIC model simulations forced with CMIP5 models for the periods of 2010–2039 (blue), 2040–2069 (red), and 2070–2099 (brown) relative to 1976–2005 reference period for Rapel, **b** Mataquito, **c** Maule, and **d** Itata basins. Left and right panels correspond to RCP2.6 and RCP8.5 scenarios, respectively. The median is represented by the bar across the box and the box-plot whiskers represent the maximum and minimum values. The box represents the 25th and 75th percentiles

is projected to be less than half of the reference period snowpack by mid-century under RCP8.5 (see Fig. S8). Even under the low emission scenario, the Andes snowpack is projected to decrease by 35–45% by mid-century. Furthermore, relative decreases in mean annual SWE for these basins reveal that largest snowpack deficits take place in the Maule, Mataquito and Itata basins with values of 87, 86, and 84%, respectively under RCP8.5 by the end of the century (see Table S5).



**Fig. 5** (a) Long-term mean annual cycle (mm) of water balance components (precipitation, evapotranspiration and runoff) and (b), (c) their absolute changes (mm) under RCP2.6 and RCP8.5, respectively by the end of the century for Rapel basin. (d), (e), (f) The same in (a), (b), and (c) but for Itata basin. Shading shows the range of individual models

We also look at the seasonal changes in water balance components (precipitation, runoff, and ET) projected to the end of the century for Rapel and Itata basins (Fig. 5). The Rapel basin has a more snowmelt-dominated regime with a secondary runoff peak in spring, whereas Itata basin is characterized as a more rainfall-dominated basin. In general, runoff change ( $\Delta R$ ) follows the changes in precipitation ( $\Delta P$ ) across the year in both basins. The weak ET change ( $\Delta ET$ ) may be due to an underestimation of ET in the VIC-CMIP5-HIST (see Fig. S4). On the other hand, in Rapel, temperature-driven snow-melting towards the end of the year contributes to seasonal changes under RCP8.5.  $\Delta R$  matches more closely  $\Delta P$  in Itata basin, under the both emission scenarios (Fig. 5e, f). Precipitation and runoff tend to decrease in March–April–May season under the both emission scenarios, yet more pronounced decrease takes places under RCP8.5 for both basins (Fig. 5c, f). RCP8.5 illustrates a robust decrease of precipitation and runoff almost in each month, whereas RCP2.6 shows a slightly increase of precipitation and runoff in July and August for both basins. ET increases (albeit not too marked) at the end of the winter due to earlier snowmelt and thus, larger water availability under RCP8.5.

## 4.2 Changes in runoff extremes

In order to evaluate projections of hydroclimatic extremes, changes in the distribution of daily runoff were analyzed using probability density functions (PDFs) and return periods (through the open source extRemes package developed by Gilleland and Katz (2015)). Figure S9 shows the PDFs of 3-day maximum runoff obtained for each basin in the reference period and future period under RCP2.6 and RCP8.5. The PDFs derived with the reference period indicate that the mean and variance of maximum daily runoff increase from north to

south (Rapel to Itata basin). The PDFs of future periods under RCP2.6 show very little or no change in variance for each basin. For instance, Itata basin features a very slight increase in the likelihood of flood events in near century, whereas Mataquito and Maule basins feature a very slight change in the shape of the distribution with slightly increase in low flows in mid century (Fig. S9b, c and d left panel). Compared to RCP2.6, RCP8.5 illustrates marked and pronounced changes. For instance, the variance tends to increase in Rapel and Mataquito basins, indicating a slight increase in the likelihood of flood events (Fig. S9a, b right panel). Furthermore, Maule and Itata basins feature a larger increase in variance, contributing to much higher likelihood of flood events in the future periods (Fig. S9c, d right panel). The increasing probability of very low maximum runoff in each basin indicates a higher likelihood of longer period of low flows, contributing to the increase in frequency and severity of drought conditions under RCP8.5.

Return periods of 3-day maximum runoff events for the reference period show that Maule and Itata basins have the largest maximum runoff values with 2, 10, 50, and 100-years return periods, while the Rapel basin has the lowest values (see Table S6). The projected return period changes show an upward shift in the maximum runoff return periods, which are more pronounced in the higher recurrence intervals by mid-century under RCP2.6 and RCP8.5, and by the end of the century under RCP8.5 (Figs. S10 and S11). Moreover, the decrease (increase) in return periods (values) of maximum runoff highlights the likelihood of more frequent flood events. For instance, by mid-century, peak flows with 50-year return periods will be greater than the reference period peak flows with 100-year return period in Maule and Itata basins under the both scenarios (see Table S6). It is important to note that higher recurrence intervals (e.g., 50 and 100-years) tend to have larger uncertainties especially for the Maule and Itata basins under RCP8.5. For small return periods (e.g., 2 and 10 years), the projections indicate small changes in the maximum runoff values in the future periods, even slight decrease in the magnitude of maximum runoff (i.e., 2 years) for each basin under the both scenarios by mid-century.

## 5 Summary and key results

The main goal in this study is to make use of the VIC model capabilities to get future basin-wide projections in key hydroclimatic variables in central Chile (CC,  $\sim 30\text{--}40^\circ$  S) under two emission scenarios: high-mitigation, Paris Agreement compatible (RCP2.6), and business-as-usual (RCP8.5). This allows contrasting the changes in hydroclimatic regimes and extremes in basins with different characteristics (e.g., snowmelt-dominated and rainfed) as well as the comparison of the different emission scenarios. Given the general lack of assessments of future hydroclimate changes in CC, we first present projected changes in the meteorological variables used to force the VIC model and then the model projections. We use three 30-year periods (2010–2039, 2040–2069, and 2070–2099) from the VIC-CMIP5-RCP2.6 and VIC-CMIP5-RCP8.5 simulations to make the contrast with the reference period (1976–2005). From this experiment, we highlight the following results:

- By the end of the century, there is a large difference between the scenarios, with projected warming of  $\sim + 1.2^\circ\text{C}$  (RCP2.6),  $\sim + 3.5^\circ\text{C}$  (RCP8.5) and drying of  $\sim - 3\%$  (RCP2.6),  $\sim - 30\%$  (RCP8.5). VIC-CMIP5-RCP2.6 indicates larger uncertainty range than that of VIC-CMIP5-RCP8.5 for precipitation and runoff by the end of the century. Larger decrease in precipitation and runoff is projected under RCP2.6 ( $\sim - 10$  and  $\sim - 12\%$ , respectively) by mid-century than that projected by the end of the century.

- CC is projected to become warmer and drier under the RCP8.5 scenario. The projections foresee a precipitation decline by 30% in the basins assessed by the end of the century, whereas runoff is projected to decrease around 40%. Extreme temperatures are projected to increase up to 4 °C, with largest warming over of Andes.
- Warming is associated with losses of snowpack and temporal shifts in peak flow. Our results indicate that even under the low emission scenario, the Andes snowpack is projected to decrease by 35–45% by mid-century. Similar results are reported for other semi-arid basins of the Andes in Chile (e.g., Vicuña et al. 2011; Demaria et al. 2013b). In more snowmelt-dominated areas, the projected hydrological changes under RCP8.5 go together with a larger decrease in the snowpack (75–85%) and a temporal shift in the peak timing of runoff over the highlands (up to 5 weeks) by the end of the century. The most significant shift takes place in the Rapel basin (30<sup>th</sup> September to 19<sup>th</sup> August) under RCP8.5.
- Seasonal changes of water balance components indicate that runoff change follows the precipitation change across the year due to a weak ET change under the both emission scenarios. RCP8.5 illustrates a robust decrease of precipitation and runoff almost in each month, whereas RCP2.6 shows a slightly increase of precipitation and runoff in July and August for both basins by the end of the century. The role of ET change is more important towards the end of the year and mainly depends on water and soil moisture availability under RCP8.5.
- The probability density functions (PDFs) of 3-day peak runoff for each basin indicate very little or no change in the shape of the distribution under RCP2.6. On the other hand, RCP8.5 shows a robust increase in the likelihood of maximum runoff values, and hence, floods, particularly for Maule and Itata basins by mid-century and by the end of the century.
- Increased probability of very low runoff in each basin under RCP8.5 indicates a higher likelihood of longer period of low flows contributing to the increase in frequency and severity of drought conditions.
- The estimated return periods of 3-day peak runoff events indicate a decrease (increase) in return periods (values). For instance, by mid-century, peak flows with 50-year return periods will be greater than the reference period peak flows with 100-year return period in Maule and Itata basins under the both scenarios.

## 6 Discussion and concluding remarks

In the last decades, CC has been facing a decline of precipitation and, in the recent years (2010–2015), a persistent precipitation deficit of approximately 30% together with warm anomalies over the Andes cordillera, exacerbating the water deficit (CR2 2015; Garreaud et al. 2017). This so-called mega-drought has affected significantly the surface hydrology and vegetation productivity, notably in the agricultural yield in central-northern Chile (Garreaud et al. 2017). Boisier et al. (2016) showed that natural climate variability plays an important role in explaining the amplitude of the current drought, but that approximately a quarter of rainfall deficit can be attributed to anthropogenic climate change. Our results highlight that drying and warming conditions are very likely to continue and strongly impact the future hydroclimatic conditions of CC and hence to aggravate water stress. For instance, the occurrence of extended droughts, such as the recently experienced mega-drought, increases from less than one to up to five events per 100 years under RCP8.5 and up to two events per 100 years under RCP2.6, emphasizing a dramatic change in the

precipitation regime of this region by the end of the century (see Fig. S12). In addition, pronounced temporal change in peak flows and earlier snowmelt under RCP8.5 will have implications for water resource management and alteration of the water cycle in CC.

In snowmelt-dominated basins, warming and precipitation related ET changes may also have a significant impact on the regional water cycle and seasonality. As mentioned by Ohmura and Wild (2002), the direction of evaporation trend is not determined by temperature alone. Particularly, in snowmelt basins a complex set of feedback mechanisms, due to both warming and precipitation related changes, may have a great impact on the water balance components at seasonal scale. Indeed, although mean annual ET changes show a weak decreasing tendency, our analysis on absolute seasonal changes of water balance components indicates that there is a slightly increase in ET in winter and late winter months, due to earlier snowmelt. Furthermore, disappearance of snow cover earlier in the year due to snowmelt leads to decrease in surface albedo in both winter and spring seasons (not shown), and hence, increase in surface net radiation and a positive feedback on ET. In addition, the change patterns of ET are also related to soil moisture. It can be argued that snowpack melting related impacts on soil moisture may alter the regional water balance cycle. For instance, temperature-driven snow-melting, and thus, significant reduction in snowpack and runoff leads to a secondary peak decrease in soil moisture in the Rapel basin towards late spring (not shown).

In hydroclimate change studies, projections of future climate change may comprise large uncertainties introduced by different sources such as choice of meteorological forcing downscaling methods (e.g., spatial resolution) and choice of hydrological model parameter sets (Hagemann et al. 2013; Mendoza et al. 2015). In the present study, our selection for gridded dataset is merely due to data availability of meteorological forcing fields at 0.25° resolution from Demaria et al. (2013a). Although this spatial resolution is too coarse to evaluate processes at the scale of secondary and tertiary watersheds in Chile (e.g., 100 to 1000 km<sup>2</sup>), it is useful to assess projected hydroclimate changes in macro scale basins of CC (e.g., 6000 to 20000 km<sup>2</sup>). In addition to spatial resolution-based uncertainties, there are other sources of uncertainties and limitations of our study associated with the use of the VIC-parameters calibrated for Mataquito basin for the whole domain. As noted by Demaria et al. (2013a), the rationale for using the same calibrated parameters for the entire domain is to avoid the possibility of allowing extensive calibration to hide the deficiencies of meteorological forcing fields. Inevitably, there are limitations, particularly associated with calibrated parameters but overall the hydrologic model adopted in this study adequately captures present hydroclimate variability and relevant information contained in the evaluation metrics; therefore, it is assumed to be a sufficient tool for assessment of climate change impacts on the key hydroclimatic variables particularly for Mataquito, Maule, and Itata basins. Results presented for Rapel basin should be considered with caution given that the weaknesses of the model for that basin is taken into account.

In summary, projected changes examined in this study could potentially have a major impact on the socioeconomic development of this densely populated region in Chile even if large uncertainties remain. On the one hand, detailed investigations and adaptation efforts are needed to increase resilience and reduce vulnerability, through collaboration and partnerships between various sectors and stakeholders. On the other hand, more research is warranted to clarify dynamics and physical mechanisms as well as regional feedback processes affecting the hydroclimate changes in CC. Finally, it is argued that a large part of the uncertainties on these results could be reduced in future by using higher resolution meteorological forcing data that can allow extensive calibration techniques and hydrologic model applications.

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