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ORIGINAL PAPER

Climate change in northern Patagonia: critical decrease in water resources

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Abstract
The current study presents an assessment of the impact of climate change on water yield, one of the main hydrological ecosystem services, in northern Patagonia. The outputs of regional climate models from the CORDEX Project for South America were used to drive the InVEST water yield model. CORDEX regional climate models project for the far future (2071–2100) an increase in temperature higher than 1.5 °C and a precipitation decrease ranging from − 10 to − 30% for the study area. The projected warmer and dryer climate emerges as a robust signal based on model agreement and on consistent physical drivers of these changes. Moreover, both the projected increase in evapotranspiration and the decrease in precipitation contribute to a strong decrease in water yield of around − 20 to − 40% in the headwaters of northern Patagonian watersheds. Comparison of the results in the two basins reveals that the land cover may be considered a buffer of water yield changes and highlights the key role of protected areas in reducing the vulnerability of water resources to climate change.

Keywords Climate change · Water yield impact · Patagonian basins · CORDEX models · InVEST model

1 Introduction

The rise in temperature associated with anthropogenic climate change affects water resources by altering precipitation, evapotranspiration, soil moisture, surface runoff patterns, and hydrological cycle. In Patagonia, whereas the increase in temperature (up to 1 °C since 1950) has been large compared to the rest of Argentina (Barros et al. 2014; Boninsegna et al. 2009; Rosenblüth et al. 1997; Villalba et al. 2003; Vincent et al. 2005), there has been no significant changes in precipitation for the past 50 years, with the exception of a significant negative trend (around 5% per decade) over the northern Patagonian Andes (Castañeda and González 2008; Masiokas et al. 2008).

Climate models project around 10–20% less precipitation over northern Patagonia by the end of the century, being the Andes area the most affected by this projected decrease in precipitation (Barros et al. 2014). In hydrological terms, these projections become even more relevant when considering that the maximum average precipitation occurs in the Andes Mountains, where the headwaters of all Patagonian rivers are. This region is one of the few in the continental areas of

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the world where models agree in the sign of precipitation change and the precipitation projections have high confidence (more than 90% of the models used for the IPCC reports project precipitation decrease) (Power et al. 2011). One of the most robust methodologies used to quantify the effect of climate changes on water resources is the use of hydrological models. These models are forced with the outputs from either general circulation models (GCM) or regional climate models (RCM). With a spatial resolution in the order of hundreds of kilometres, the last generation of GCMs has a limited capability to represent processes at the regional scale. However, RCMs driven by GCMs provide information at smaller scales and therefore allow for a more detailed evaluation of climate change impacts (Solman 2016).

In order to account for the uncertainty in climate projections, several GCMs or RCMs and different future emission scenarios are used (Faramarzi et al. 2013; Solman, 2016; Yira et al. 2017).

In the current study, the CORDEX Project (Coordinated Regional Climate Downscaling Experiment; Giorgi et al. 2009) simulations for South America were used to force the water yield model available within the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs; Sharp et al. 2016) set of models. The RCM simulations generated within the CORDEX framework (from now on, CORDEX-RCM) for different RCP (Representative Concentration Pathways) emission scenarios are being widely used by the scientific community to force hydrological models in other regions of the world (Li et al., 2016; Tramblay et al. 2013; Yira et al. 2017). However, in South America and in particular in Patagonia, no studies have analysed this set of data yet. On the other hand, the InVEST water yield module allows for spatially explicit estimations of water yield at the subbasin scale. Based on the Budyko curve (Budyko, 1974), this InVEST module is a simple water yield model that has been successfully applied in Patagonian basins where it has already been validated and calibrated (Pessacg et al. 2015 and Pessacg et al. 2018). InVEST has also been used to analyse the impact of climate change on water resources in different basins around the world such as Mediterranean basins (Bangash et al. 2013; Boithias et al. 2014), Tualatin and Yamhill basins in the USA (Hoyer and Chang 2014), Francoli River basin in Spain (Marquès et al., 2013), Chinese Loess Plateau (Su and Bojie, 2013), and Thadee basin in Thailand (Trisurat et al. 2016), among others.

This study is focused on two large river basins of northern Patagonia, Argentina: the Chubut River basin and the Limay River basin. These basins are important in both economic and social terms. The Chubut River supports irrigation for agriculture and provides urban and industrial water for 50% of the population of the Chubut province. On the Limay River, five dams produce 25% of the hydropower of Argentina; this watershed also supports 40% of the tourist industry in continental Patagonia (García Asorey et al. 2015). These rivers support the two main agricultural areas of Patagonia and are relevant in terms of hydrological ecosystem services in view of different development projects related to the expansion of hydroelectric production, agriculture, mining, tourism and urban areas. Recent studies have shown that a negative trend in annual and summer flow rates has already been registered for the Limay River (Vich et al. 2014), together with a negative trend in the autumn and summer flow rate for the Chubut River (Pasquini and Depetris, 2007; Vich et al. 2014). Given society's dependence on the availability of water in these two rivers, understanding the impact of climate change on water resources is fundamental to design and implement mitigation and adaptation strategies (Bates et al. 2008). However, not many studies have quantified the impact of climate change on water resources in Patagonia.

The aim of this paper is to evaluate the impact of climate change on water yield for the two above-mentioned Patagonian river basins using an ensemble of CORDEX simulations for South America in combination with the InVEST water yield model to simulate future water yield in northern Patagonia.

2 Methodology

The research methodology used to achieve the objectives of this study is outlined in Fig. 1.

2.1 Study area

This study focuses on two relevant Patagonian basins: Chubut River basin (ChRB) and Limay River basin (LRB; Fig. 2). Both basins have their headwaters located over the meridional precipitation gradient observed along the Andes region, with precipitation values ranging from 2600 mm yr^{-1} in the border

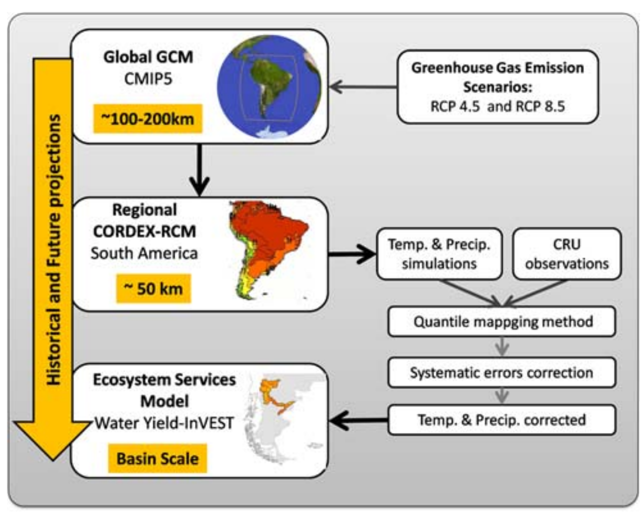

Fig. 1 Research approach and applied methods

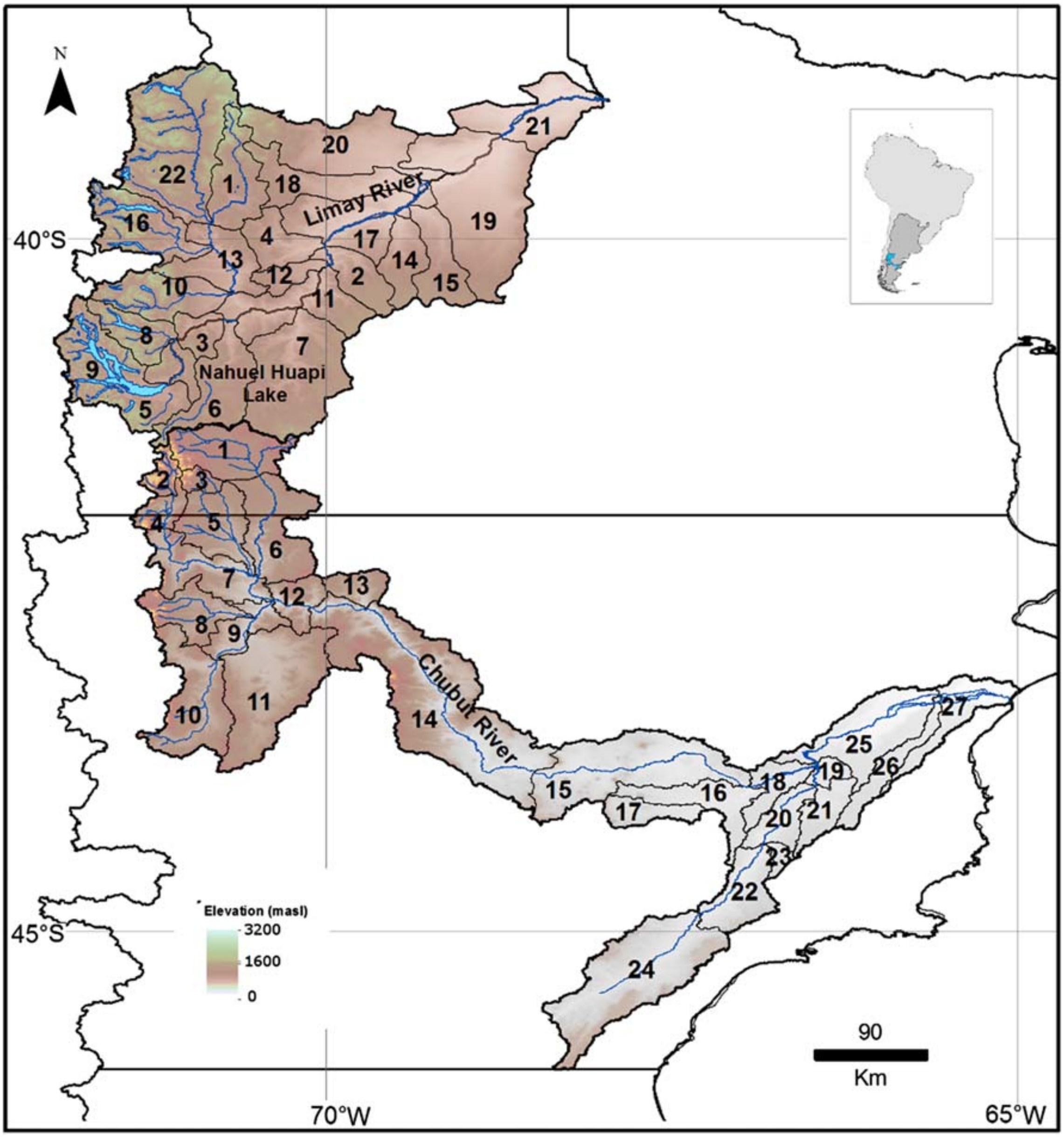

Fig. 2 Geographic location and topography (meters above sea level) of the Chubut and Limay River basins

between Argentina and Chile to 200 mm yr^{-1} 200 km eastward. The reason for the precipitation gradient east of the Andes is the mountain range itself, which affects regional scale climate by blocking the prevailing westerly winds. The orographic effect leads to precipitation occurring mostly along the western flanks of the Andes and decreasing eastwards (Insel et al. 2009), where subsidence forced by the mountains drives to very dry conditions over the Patagonian plateau (Garreaud, 2009). Whereas the LRB sources are located in the high Andes, the headwaters of the ChRB are more eastwardly located (Pessacg et al. 2015).

The ChRB covers a total area of 57,400 km^2, is divided into 24 subbasins and is located in the central Patagonian region. The lower sector of the basin is the most populated with 50% of the population of the province living in that area. The source of the Chubut River is located in extra-Andean Patagonia and flows to the east through the Patagonian plateau and towards the Atlantic Ocean (Fig. 2). This river presents two annual peak flows: one in autumn due to precipitation and another in spring due to snowmelt. The Chubut River is the only surface water supply for over 200,000 people (Commendatore and Esteves, 2004).

The LRB covers an area of 58,800 km^2 in the northwest of the Patagonian region and is divided into 22 subbasins (Fig. 2). The Limay River is the outlet of the Nahuel Huapi Lake and runs to the northeast – with an average flow rate of 650 m^3 s^{-1}

(Martínez 2002) – where it joins the Neuquén River to form the Negro River. The Limay-Neuquén-Negro River Basin is the most important hydrographical system of Patagonia (AIC Documents, Interjurisdictional Authority of the Limay, Neuquén y Negro River Basins; www.aic.gov.ar).The Limay River has a flow regime regulated by several natural glacial lakes in its source and with two annual peak flows: one in winter due to precipitation and another one in the spring due to snowmelt. The LRB provides water for several uses, such as agricultural and irrigation, oil and mining exploitation, hydropower generation, tourism and international sport fishing. This basin is also home to two large national parks (Nahuel Huapi National Park and Lanin National Park) which cover approximately 40% of the basin area, including most of the basin headwater (Pessacg et al. 2018).

2.2 Climate change scenarios inputs

Water yield simulations for climate change scenarios require precipitation and reference evapotranspiration data for both present conditions and future scenarios. The data used for this study was provided by the CORDEX Project for the South American domain. The CORDEX Project provided a set of coordinated dynamical downscaled simulations with RCMs (CORDEX-RCM) for past and future periods driven by CMIP5 (Coupled Model Intercomparison Project Phase 5) Global Circulation Models at a spatial resolution of 0.44° (approximately 50 km; Giorgi et al. 2009; Jones et al. 2011).

In the current study, simulated present and future climate for two RCPs, RCP45 and RCP85 were used. RCPs are scenarios that combine different technological, economic, demographic, policy and institutional trends to represent total radiative forcing pathways and levels by 2100 (van Vuuren et al. 2011). RCP45 and RCP85 represent scenarios where radiative forcing are 4.5 and 8.5 Wm^{-2} (respectively), by the end of the century. While the RCP45 scenario assumes the implementation of climate policies to reduce emissions (Thomson et al., 2011), RCP85 represents the highest greenhouse concentration trajectory and assumes the absence of climate policies or mitigation measures (Riahi et al. 2011).The mean global warming projected by the end of the twenty-first century ranges from 1.1 to 2.6 °C and from 2.6 to 4.8 °C for RCP45 and RCP85, respectively (Stocker et al. 2013). The choice of these two scenarios is intended to capture a wide range of possible future climate conditions.

The CORDEX-RCMs used to force InVEST water yield model are listed in Table 1. Simulations using WRF and RegCM4 CORDEX-RCM models were only available for the RCP45 and RCP85 scenarios, respectively (see missing information in Table 1).

The selection of the CORDEX-RCMs used for this study includes different RCMs nested in the same GCM and also some RCMs nested in different GCMs (see Table 1). This choice allows for the assessment of the uncertainty due to both the choice of either the RCM or the driving GCM. In addition, evaluating different RCPs allows for the assessment of the uncertainty associated with the emission scenarios.

The CORDEX-RCM simulations were interpolated from the native model grid to a regular lat-lon grid with a spatial resolution of 0.5° × 0.5°.

In the current study, the climate change signal for different variables is calculated as the difference between the far future and the historical period simulations for each RCM. In addition to this, the model uncertainty is calculated as the spread between the minimum and maximum change values obtained from the different CORDEX-RCM simulations. Finally, the significance of the changes is evaluated by comparing the projected change from the ensemble mean with the spread among ensemble members (one standard deviation) (Meehl et al. 2007).

Table 1 Matrix of CORDEX-RCM simulations and periods covered

				Periods/RCPs scenarios		
CORDEX-RCM	RCM	GCM	Historical	Far future/RCP4.5	Far future/RCP8.5	Reference
RCA/ICHEC	RCA4	*ICHEC*-EC-EARTH	1979–2005	2071–2100	2071–2100	Strandberg et al. 2014
RCA/MPI	RCA4	MPI-ESM-LR	1979–2005	2071–2100	2071–2100	Strandberg et al. 2014
REMO/MPI	REMO	MPI-ESM-LR	1979–2005	2071–2100	2071–2100	Jacob et al. 2001 Teichmann et al. (2013)
REG/HAD	RegCM4	HadGEM2	1979–2005	–	2071–2100	Giorgi et al., 2012 Llopart et al. 2014
REG/MPI	RegCM4	MPI-ESM-LR	1979–2005	–	2071–2100	Giorgi et al., 2012Llopart et al. 2014
REG/GFDL	RegCM4	GFDL-ESM2M	1979–2005	–	2071–2100	Giorgi et al., 2012 Llopart et al. 2014
WRF/CAN	WRF	CanESM2	1979–2005	2071–2100	–	Skamarock et al. 2008 Fernández et al. 2011

2.3 Statistical bias correction

Climate models are far from being out of systematic biases. Climate variables, such as precipitation and temperature simulated using RCMs, present systematic errors that need to be corrected before being used for impact studies, including hydrological modelling (Hagemann et al. 2011; Olsson et al. 2013). These errors stem from imperfect conceptualization and discretization of physical processes within the grid cells of the RCMs (Teutschbein and Seibert 2012).

Previous studies have used different statistical methods to reduce these errors and improve the agreement between weather observations and simulations (Piani and Haerter 2012; Saurral et al. 2013; Teutschbein and Seibert 2012; Vidal and Wade 2008a and b, 2009). In the current study, the systematic distributional biases in precipitation and temperature from the CORDEX-RCM simulations were corrected using the quantile mapping method, which has been proved to be an efficient method for reducing biases, in particular at high quantiles (Themeßl et al. 2011). In South America, for example, this method was used to correct the outputs from RCMs before forcing the hydrological model VIC. The authors found that the method successfully reduced the biases in the water cycle variables simulations for La Plata Basin (Saurral et al. 2013).

In the current study, the quantile mapping method was applied following the methodology proposed by Wood et al. (2002) and Saurral et al. (2014). The quantile mapping is based on a non-parametric transformation by means of the calculation of monthly percentiles in temperature and precipitation simulated using RCM and observations during a calibration period. This procedure allows for the calculation of a transfer function that is then applied to the historical simulations and projected climate scenarios. The quantile method assumes that the model bias behaviour does not change with time and consequently can be assumed to be the same in future simulations (Hagemann et al. 2011).

The quantile mapping correction method is limited by the quality of the observational data considered. Observed precipitation datasets have high uncertainties that make their comparison against RCMs outputs difficult. This is of particular importance in Patagonia with a large west-east precipitation gradient and a sparse meteorological network. In this context, monthly gridded precipitation and temperature observations from the Climate Research Unit (CRU) database (Mitchell and Jones 2005) were used for the current study. Other precipitation databases are not available for long periods of time or have been proved to perform poorly when modelling water yield in Patagonian watersheds (see Pessacg et al. 2015 and Pessacg et al. 2018 for more details on precipitation databases).

In the current study, the bias correction transfer function was derived for a calibration period of 25 years (1970–1994) and then applied to a validation period of 11 years (1995–2005) and finally to the historical period (1979–2005) and to the far future scenario period (2071–2100). The correction was applied to the monthly mean temperature and precipitation values; the annual mean temperature and precipitation were calculated thereafter.

2.4 Water yield model

The Reservoir Hydropower Production module of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs; Version 3.3.3; Sharp et al. 2016) was used to simulate water yield for the ChRB and LRB. This model was developed by the Natural Capital Project (www.naturalcapitalproject.org) with the aim to map and quantify the provision of hydrological ecosystem services in watersheds. Input requirements and data sources used in this study are described in Table 2. More details on how the model works are provided in Supplementary Material.

The model has already been calibrated for the ChRB and LRB in previous studies. Pessacg et al. (2015) and Pessacg et al. (2018) evaluated the performance and calibrated the model using different precipitation databases and gauge stations data in the ChRB and LRB, respectively. On the other hand, Flaherty et al. (2017) and Pessacg et al. (2018) evaluated the water yield sensitivity to different land use/land cover (LULC) databases for the ChRB and LRB. The results showed that the best performance is achieved using the INTA LULC database (http://geointa.inta.gov.ar).

Furthermore, the sensitivity of the InVEST model forced with CORDEX-RCM data for the historical period was tested following the methodology described in Pessacg et al. (2015, 2018) resulting in errors lower than 10 and 20% for the ChRB and LRB, respectively. These results are in line with the errors found for the model when using the CRU precipitation dataset for the calibration period.

Finally, potential evapotranspiration was calculated as a function of temperature following the Holdridge equation (Holdridge 1959) and then calibrated using the historical values from FAO (Allen et al. 1998).

3 Results

3.1 Climate change projections

A preliminary evaluation of the selected CODEX-RCMs capability to represent the spatial pattern and annual cycle of temperature and precipitation over the target region was first performed. It was found that the CORDEX-RCMs adequately represent the seasonal variations and area-averaged annual cycles of precipitation and temperature, compared against the CRU dataset, though several systematic biases were identified. In particular, it was found that every model underestimates the annual mean temperature, similarly to other studies based on different climate models (Solman, 2013). The mean biases for the annual mean temperature averaged over Patagonia range from − 1.5 to − 3 °C (Fig. 3b), depending on the model. Precipitation is strongly overestimated by every CORDEX-RCM in more than 400 mm yr^{-1} (nearly the same value as the mean annual precipitation) (Fig. 3a), being this a common shortcoming of RCMs in the region (Solman, 2013). Inspection of the spatial pattern of the annual mean bias (not shown) reveals that the largest precipitation errors occur close to the Andes, probably as a result of a smooth representation of the Andes by the models.

After applying the quantile mapping bias correction methodology to the raw model outputs, it was found that errors in annual mean precipitation simulations were reduced in more

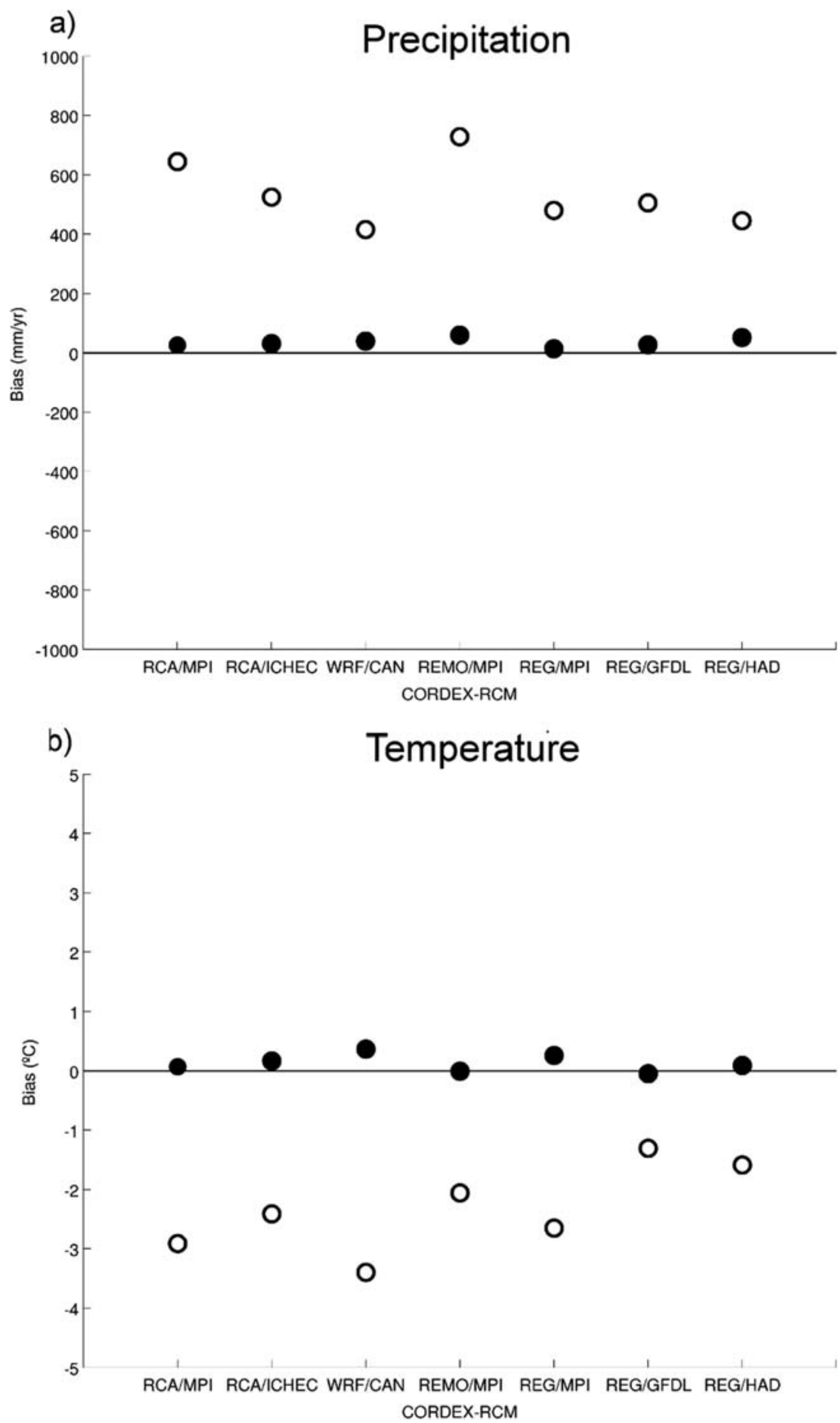

Fig 3 **a** Annual mean precipitation bias and **b** annual mean temperature bias for corrected (black dots) and uncorrected (white dots) CORDEX-RCM simulations compared to CRU observation in Patagonia region, for the validation period

than 85%, as depicted in Fig. 3a. In addition, the errors in annual mean temperature simulations over Patagonia were reduced in more than 25% (Fig. 3b). In particular, corrected model simulations show precipitation errors of less than ± 10% for both the LRB and ChRB (not shown). In terms of temperature, the errors are less than 0.2 and 0.6 °C in the ChRB and LRB, respectively (not shown). In consequence, the bias correction method satisfactorily reduced errors to a range of values that is well within the observational uncertainty range (Solman, 2016).

Climate change projections, for the corrected CORDEX-RCM simulations, show three hot spots in the precipitation change for the far future in Patagonia (Fig. 4). First, an increase in precipitation is projected for the northeastern Patagonia. Several authors relate this precipitation change to (1) the enhanced cyclonic circulation in the northwest of Argentina (Chaco Low) and (2) a southwards shift of the South Atlantic High which in turn increases moisture transport to the northern Patagonia (Blázquez et al. 2012 and references therein). Second, the majority of the projections, except RCA/ICHEC, show a precipitation decrease ranging from − 10 to − 30% in western and central Patagonia (Fig. 4). This precipitation decrease was also found in previous studies based on either different RCMs or global circulation models. Several authors have suggested that this consistent signal may be associated with a southwards shift of the Pacific Ocean storm track associated with the poleward expansion of the Pacific subtropical high in a global warming scenario (Boisier et al., 2016 and references therein). And finally, the majority of the projections show a 10 to 30% increase in precipitation in Tierra del Fuego province (Argentina) and southern Chile. This behaviour is in line with a positive trend in precipitation observed in the last 50 years over this region. These positive trends are correlated with an increase in the intensity of the *westerly* winds observed in southernmost Chile and Argentina (south of 50 °S), which is in turn related to changes in the hemispheric-scale Antartic annular mode (AAO) (Garreaud et al. 2013).

Overall, CORDEX-RCMs used in this study indicate a clear consistent signal of precipitation decrease in the ChRB and LRB ranging from − 10 to − 30% (Fig. 4), except the RCA/ICHEC which present a weak signal over the two basins. In the headwaters of the basins, the precipitation decrease is around − 10 and − 12% in the ChRB and − 12 and − 15% in the LRB, for the RCP45 and RCP85 emission scenarios, respectively. Previous studies (Pessacg et al. 2015 and Pessacg et al. 2018) showed that the maximum water yield is located in the headwaters partly due to the maximum annual precipitation (1000 mm yr^{-1} in the ChRB and 1500 mm yr^{-1} in the LRB) occurring there. Therefore, the projected change in precipitation over these areas is expected to have a strong impact on water yield.

In terms of temperature, CORDEX-RCM climate projections show an increase over the whole of Patagonia for the far future ranging from 1 to 2 °C and from 2 to 4 °C for the RCP4.5 and RCP8.5 scenarios, respectively (Fig. 5). In particular, in the LRB and ChRB, the increase in temperature ranges from 1.5 to 3 °C for the RCP45 and RCP85 emission scenario, respectively (Fig. 5). In the headwaters of the basins, the temperature increase is around 1.4 and 2.4 °C in the ChRB and 1.3 and 2.1 °C in the LRB, for the RCP45 and RCP85 emission scenarios, respectively (Fig. 5). It is worth to recall that changes in temperature impact linearly on evapotranspiration, and thus, these changes are expected to exert a large impact on water yield as well.

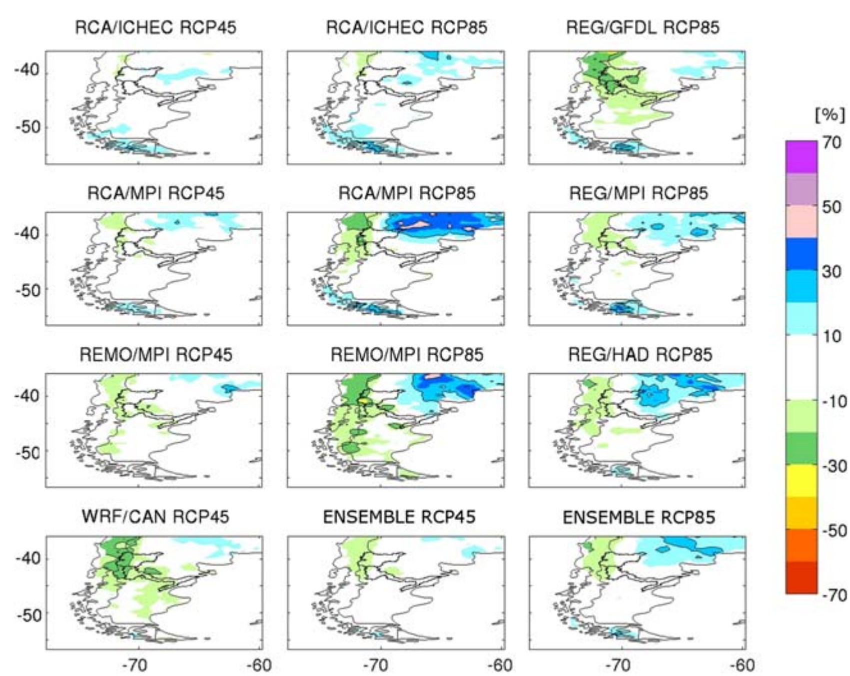

Fig. 4 Annual mean precipitation change for far future period for CORDEX-RCM corrected simulations and the RCP45 and RCP85 ensembles. Units: %

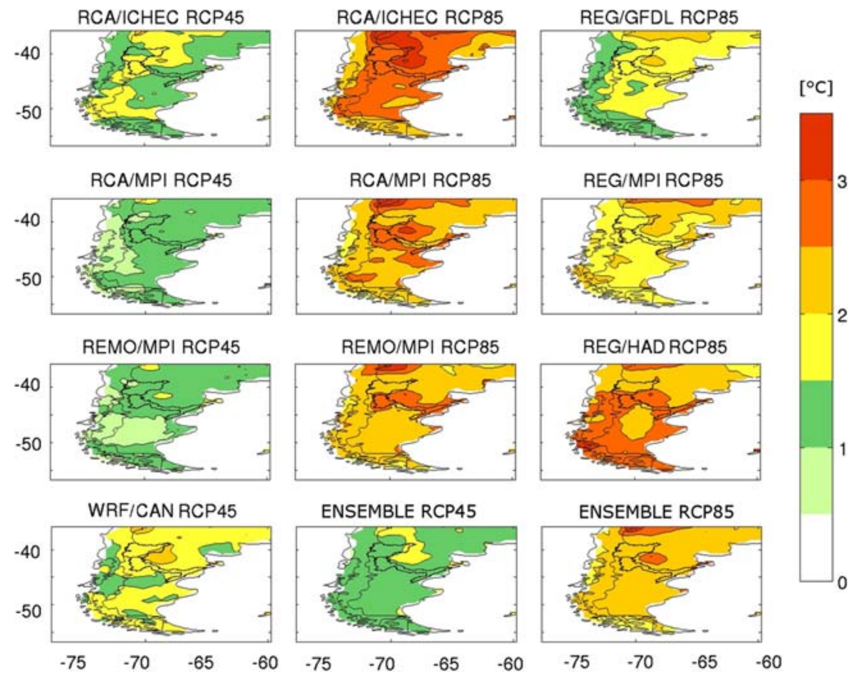

Fig. 5 Annual mean temperature change for far future period for CORDEX-RCM corrected simulations and the RCP45 and RCP85 ensembles. Units: °C

The difference between scenarios in the headwaters of the basins is evident in the temperature projections, which show that the projected temperature change is approximately 1 °C larger for the RCP85 scenario compared with the RCP45 scenario, as expected. On the other hand, the precipitation projections in the headwaters of the basins are similar for the two emission scenarios. It is also important to highlight that climate change signal is similar in both basins although the average precipitation changes projected by the end of the century are a bit lower in the headwater of the ChRB than in the LRB, and the pattern is the opposite for temperature projections.

3.2 Water yield projections

In ChRB, the projected changes in water yield provided by InVEST model forced by CORDEX-RCM for the far future under RCP45 and RCP85 are displayed in Fig. 6. The most consistent feature in all simulations is that the highest projected relative changes in water yield are located in the middle basin. However, water yield values in this part of the basin are low as a consequence of the low mean annual precipitation values (less than 200 mm yr^{-1}, Pessacg et al. 2015). In absolute terms, the most relevant changes are located in the upper basin where water yield is higher (subbasins 1, 2, 3, 4, 7, 8 and 10 as found in Pessacg et al. 2015). In these subbasins, most of the models project a reduction in water yield higher than − 30% for the RCP45 and − 40% for the RCP85 scenario (Fig. 7). These projected changes are larger than the ensemble spread (except for the RCA/ICHEC RCP 45) which indicate that changes in water yield for the RCP45 and RCP85 ensemble simulations are significant.

Inspection of individual models suggests that although all the models agree on water yield decrease in the ChRB, there are large differences in the magnitude of the projected change. In the upper ChRB, these changes range from − 60% for the REMO/MPI and REG/GFDL to − 25% for RCA/ICHEC for the RCP85 scenario. The difference on the projected water yield among simulations indicates that the uncertainty associated with the models driving the water yield simulation is relevant.

A measure of the uncertainty, quantified in terms of the difference between the maximum and minimum RCMs signal, was computed for the upper basin, and the results are displayed in Fig. 7. In the ChRB, the uncertainties in water yield projections due to the selection of the CORDEX-RCM are in average (in the upper ChRB) around ± 20% for both the RCP45 and RCP85 scenarios (Fig. 7c, f). Uncertainties in water yield reflect the uncertainty in evapotranspiration (mostly driven by temperature changes) and precipitation projections, main drivers of the water yield model. The uncertainty in precipitation projections is in average around ± 10% for both scenarios in the upper basins (Fig.7a, d), whereas the uncertainty in evapotranspiration between the different CORDEX-RCMs simulations is around ± 7% for both scenarios (Fig.7b, e). It is relevant to note that the uncertainties for the two emission scenarios are similar for the two evaluated variables.

In the LRB, climate change projections show a decrease in water yield for most of the basin and for all simulations carried out with the different CORDEX-RCMs (Fig. 8). As in the ChRB, the subbasins with higher water yield are located in the upper basin (subbasins 1, 8, 9 10, 16 and 22, as found in Pessacg

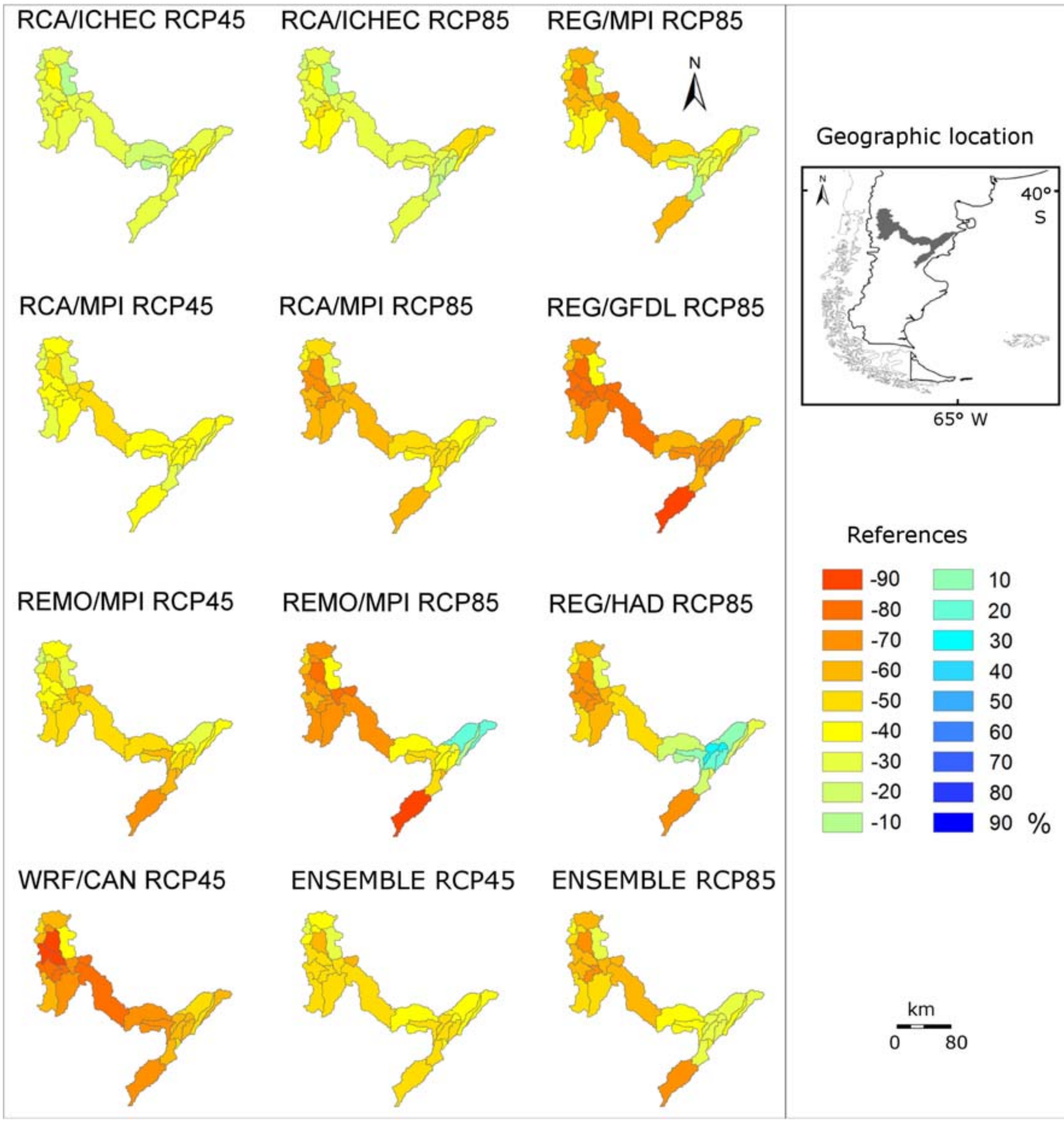

Fig. 6 Annual mean water yield change for the Chubut River basin for far future period. Units: %

et al. 2018). In such subbasins, the projected decrease in water yield for the far future scenario is around − 20% for the two RCPs scenarios evaluated (Fig. 8). These projected changes are larger than the ensemble spread which indicate that the projected decrease in water yield is significant. For the RCP85 scenario, simulations forced with the REMO/MPI and RCA/MPI show the highest values in the south of the basin headwater, with changes higher than − 35% in some subbasins (Fig. 8). As in the ChRB, simulations forced with the RCA/ICHEC model show the lowest values of water yield change in the headwater of LRB (lower than − 10% in some subbasins) (Fig. 8). It is interesting to note that the RCA/ICHEC simulation projects the lowest precipitation change for the upper ChRB and LRB but the highest temperature change for the far future (Figs. 4 and 5).

Uncertainties in water yield simulation in the headwater of the LRB due to the selection of the CORDEX-RCM are in average (in the upper LRB) around ± 8% for both scenarios (Fig. 9c, f).This uncertainty in water yield simulations stems mostly from uncertainties in precipitation of the order of ± 7% for both RCPs scenarios (Fig.9a, d) and uncertainties in evapotranspiration (temperature) of the order of ± 4 and ± 7% in average in the upper basin for the RCP45 and RCP85, respectively (Fig.9b, e).

Water yield simulations not only reflect the uncertainties among RCMs but also the uncertainties related to the GCMs used to force the RCMs and uncertainties due to the emission

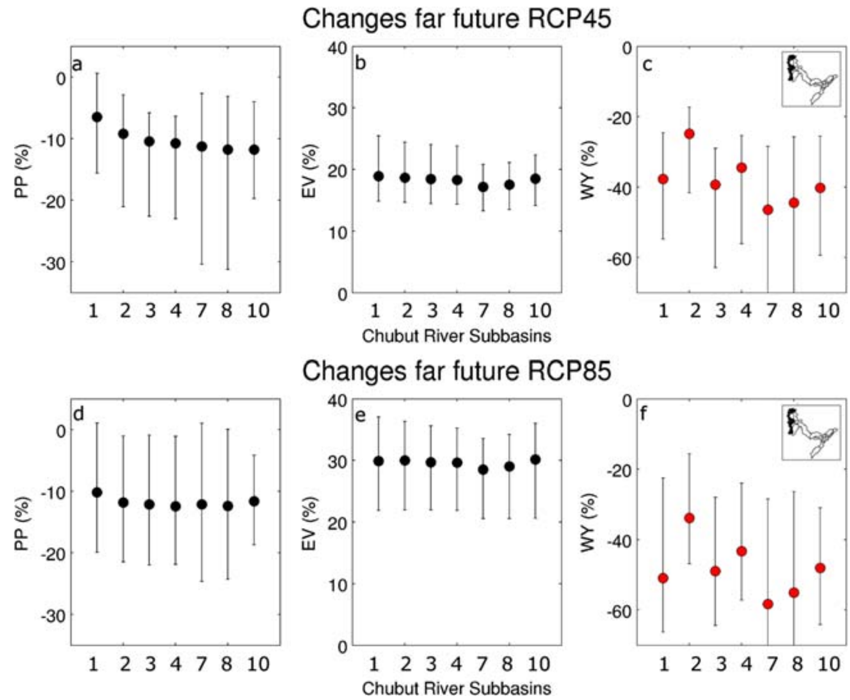

Fig. 7 Changes in annual mean precipitation (PP) (**a**, **e**), actual evapotranspiration (EV) (**b**, **e**), and water yield (WY) (in %) for far future compared to the historical period (**c**, **f**). Changes are shown for the subbasins with more water yield in the Chubut River basin (1, 2, 3, 4, 7, 8 and 10, in black in the ChRB drawn in the right panel). Dots indicate the value for the model's ensemble, and bars indicate the range between maximum and minimum change value provided by the CORDEX-RCMs. Upper panels **a**, **b** and **c**: results for the RCP45 scenario. Lower panels **d**, **e** and **f**: results for the RCP85 scenario

scenarios. Three of the CORDEX-RCMs simulations used in this study are performed with the same RCM but driven by three different GCMs (REG/HAD, REG/MPI, REG/GFDL, see Table 1). The results clearly show important differences among these three simulations, with the REG/GFDL showing the highest decrease in water yield for the far future in both basins (Figs. 6 and 8). Differences in precipitation and evapotranspiration among these three simulations (not shown) present a range of values of around ± 10% which translate into differences in water yield of around ± 8 and ± 13% for the headwater of LRB and ChRB, respectively.

Concerning the uncertainty related with the emission scenarios, simulations for the two different RCPs (RCP45 and RCP85) are available for three of the CORDEX-RCMs used in this study (see Table 1) so that the differences between the scenarios have also been assessed. Note that future precipitation and temperature changes for either RCP45 or RCP85 based on the RCA and REMO CORDEX-RCMs (Figs. 4 and 5) display the same spatial pattern, respectively, but the magnitude of the changes is larger for the higher emission scenario, as expected. Moreover, with the exception of the RCA/ICHEC model, the projected precipitation decrease, temperature increase and water yield decrease over the headwaters of ChRB and LRB are approximately doubled for the RCP85 when compared with the RCP45 scenario. The differences in water yield projections between the two scenarios are in the order of 17% for the RCA/MPI and 26% for REMO/MPI in the headwater of the ChRB and in the order of 11% for both models in the headwater of the LRB (not shown).

Inspection of Figs. 6 and 8 also evidences that the WRF/CAN simulation for the RCP45 emission scenario shows the largest water yield reductions in the headwaters of both basins, even larger than results from other models under the RCP85 scenario. This is due to the fact that this model projects a large decrease in precipitation for the far future in the headwaters of the basins (Fig. 4).

Finally, it is relevant to note that, although changes in projected temperature and precipitation over the headwaters of the two basins are similar, the response of water yield in the ChRB and LRB to these changes are very different (in average − 40% for the ChRB and − 20% for the LRB). This result suggests that the ChRB is more sensitive to changes in the climatic variables evaluated than the LRB Table 2.

4 Discussion and conclusions

In light of the evidence of the recent warming trend in temperature observed in Patagonia (Barros et al. 2014) and considering the impact of temperature anomalies on water resources, it is highly relevant to assess the impact of global warming on water availability in the region. For that purpose, several CORDEX-RCMs simulations under two emission scenarios were used to force the InVEST hydrological model in order to assess the impact of climate change on water yield.

Given the systematic biases found when using the CORDEX-RCMs to represent observed climatic conditions for the region, the quantile mapping method was first applied to precipitation and temperature data. It was found that errors

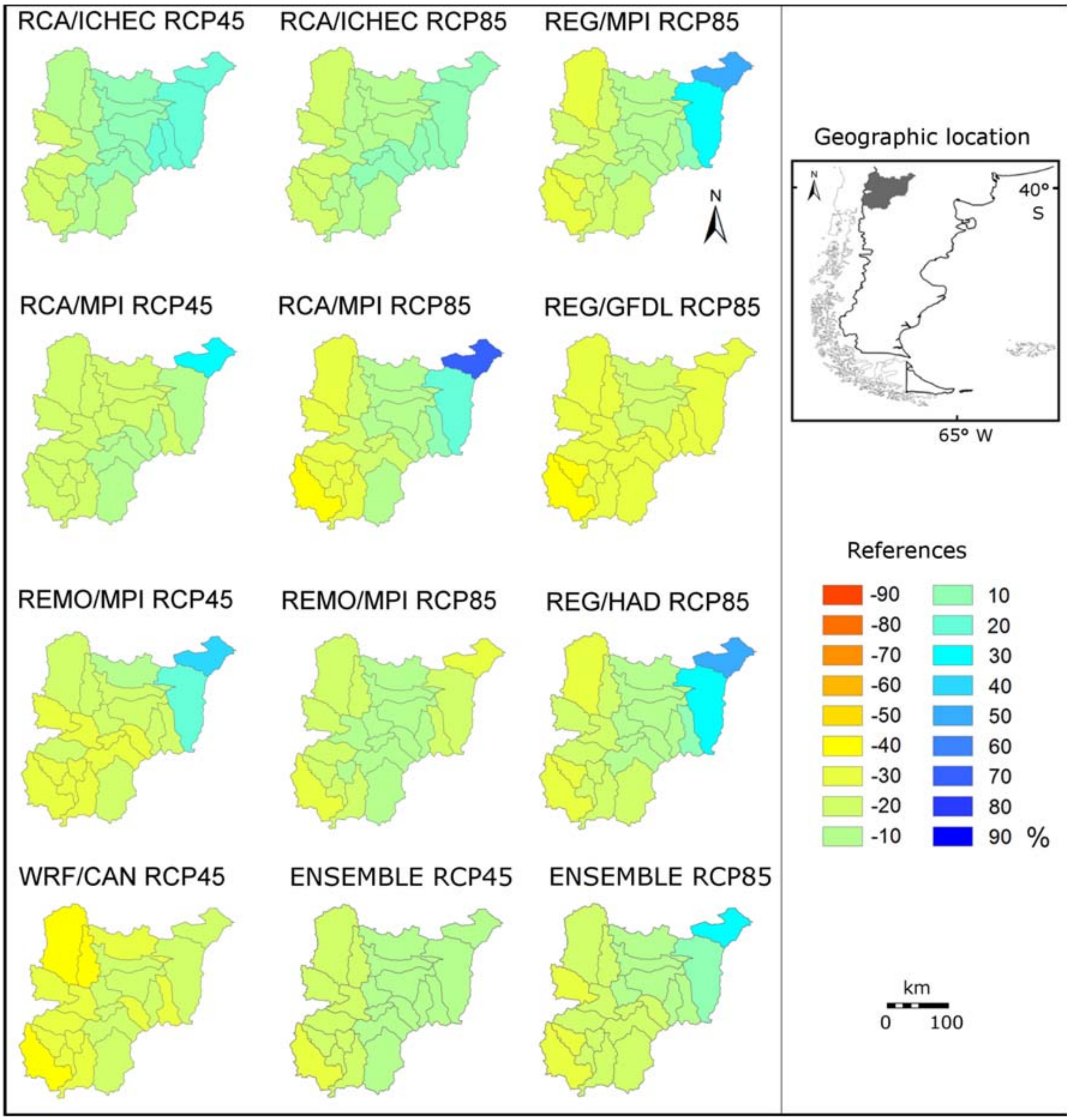

Fig. 8 Same as Fig. 6 but for the Limay River basin

in mean annual temperature and precipitation were strongly reduced, suggesting that the bias correction methodology selected for the annual mean variables is adequate. Future climate projections derived from the CORDEX-RCMs set of models agree on a clear signal of precipitation decrease ranging from − 10 to − 30% in the ChRB and LRB for the far future scenario (2071–2100). This precipitation signal is consistent among the seven CORDEX-RCM simulations. In terms of temperature, these CORDEX-RCM simulations project an increase from 1.5 to 3 °C for the far future scenario over both the Limay and the Chubut River basins. The increase in evapotranspiration (associated with the increase in temperature) and the decrease in precipitation projected for the far future both contribute to reductions in water yield for the two Patagonian basins. The results of the InVEST model simulations for the far future show a − 20% decrease in water yield for the headwater of Limay River basin and a − 40% for the headwater of the Chubut River basin. The change in the water yield signal is consistent among all InVEST simulations. These results are in line with the negative trends in average annual flow rate that have been registered over the last decades for the main rivers in northern and central Patagonia, including the Limay and Chubut Rivers (Fundación e Instituto Torcuato Di Tella 2006; Moyano and Moyano 2013; Pasquini and Depetris 2007; Vich et al. 2014).

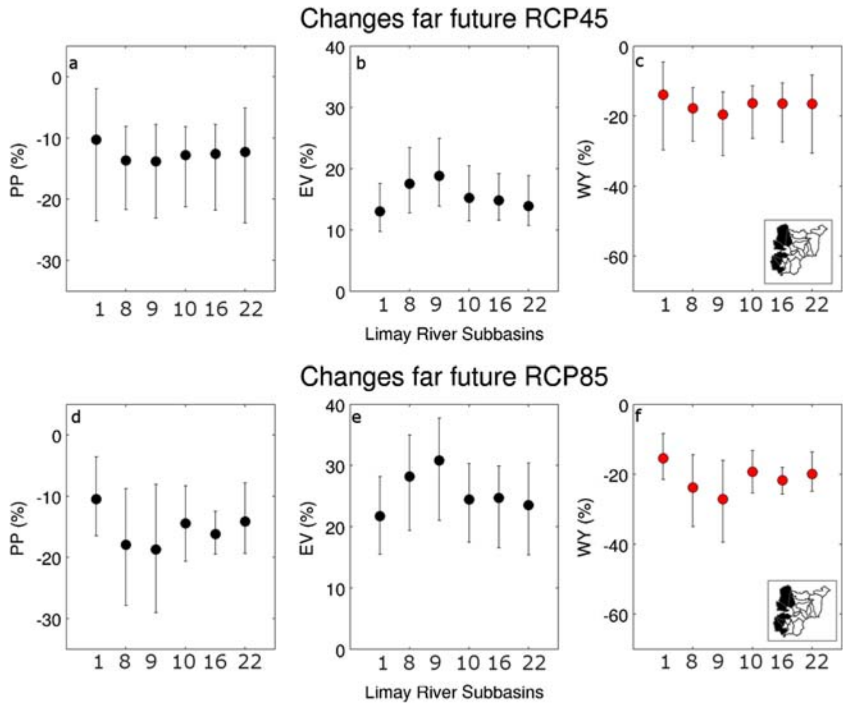

Fig. 9 Same as Fig. 7 but for the subbasins with more water yield in the Limay River basin (1, 8, 9, 10, 16 and 22, in black in the LRB drawn in the right panel)

It is also relevant to assess the relative impact of precipitation and evapotranspiration changes on water yield change in order to understand the main drivers of the impact. Figure 10 summarizes the changes in evapotranspiration/precipitation and in water yield for each individual CORDEX-RCM for the two basins. The decrease in precipitation seems to have a larger effect on water yield than the increase in evapotranspiration. While there is a strong linear relationship between the decrease of both water yield and precipitation, the relationship between the increase in evapotranspiration and the decrease in water yield is not clear. Moreover, it can also be remarked that the sensitivity of water yield to climatic changes is stronger in the ChRB compared with the LRB. Considering that the two basins are located nearby, the projected changes in both temperature and precipitation for each basin are similar. However, the impact of these changes on the water yield is not. In fact, a similar change in temperature and precipitation leads to a decrease in water yield for the ChRB that is two times larger than for the LRB. Considering that the main drivers of water yield are precipitation and land use/land cover (Pessacg et al. 2018), the response of water yield to changes in precipitation and temperature may be modulated by the LULC in each basin.

Table 2 Input variables and files for the InVEST water yield module (InVEST version 3.3.)

Input	Description/units	Source
Root restricting layer depth	Soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics/mm	INTA soil map http://geointa.inta.gov.ar
Precipitation	Average annual precipitation/mmyr^{-1}	Precipitation from RCMs (see Table 1)
Plant available water content	Fraction of water that can be stored in the soil profile that is available for plants' use/mm	INTA & Ministry of Agriculture, Food & Fisheries, British Columbia (Canada)
Reference evapotranspiration	Average annual reference evapotranspiration/mm	Calculated with Holdridge equation using temperature from the RCMs (see Table 1)
Land use/land cover (LULC)	Land use/land cover map	INTA http://geointa.inta.gov.ar
Watersheds	Main watersheds	GIS tools ArcHydro
Subwatersheds	Subwatersheds within the main watersheds	GIS tools/ArcHydro
Root depth	Maximum root depth for vegetated LULC classes/mm	Canadell et al., 1996
Plant evapotranspiration coefficient	Plant evapotranspiration coefficient for each LULC class	FAO (http://www.fao.org)
Seasonality factor (Z)	Seasonal distribution of precipitation	Donohue et al., 2012 Z = 1 Limay (Pessacg et al. 2017) Z = 15 Chubut (Pessacg et al. 2015)

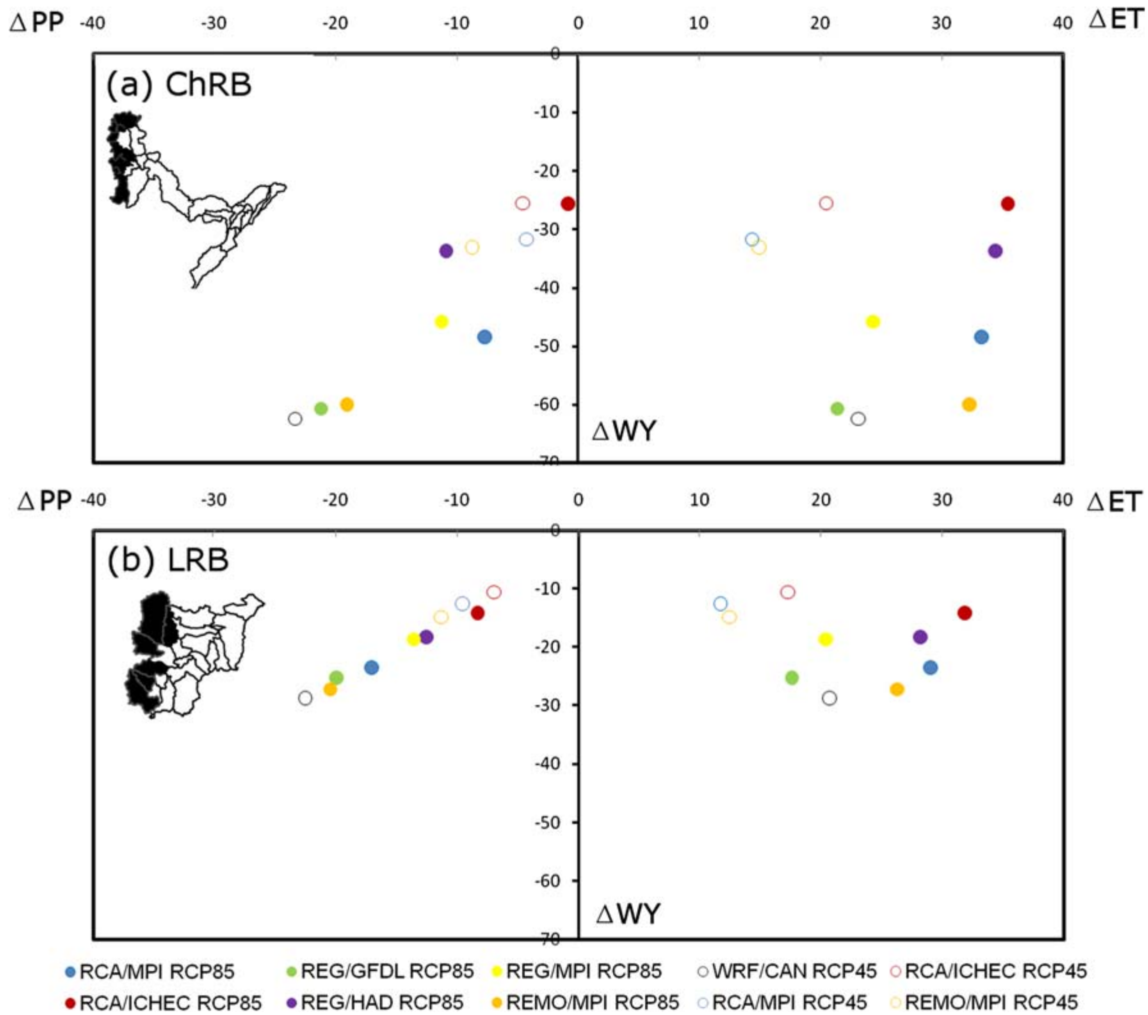

Fig. 10 Relative impact of precipitation changes (∆PP) and evapotranspiration changes (∆ET) in water yield changes (∆WY) for the Chubut River upper basin (**a**) and the Limay River upper basin (**b**) (Unit: %). Each dot indicates a different CORDEX-RCM. Full (open) dots indicate the CORDEX-RCM models for the RCP85 (RCP45) emission scenarios

The headwater of the LRB is located over a protected area with more than 50% of the region characterized by the presence of woods, while the headwater of the ChRB is located in the extra-Andean Patagonia that is characterized by grassland (Flaherty et al. 2017). Accordingly, the water yield sensitivity to precipitation changes is larger for LULC categories with higher values of evapotranspiration (Pessacg et al. 2015). Hence, land cover may be considered a buffer of water yield changes. This highlights the key role that protected areas play in reducing the vulnerability of water resources to climate change.

Uncertainties in water yield future projections stem from a number of sources, such as internal variability in the GCMs and RCM simulations inherent to the chaotic and nonlinear nature of atmospheric processes (Hawkins and Sutton 2011); dispersion among the RCMs simulations due to boundary conditions (depending on the GCMs selection), dispersion among simulations due to the selected models (RCMs and hydrological models) and emission scenario. Previous studies have shown that GCMs are the main sources of uncertainties in climate change (Sanchez et al. 2015). However, in the current study, the results show that water yield uncertainties related to the selected GCM (± 13 in the ChRB and ± 8% in the LRB) are of the order of those related to the selected RCMs (± 20 in the ChRB and ± 8% in the LRB) and emission scenarios (± 15 in the ChRB and ± 5% in the LRB). The uncertainties in the water yield projections in LRB are lower than the uncertainties in the ChRB. Furthermore, the signal in water yield for the far future for the two basins is larger than the range of uncertainty in the simulations, no matter which uncertainty source is being considered. All in all, it is clear that the projections of decrease in water yield for the two Patagonian basins are robust.

The results discussed above are based on bias corrected model results. However, the bias corrected data is expected to depend on the bias correction methodology applied (Maraun et al. 2017). Moreover, the performance of any correction method is, to a large extent, dependent on the quality of the observations used for calibrating the method, and hence, the results can vary depending on which observational database is used. This element may be considered an additional source of uncertainty that should be taken into account. Moreover, one additional caveat when applying bias correction methods is the assumption that the bias for both present and future climate conditions is the same, which may not be valid. Assuming that the transfer functions are time-invariant could lead to changes in climate change trends. In particular, in southern South America, Solman (2016) show that models' bias behaviour may affect the future climate signal. In the current study, the corrected and uncorrected CORDEX-RCM simulations show the same sign of climate change trends, but the magnitude of changes is weaker for the corrected simulations compared with the raw model data, and this behaviour may have a strong impact on the projected changes in water yield.

Finally, only changes in annual mean values were analysed in the current study. However, there has been an increase in the frequency of extreme precipitation events in several regions of the world, and simulations indicate that this pattern will continue in the future (Scott et al. 2016; Stocker et al. 2013). A recent event illustrates the local impact of extreme events on hydrological ecosystem services. In March–April of 2017, an extreme precipitation event in the south of the Chubut province activated the Río Chico, an affluent of the Chubut River that had been dry for 80 years (Kaless et al. 2019). As a consequence, large amounts of sediments accumulated on the river were transported into the main course of the Chubut River. The sediment content in the river water slowed down the water purification process, leaving more than 250,000 people with very limited water supply for more than 20 days. Further research should focus on analysing the impact of changes in extreme precipitation events along with changes in annual mean values, as this would allow for a better evaluation of the ecohydrological impact of these changes, as well as for a broader assessment of the social and economic implications.

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