Water availability in a mountainous Andean watershed under CMIP5 climate change scenarios

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Abstract Recent updates to climate change scenarios developed under the Coupled Model Intercomparison Project Phase 5 (CMIP5) are used to compare water resources availability in an Andean mountainous snow-dominated watershed, Maipo en San Alfonso, located in the vicinity of Chile's capital city, Santiago. monthly hydrologic simulations for a base line period and future scenarios are carried out through the software WEAP, considering precipitation and temperature monthly time series predicted for scenarios A2 by GCM MK3.0, as well as for RCPs 2.6 and 8.5 scenarios by GCM MK3.6. Ensembles given by the GCM MK3.6 are used as inputs to the hydrological model to obtain uncertainty of water availability projections. Future hydrological simulations are carried out from years 2011 to 2070. Results show that mean annual flows tend to decrease by 8%, essentially during the snowmelt period for A2 and RCP 8.5 scenarios. Nevertheless for the RCP 2.6 scenario, the tendency to decrease is reversed at the end of the period.

Key words water availability; CMIP5 climate change scenarios; uncertainty; mountainous Andean basin

INTRODUCTION AND CLIMATE PROJECTIONS BACKGROUND

Future water availability is a key point for human development. Current surface water availability in a given location depends on watershed characteristics such as soil type and use, coverage, altitude, orientation and exposition, but local climate also plays an important role in the magnitude and distribution of river runoff throughout the year.

Projections of meteorological variables based on the range of non-mitigation scenarios developed by the IPCC Special Report on Emissions Scenarios (SRES) indicate that projections of future precipitation changes are more robust for some regions than for others; also it is stated that projections become less consistent between models as spatial scales decrease (Bates *et al.*, 2008). It is also recognized that many semi-arid and arid areas are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources.

In addition, water supplies stored in glaciers and snow covers are projected to decline in the course of the century (Barnett *et al.*, 2005) and long-term changes, in particularly in the snowmelt-dominated parts of the world are expected. The decreases on the magnitude of precipitation tend to change the annual volume of runoff, and together with the increase of temperature, tend to affect mainly the snow accumulation volume due to the occurrence of liquid precipitation at higher altitudes. These lead to earlier runoff in winter or spring.

The detected trends in Chilean basins (Cortes *et al.*, 2011) are only consistent with trends in precipitation, as rivers that showed high correlation to temperature do not show any trend. This conclusion suggests that rivers in the region show a different response to temperature changes when compared to rivers of similar regime in the Northern Hemisphere, and that precipitation amount and timing are the source of most of the variability in streamflow timing for both snowmelt and rainfall-dominated watersheds.

Recently, under the fifth phase of the Coupled Model Intercomparison Project (CMIP5) some global circulation models have been updated to deliver in the near-term experiments, as part of a forecast system, a full prediction of climate change, whereas in the long-term experiments the models will provide a projection of the "forced" responses of climate to changing atmospheric composition and land cover (Taylor *et al.*, 2012). The CMIP5 projections of climate change are driven by concentration or emission scenarios consistent with the representative concentration pathways, RCPs, described in Moss *et al.* (2010). Four RCPs have been formulated that provide a rough estimate of the radiative forcing in the year 2100 (relative to pre-industrial conditions). The fifth phase of the CMIP5 centres on performing a suite of climate simulations that focus on major gaps in understanding of past and future climate changes. The new scenarios, called "RCP", assume fixed levels of radiative forcing (i.e. net warming) by year 2100 and are not built on any social or economic assumptions. The four RCP scenarios being used are outlined in Table 1.

Table 1 Representative Concentration Pathways. Source Moss *et al*. (2010).

Name	Radiative forcing (Wm^{-2})	Concentration [ppm]	Pathway
RCP 8.5	> 8.5 in 2100	> 1370 CO_2-equiv. in 2100	Rising
RCP 6.0	~6 at stabilization after 2100	~850 CO_2-equiv. (stabilization after 2100)	Stabilization without overshoot
RCP 4.5	~4.5 at stabilization after 2100	~650 CO_2-equiv. (stabilization after 2100)	Stabilization without overshoot
RCP 2.6	Peak at ~3 before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline

Many studies of projected climate change and water availability consider a range of plausible changes in population and economic activity over the 21st century; among these scenarios the most negative is SRES A2 scenario. For this scenario global circulation models (GCMs) in general suggest decreases in precipitation over many mountainous areas in central Chile and increases in temperature. Among the best model performance for the study area, meteorological forcing given by MK 3.0 model developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was selected for the SRES A2 scenario.

For RCPs scenarios, the GCM MK 3.6, the improved version of the CSIRO global circulation model, was chosen. This GCM, differs from it predecessor, Mk3.0, by inclusion of modified schemes for aerosol particles, radiation and boundary layer treatment. For the analysis we selected the RCP 2.6 and RCP 8.5 as the most favourable and negative scenarios. It is important to note that 10 future ensembles of these meteorological projections that differ in their starting set up, but have the same radiative forcing conditions, are available. Through these different ensembles of the models it is possible to then examine the uncertainty related to the variability projected for the hydrological model under each of these scenarios, Comparison of the climate simulations in Mk3.6 with those in Mk3.0 for Maipo en San Alfonso, an Andean mountainous snow-dominated basin in central Chile with an area of 2840 km^2, especially regarding winter rainfall and uncertainty of future flows under SRES A2 and RCPs, is the problem we aim to assess in this article.

STUDY AREA

The area selected for the study was the upper Maipo River located in the vicinity of Chile's capital city, Santiago, as shown in Fig. 1. This basin concentrates important glacier areas and the water resources are mostly dedicated to civil consumption, industrial activities and irrigation. Also, some hydroelectric power plants are located in the area.

Observed data registered from April 1981 to December 2005 by the national water bureau, the Dirección General de Aguas (DGA) was used to calibrate the hydrologic simulation model. For this study two meteorological stations located at Maipo River basin and three hydrological stations (see Table 2) at the highest part of the basin were considered.

Table 2 Meteorological and hydrological stations.

		Latitude	Longitude	Altitude (masl)
Meteorological	San Gabriel	33°47'1"S	70°14'W	890
Meteorological	Pirque	33°40'1"S	70°35'W	1500
Hydrological	Río Volcán en Queltehues	33°48'21"S	70°12'32"W	1365
Hydrological	Río Maipo en San Alfonso	33°43'54"S	70°17'57"W	1108
Hydrological	Río Maipo en Las Melosas	33°50'54"S	70°11'46"W	1527

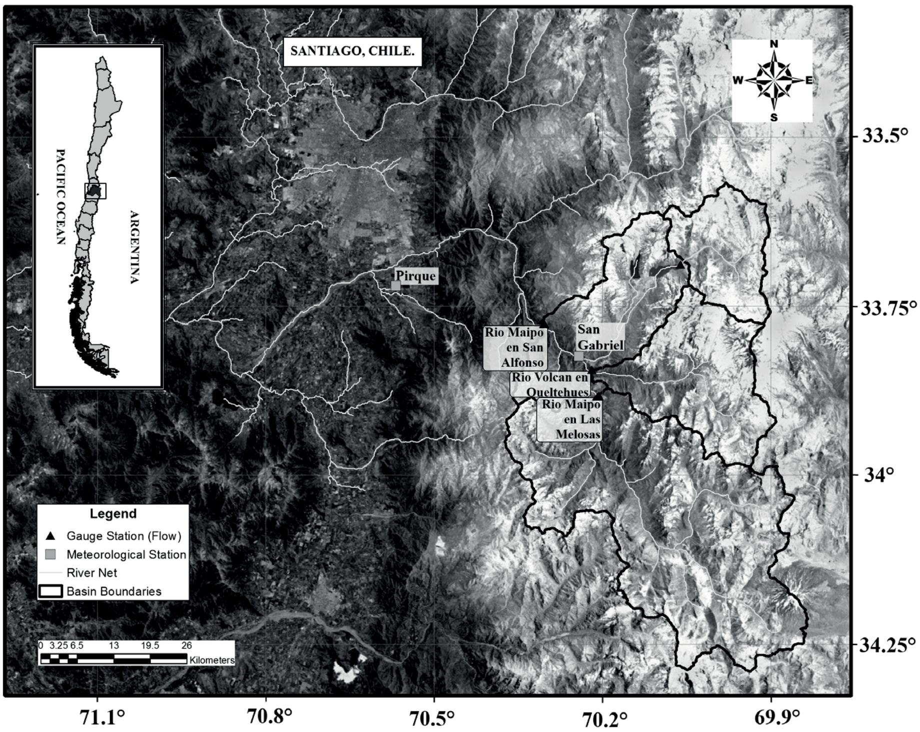

Fig. 1 Study area.

METHODOLOGY

To study the local effects of the climate change, at Maipo en San Alfonso basin, a downscaling of the GCM meteorological data is necessary, in order to get data comparable with meteorological observations at the base stations, used for calibration of the hydrological simulation model. The downscaling considers the spatial and temporal scaling of the meteorological forcing to the local stations, San Gabriel for precipitation and Pirque for temperatures. The relation established in the baseline period (BL) for the selected GCM, is considered valid in the future, allowing us to determine for each scenario the time series of precipitation and temperature in the local stations mentioned above. First, the spatial interpolation using the GCM grid values is done and then comparison of monthly duration curves for the observed period temporal downscaling.

In order to simulate hydrologic conditions we use the Water Evaluation and Planning (WEAP) model, which has been successfully used in former studies to create hydrological models in the Andes mountains (Vicuña *et al*., 2010). WEAP is a computational tool for integrated water resources planning developed by the Stockholm Environment Institute and the Boston-based Tellus Institute. The hydrological module considers the basin configured as a contiguous set of sub-catchments that cover the entire extent of a given basin. The software WEAP does not consider glacier contribution to runoff; in order to overcome this fact a particular sub-catchment contributing to the highest sub-catchment was defined. The magnitude of this contribution was obtained from *in situ* measurements available on previous studies (not published) weighted by a monthly factor. For the future, a yearly glacier area reduction of 1% (Bown *et al*., 2008) was taken.

For the calibration, monthly precipitation, temperature and streamflow data observed at stations indicated in Table 2 are used, considering the period from April 1982 to March 2000, meanwhile the validation period is defined from April 2000 to March 2005. Nash-Sutcliffe (NS) and NS-Log efficiencies parameters (Kraus *et al*., 2005) are set as objective functions, varying the model parameters manually in order to keep values inside established ranges. Resulting indexes at Maipo en San Alfonso were NS = 0.85 and NS-Log = 0.85 for calibration and NS = 0.81 and NS-Log = 0.88 for validation. Figure 2 shows good agreement between observed and simulated data.

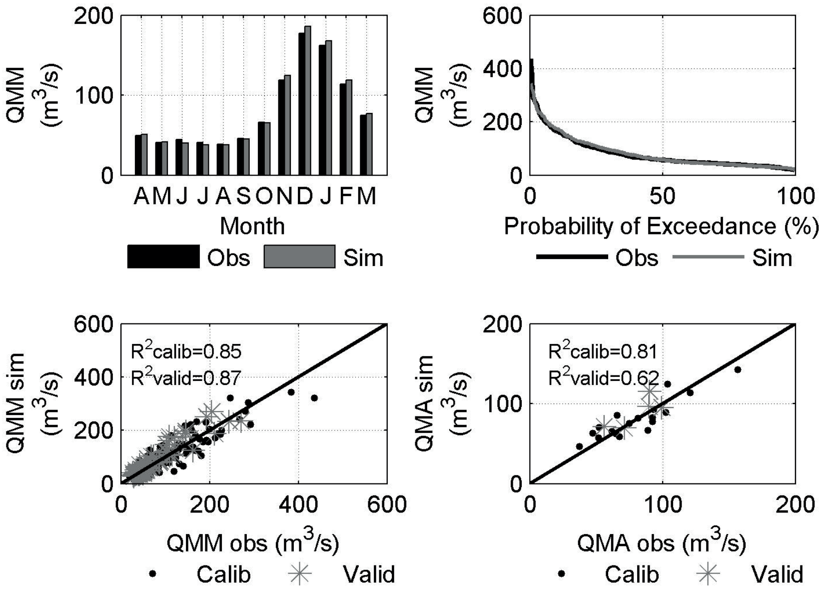

Fig. 2 Mean monthly flow (QMM) at Maipo en San Alfonso. Observed and simulated average values (top left); duration curve (top right); observed and simulated mean monthly values (bottom left) and observed (QMA obs) and simulated (QMA sim) mean annual flow (bottom right).

RESULTS

For the analysis of future water resources availability, we divide the period under study in to two windows, the near-term from 2011 to 2040 (W1) and the long-term from 2041 to 2070 (W2). For RCPs scenarios we randomly selected three of the 10 ensembles available for each chosen scenario at the meteorological base station. For example, for RCP 8.5 projections a larger variation is detected among precipitation ensembles than among temperature ensembles. In Fig. 3 we can appreciate in each temporal window, the behaviour of the mean monthly precipitation for the base line period (1982–2005), the average value together with the standard deviation value of the 10 ensembles, and the particular mean monthly precipitation of each one of the three selected ensembles. We can say that the three selected meteorological projections can be considered representative of the 10 ensembles. Furthermore, we can observe that in general RCP 8.5 projections of precipitation during the winter season (April to September) tend to decay as compared to the base line period in the long term, but in the near term values tend to slightly increase. However, temperatures tend to have a larger increase in the long term in this scenario. The differences on the RCP 2.6 projections at the two time scales are not so obvious, but we can observe a larger standard deviation for precipitation in the wetter months (June and July).

Figure 4 shows the behaviour of the mean monthly flows associated with different probability of exceedence for both RCPs. Shadow zones give the uncertainty for each scenario. It is observed that for streamflow normal years (50% of probability) there is an increase of winter and spring flows for the near term, but for the long term the decrease of flows during the summer or recession of snowmelt period is significant. During wet years (5% of probability of exceedence) the behaviour is similar but the change is more evident particularly in the long term due to severe precipitation and the high temperatures, but also the uncertainty increases.

Table 3 shows an increase of precipitation for both RCPs scenarios under the first window of analyses, but only the RCP 2.6 maintain that tendency for the long term. Temperature at W1 is also very similar among scenarios and the variation of precipitation is not significant; in fact, this gives a streamflow variation smaller than 3 m^3/s. As to W2, we observed that the RCP 8.5 present a 10% decay in mean annual precipitation and also an increase of 1°C (higher than the 0.8°C in A2), which result in a strong decay of the mean annual streamflow to 74.1 m^3/s. This is far more severe than scenario A2. This decay in streamflow is also reflected in terms of runoff ratio, Q/P.

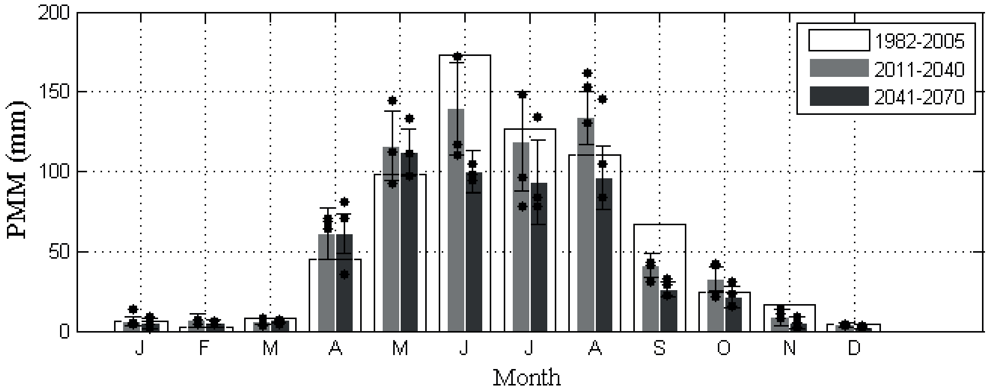

Fig. 3 Mean monthly precipitation (PMM) and ten ensembles projections at San Gabriel gauge. Dots represent data of three selected ensembles. Global Circulation Model MK 3.6, RCP 8.5.

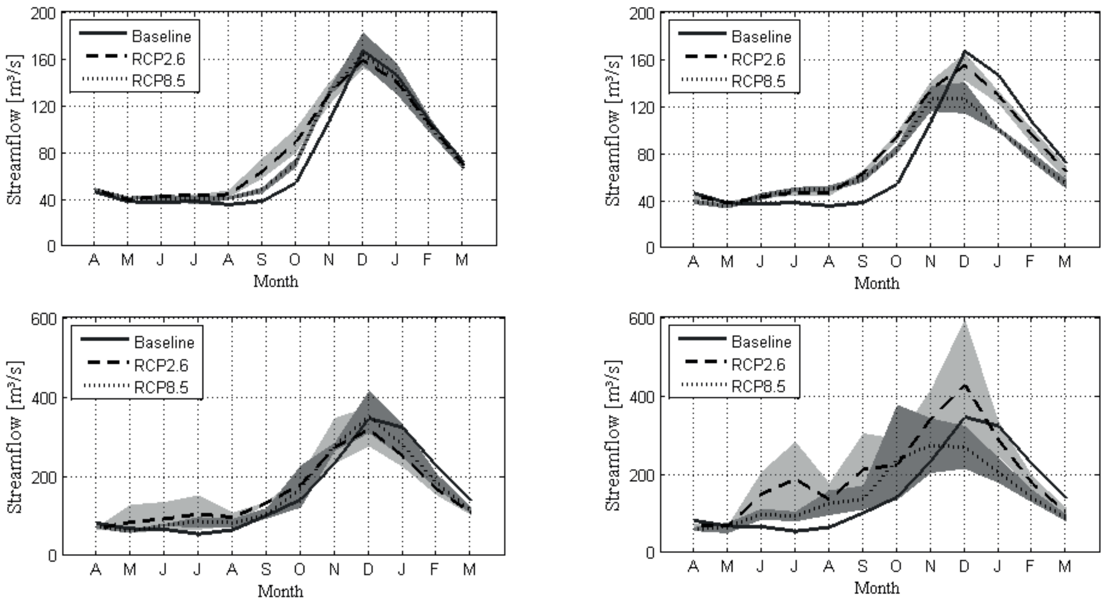

Fig. 4 Mean monthly streamflow for 50% probability of exceedence near term (top left) and long term (top right); Mean monthly streamflow for 5% probability of exceedence near term (bottom left) and long term (bottom right). Dashed lines represent the average of the ensembles for each RCP. Shadow zones give the uncertainty for each scenario.

Table 3 Summary of mean annual results for the Maipo en San Alfonso basin: Precipitation (P) in mm, Temperature (T) in °C, streamflow (Q) in m^3/s and runoff ratio (Q/P).

Period	OBS			BL			W1			W2			Q/P			
Scenario	Q	P	T	Q	P	T	Q	P	T	Q	P	T	OBS	BL	W1	W2
RCP 2.6	80.9	1104	5.2	87.4	1103	5.22	87.0	1176	5.92	88.8	1186	6.29	0.82	0.89	0.83	0.84
RCP 8.5	80.9	1104	5.2	87.4	1103	5.22	84.1	1133	5.86	74.1	1012	6.93	0.82	0.89	0.83	0.82
SRES A2	80.9	1104	5.2	81,0	1098	5.18	74.6	1103	5.75	74.9	1101	6.51	0.82	0.83	0.76	0.76

Table 4 shows the streamflow projections together with mean temperatures and precipitation for the warm and cold seasons, to reveal changes in seasonality. The cold period (APR-SEP) mean streamflow tends to increase for the RCPs scenarios. A2 presents a negligible variation. The future reduction for all scenarios is in the warm season flows. Here the RCPs shows almost the same flow in W1 with a reduction near to 9 m^3/s with respect to base line period, and A2 presents a decay of 11 m^3/s. The difference appears in W2, RCP 2.6 shows a slight recovery, but RCP 8.5 presents the highest decay of 22 m^3/s from W1, making this scenario far more severe than A2. Observing the meteorological data, it is possible to relate the increase of flows in the cold season to the rise in the mean temperatures during the same season since this would cause reduction of the basin area that stores water as snow. This last comment also relates to the decrease of flows in the warm season since the projections show a reduction of the snow cover. The differences of the magnitude of precipitation during both seasons explain additional variations of streamflow.

Table 4 Summary of streamflow, temperature and precipitation in cold (APR–SEP) and warm (OCT–MAR) seasons for all scenarios and time windows.

	OCT–MAR Streamflow (m³/s)			Temperature (°C)			Precipitation (mm)		
Scenario	BL	W1	W2	BL	W1	W2	BL	W1	W2
RCP 2.6	131.6	123 ± 3	124 ± 2	8.7	9.3	9.7	115.1	132.8	102.8
RCP 8.5	131.6	121 ± 5	99 ± 6	8.7	9.3	10.3	115.1	115.7	87.6
SRES A2	119.9	108.4	106.5	8.7	9.4	10.2	99.2	88.5	100.3
	APR–SEP Streamflow (m³/s)			Temperature (°C)			Precipitation (mm)		
Scenario	BL	W1	W2	BL	W1	W2	BL	W1	W2
RCP 2.6	43.3	51 ± 3	54 ± 1	1.7	2.6	2.9	987.4	1043.3	1083.6
RCP 8.5	43.3	46 ± 2	49 ± 1	1.7	2.4	3.5	987.4	1017.1	924.8
SRES A2	42.1	40.7	43.3	1.8	2.7	3.6	993.9	1014.1	1000.4

SUMMARY AND CONCLUSIONS

In the near term, global circulation model MK 3.6 projections for scenarios RCPs tend to be more favourable than former scenario SRES A2 for water resources availability. The main source of this behaviour is attributed to the differences in winter precipitation projections. Nevertheless there are some extreme monthly precipitation values that together with higher future temperatures, generate mean monthly flows during winter time much greater than those simulated in the base line period. In the long term, RCP 8.5 is the most negative for water resources availability; this is attributed to the higher temperatures that generate more losses and a consistently lower runoff ratio.

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