Climate Change Impacts on Water Availability in the Arid Elqui Valley, North Central Chile: A preliminary Assessment

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Abstract

In the vulnerable north central Chile (*Norte Chico*), where agriculture still serves as a backbone of the economy as well as ensures the well being of the people, the knowledge of future water resources availability is essential. The region is characterised by an arid climate with a mean annual precipitation inferior to 100 mm. Moreover, the local climate is also highly influenced by the ENSO phenomenon, which accounts for the strong inter-annual variability in precipitation patterns mainly occurring in high altitude areas.

The outputs of the HadCM3 A2a and B2a SRES scenarios were regionalised for the Elqui watershed for a 60-years period (2000-2059) by means of the SDSM statistical downscaling technique. Thereafter, the hydrological model (HEC-HMS) was calibrated and fed with downscaled scenarios. Accordingly, future streamflows were simulated for the studied period.

Results proved that local temperatures are expected to rise in the region, whereas precipitations may decrease. However, minimum and maximum temperatures are likely to increase with a faster rate in high altitude areas with an increase ranging from 1.0 °C to 2.05 °C by 2059. Further, lower altitudes areas expect an increase from 0.6 °C to 0.78 °C. The Andes mountain range may encounter warmer winters with a dramatic decrease of icing days (Tmax<0 °C). As for precipitation, both SRES scenarios return a diminishing trend of ca. 25%, though the A2a scenario results show a faster decrease rate. In addition, the region expects an augmentation of dry spell in middle altitude areas during the six decades. Results indicate potential strong inter-seasonal and inter-annual perturbations in the region. These, in turn, would impact the pattern of streamflows. By 2059, both A2a and B2a scenarios return a high variability in annual flows. Moreover, forecasted fluctuations of flows underline an increase of the sensitivity of the region in terms of hydrological responses to climatic variations. Hence, the hydrology of the Elqui valley could be strongly affected by climate change. Nevertheless, an insufficient number of high altitude meteorological stations does not allow us to draw definitive conclusions on future climate variability.

Thus, this work reveals the gap of knowledge concerning simulation of future extreme rainfall events on a local level for mid- and long term prognosis. Accordingly, concrete suggestions are made for future research to be taken in order to fill these data gaps.

Keywords: *Climate Change, Streamflow Simulation, Statistical Downscaling, Chile, Regional Impacts, Arid Watershed, HadCM3, HEC-HMS, SDSM*

1. Introduction

Nival regime driven basins in arid areas, such as the Elqui watershed are expected to be among the ecosystems most affected by climate change (Mata *et al*., 2001). Rainfall alterations from the ENSO events, the low cover of vegetation, poor mineral soil and severe droughts form the special features of the Elqui watershed. Moreover, the desertification or productivity deterioration in arid and semi-arid environments has been recognized as a critical problem worldwide (UNCCD, 1994). This problem is of particular concern for North Central Chile (the so-called "*Norte Chico", 26º-33ºS*), in particular de Atacama and Coquimbo Regions. For the latter, more than one half of its surface is classed as "grave" by the UNCCD in term of desertification. Consequently, immediate action and mitigation is needed in these watersheds (UNCCD-Chile, 2000, UNCCD-Chile, 2006). The average precipitation in La Serena, the most important city located in the Coquimbo Region, has reduced dramatically in the past 100 years. The 30-year monthly average has decreased from 170 mm in the early 20th century to values under 80 mm nowadays (Novoa & López, 2001). However, it is important to note that for those regions located east of the Andes mountain range, at the same latitude, an opposite trend in the precipitation time series has been registered (IPCC, 2007a).

Climate change is expected to strengthen these effects and to influence the local climate on an annual basis. In addition, the actual rate of climate change is greater than those recorded in the past (IPCC, 2001; 2007a). A shift in temperature, especially in higher altitudes where the glaciers account for important water reserves, might have adverse impacts on the hydrology of these arid watersheds. Moreover, the

ENSO phenomenon, affecting the regional climate, is expected to be influenced by global warming and global change (McPhaden *et al.*, 2006). Consequently, the species and communities will not have enough time to cope with the new conditions (IPCC, 2001; 2007b).

This paper aims at addressing in a preliminary approach these questions at a local scale. Scenarios (2000-2059) for the Elqui watershed, including specific features (Snowmelt, ENSO, semiarid conditions) of the watershed will be developed in order to carry on an analysis of the future climate (temperature and precipitation) with selected climate indices. Furthermore, qualitative and quantitative modelling of climate change impacts on the water availability will be simulated in the Claro sub-watershed, one of the main tributaries of the Elqui River. Finally, some sources of uncertainties are addressed and discussed.

2. Study Area: The Elqui Basin

The Elqui basin is located between 29.21°S to 30.3°S and 70.35°W to 69.49°W in the Coquimbo Region, within the so-called "*Norte Chico*" – the Small North. The Elqui river basin covers a total surface of 9,600 km^2. It has two main tributaries: the Turbio and the Claro Rivers. The Elqui watershed has climatic, physiographic and ecological features (Cepeda and López-Cortés, 2004), which make of it a natural and human system of high vulnerability to climate changes (UNCCD-Chile, 2006).

The research area is located in the southern upper Elqui watershed and has an covers a surface of 1,510 km², ranging from 820 m.a.s.l. to 5380 m.a.s.l.. It includes the Claro River, the second most important contributor to the Elqui River. With a high mean elevation (4560 m.a.s.l.) and an important delineation, the Claro watershed is typical of the region, where the high contribution of rainfall as snow plays a crucial role in the basin's hydrology.

The Claro River drains the southern side of the Elqui basin with an average flow of 5.16 m^3/s (Average 1990-2000). Because of the small amount of rainfall (<100 mm.a^{-1}) in the lower part of the Elqui basin, the Claro watershed is an important source of water for agriculture within the Cochiguaz valley. It shelters an important part of the agricultural production of the Elqui valley and counts as one of the important water consumer of the upper Elqui watershed with 15.9% of the water rights (Junta de Vigilancia del Río Elqui, 2007). However, these intakes are very variable from one year to another.

The climatic gradients from the coastal zone towards inland reduce the aridity along the coast, and increase the aridity towards inland. During El Niño years there is a significant increase in precipitation, which volume could attain 2 to 3 time a "normal year one". The dry season lasts approximately 10 to 12 months yearly. Along the coastal belt, at some few places, an abundant condensation accumulates, which may exceptionally contribute with more than 500 mm of additional precipitation per year (Santibáñez, 1985).

Another characteristic of the region, with regard to precipitations, is the very uneven distribution of rainfall amounts throughout the years. Due to the influence of the ENSO phenomenon, rainfall amounts may have huge variations. These variations influence dramatically the region's agriculture, highly dependent on water availability for irrigation. For instance, 1997 was a strong El Niño event, followed by a severe series of dry years. There is also a unknown yet estimated high spatial variation in precipitation amounts.

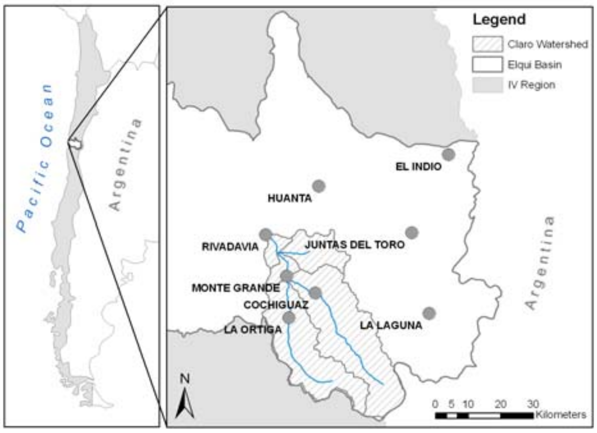

Figure 1. *Location of the Elqui Basin and Research Area*

The dominant natural vegetation is steppe, or matoral, mainly represented by bushes of sparse distribution. "Matoral" and "matoral with cactus" are the major coverage type in the basin, which makes the Elqui region particularly sensible to desertification. Sunshine is strong, particularly at middle and high elevations, and there are strong winds causing a rapid desertification (Downing *et al.*, 1994). The Elqui Valley lithology is composed mainly of three rock types: Intermediate granite rocks, and volcanic rocks in hillslopes and mountains, and sediments and quaternary sediments filling the bottom of the rather narrow valleys.

3. Methodology and Data

Climate Change Scenario Development

The development of scenarios is crucial to impact assessment studies. Different methods are available, from the simplest incremental one to complicated simulation with regional models. The choice of the Atmosphere-Ocean General Circulation Model (AOGCM) is also an important issue, since not all AOGCM have the same abilities of prediction. The selection of a AOGCM should be driven by the purpose of the study, the data available, and the methodology chosen. In this case, the choice of the AOGCM was imposed by the downscaling method. The SDSM (Wilby, 2004) only supports the HadCM3 AOGCM (Gordon *et al.*, 2000) for the given research area. However, the HadCM2 and HadCM3 models have proven to return good results for semi-arid regions with a strong seasonal cycle (Krol *et al.*, 2003). In addition, HadCM3 is one of the most successful AOGCMs at simulating ENSO variability (Busby *et al.*, 2007).

Hence, although only one AOGCM was applied in this study, the HadCM3 AOGCM shows a high compliance with the study area, which climate remains largely under the influence of the ENSO phenomenon. Both A2a and B2a storylines from the Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000) were chosen for the HadCM3 AOGCM. A2a scenario describes a very heterogeneous world, whereas B2a scenario emphasises global solutions and sustainability.

The Statistical Downscaling Modelling System

General Circulation Models (GCMs) suggest that rising concentrations of greenhouse gases will have significant implications for climate at global and regional scales (IPCC, 2001; 2007a). Less certain is the extent to which meteorological processes at individual sites will be affected. So–called "downscaling" techniques are used to overcome the spatial and temporal resolution gaps between what climate modellers are able to provide and what impact assessment requires.

Different approaches are used for downscaling. One advantage of statistical downscaling is its easy implementation and generation of downscaled values. The latter advantage ensures the maintenance of local spatial and temporal variability in generating realistic time series data. However, this topic is subject to ongoing research (Wilby and Dawson, 2007).

For the present study, the SDSM model based on the statistical approach was implemented. The Statistical Downscaling Model 4.1 (SDSM) was developed by Wilby and Dawson (2007) on behalf of the Environment Agency of England and Wales as part of the Thames Estuary 2100 project. It is best described as a hybrid of the stochastic weather generator and transfer function methods. It is designed to implement statistical downscaling methods to produce high-resolution monthly climate information from coarse-resolution climate model (AOGCM) simulations.

The model is calibrated based on daily historical data in precipitation (1990-2000) and maximum and minimum temperature (1990-2000). To ensure a proper calibration, predictors from the NCEP re-analysed data should be judiciously chosen. The calibration parameters were then validated against an independent period of historic data. Time series in precipitation, temperature maxima and minima are then allocated to a hydrological model previously calibrated for the research area.

The Watershed Simulation Model HEC-HMS

After having tested several models based on criteria fixed by Cunderlik (2003), the HEC-HMS 3.1.0 has been selected for its good compliance with this study's constraints. The Hydrologic Modelling System (HEC-HMS) 3.1.0 was designed by the United States Army Corp of Engineers (USACE) (USACE, 2000). It aims at simulating the precipitation-runoff processes of dendritic-shaped watershed systems. In addition HEC-HMS provides a geographic information system (GIS) that allows the definition of numerous physically based parameters and the watershed physical description.

Recent studies undertaken with HEC-HMS on topics related with climate change impact modelling reveals the ability of the model for climate change impact studies on water availability (Pincovschi *et al.*, 2007). The model has been successfully applied to the Llaulini catchment within the month of February 2006 in the Bolivian Cordillera (Ramirez *et al.*, 2006). Al-abed *et al.* (2006) applied it in the Zarqa Basin, Jordan with a high efficiency of the model to simulate streamflow under climate forcing.

However, the specificity of the research area, with its arid climate and heterogeneous topology, makes the application of hydrological models difficult. The capacity of snow modelling is determinant for the pertinence of the model application. The HEC-HMS provides a simple, though efficient snow model, using the degree-day method. The degree-day method presents the advantage of not requiring excessive data. Though, critics underline that the method is not as efficient as the physically based energy balance (Rango and Martinec, 1995; USACE, 2006). In this case, and given the restricted information about snow melt in high altitude, the degree day method seemed to be the best adapted solution.

Available Data

Given the restricted number of meteorological stations, climate scenarios were restricted to the Elqui basin, whereas hydrologic simulations were performed in the Claro sub-watershed. Most of the meteorological and fluviometric data was collected by the Chilean Water Agency ("*Dirección General de Aguas*", DGA). Thereafter, time series were submitted to a drastic quality control process and missing data were simulated through correlation analysis.

A digital Elevation Model (DEM) of 100mx100m resolution was used for prior geographical calculation and the simulation into the HEC-HMS. This DEM was the basis for several physically based geographical analyses on the watershed terrain. After the reconstruction of streamflows and the delineations of sub-watershed for the hydrologic simulation, different elevation bands were created for the snowmelt simulation.

4. Results and Discussion

Station Selection for Downscaling

In order to reduce the number of downscaled data, inter-comparison between stations observed precipitation and temperature data series was carried out. Averaged monthly data sets ranging from 1990 to 2000 were used for calculating correlation coefficients.

Table 1. *Selection of Meteorological Stations in the Upper Elqui Watershed*

Station	**Altitude (m.a.s.l.)**	**Latitude (OS)**	**Longitude (OW)**
Rivadavia	820	-30.0	-70.6
Monte Grande	1120	-30.1	-70.5
Huanta	1240	-29.8	-70.4
Cochiguaz	1560	-30.1	-70.4
La Ortiga	1560	-30.2	-70.5
Juntas del Toro	2150	-30.0	-70.1
La Laguna	3160	-30.2	-70.0
El Indio	3867	-29.8	-70.0

Note: Station selected for downscaling in bold

The whole set of stations available in the research area was involved in correlation calculations. Height stations provided data for precipitation whereas five stations provided data for maximum and minimum temperatures. All data used in these calculations and downscaling processes were checked and missing values were filled up through correlation analysis. As the correlations between observed temperatures in stations of nearest altitude are high, a judicious choice will be to choose both stations of medium and high altitude. Hence, the station of Rivadavia (820 m.a.s.l.) and of La Laguna (3160 m.a.s.l.) were selected for the downscaling process. As the range of correlation coefficients is broader for precipitations, three stations were selected. Precipitations in the upper Elqui watershed are not only driven by altitude differences but are also subject to variation due to the topography of the region.

Therefore, the selection of the stations was guided by an isohyets map of the watershed. Hence, the selection was made both through the station's altitude and its area of influence represented by the area between isohyets lines. The three stations selected were Huanta, Juntas del Toro and La Laguna (compare Figure 1).

Calibration and Validation

One of the most important steps in the downscaling process is the choice of predictors. The relevance of the relationship between predictors (i.e., NCEP re-analysis data) and the forecast variables (also called predictands i.e., Precipitations, Minimum Temperature, Maximum Temperature from local stations) will determine the model ability to produce good climate predictions for the research area. This is based on the assumption that the predictor-predictand relationships under the current condition remain valid under future climate conditions (Wilby and Dawson, 2007). After a calibration process during a 15-year period (1980-1995) for temperature and 10-year (1980-1990) for precipitation, the predictors-predictands relationships determined calibration parameters for each station. These parameters were then tested during a 5-year validation period (1996-2000) for temperatures and a 10-year (1991-2000) validation period for precipitation (as rainy days are very scarce in the region, a longer validation period was necessary).

The coefficient of determination (R^2) and the Standard Error (SE) for the validation period are displayed in Table 2. R^2 and SE indicate a very satisfactory goodness of fit for minimum and maximum temperatures. The performance of the predictor-predictand relationship is even higher in the high altitude station (La Laguna). Maximum temperatures return as well a better correlation than minimum temperatures. Precipitation's coefficients of determination are rather satisfactory.

Table 2. *Goodness of Fit Indicators for Validation of the Models for Precipitations, Minimum Temperatures, and Maximum Temperatures.*

Predictands		**R^2**	**SE**
Precipitation			
	Huanta	*0.569*	*17.81*
	Juntas del Toro	*0.524*	*18.71*
	La Laguna	*0.570*	*19.88*
Minimum Temperature			
	Rivadavia	*0.837*	*0.911*
	La Laguna	*0.901*	*1.284*
Maximum Temperature			
	Rivadavia	*0.870*	*1.183*
	La Laguna	*0.953*	*1.104*

However they return a very high standard error that confirms the lower reliability of SDSM in modelling precipitations pattern. This is mainly due to the scarcity of rainfall data itself. In a semi arid climate, with an average annual precipitation of 100mm, there is not enough values to allow an accurate regression with the NCEP and the AOGCM data. The high standard error could be also explained through the presence within the calibration year of a particularly strong El Niño event in 1997. Hence, the model performs very well for maximum and minimum temperatures in the upper part of the basin and well for minimum temperatures. However, its performance for precipitation still is an acceptable range but should be handled with caution. Therefore, as mentioned by Krol *et al*. (2003), one should consider, while handling AOGCM outputs, both increase and decrease in precipitations.

General Temperature Trends

The general trend for each curve has been calculated based on a 25-year moving average. However, for illustration purposes a 10-year moving average is displayed in Figure 2. The trends lines for scenarios are displayed by the bold line with the respective scenario colours. Both maximum and minimum temperature will increase in the research area, with different intensity.

In La Laguna, scenario HadCM3 A2a shows an increase within the simulation period (2000-2059) of 2.0°C for maximum temperature and of 1.2°C for minimum temperature, whereas HadCM3 B2a scenario values return an increase of 2.1°C for maximum temperatures and 0.8°C for minimum temperatures. In Rivadavia, the intensity of variations is milder. Nevertheless, HadCM3 A2a scenario shows an increase within the simulation period of 0.9°C for maximum temperature and of 0.7°C for minimum temperature, while HadCM3 B2a scenario values return an increase of 0.7°C for maximum temperatures and 0.5°C for minimum temperatures. Hence, HadCM3 B2a scenario projects an increase in temperature (max and min) of less intensity in both stations.

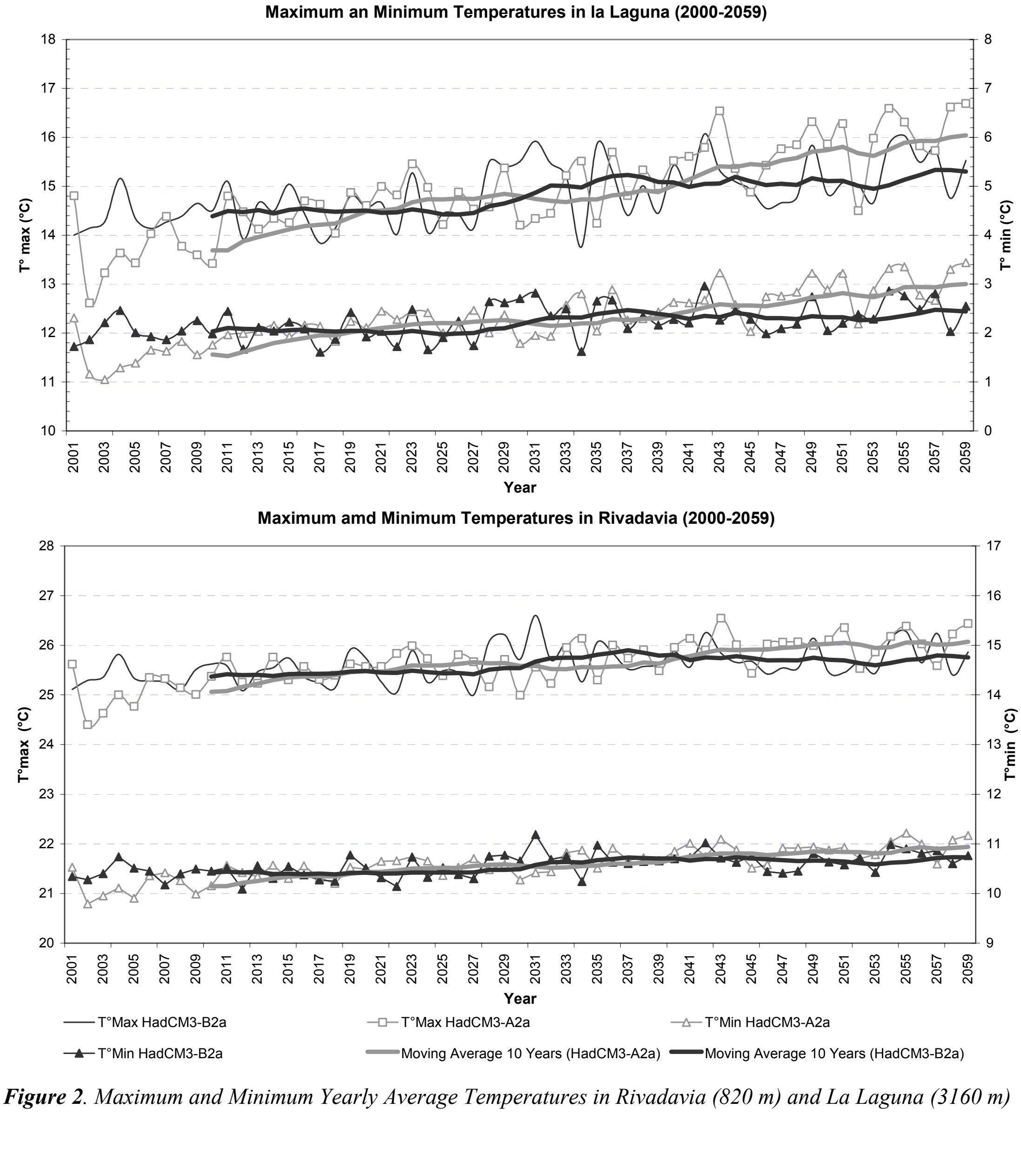

Figure 2. *Maximum and Minimum Yearly Average Temperatures in Rivadavia (820 m) and La Laguna (3160 m)*

Consequently, the increase in maximum temperature in La Laguna will range from 2.0°C to 2.1°C and from 0.8°C to 1.2°C for minimum temperatures by 2059 (Averaged temperature increase: 1,0°C to 2.05°C). In Rivadavia, the increase will range from 0.7°C to 0.9°C for maximum temperature and from 0.5°C to 0.7°C for minimum temperatures by 2059 (Averaged temperature increase: 0.60°C to 0.78°C).

Hence, increase in temperature is expected to be of greater intensity in high altitude areas than in middle altitude areas. Moreover, variation of temperatures is different between maximum and minimum temperatures. Increase in maximum temperature is expected to be higher than for minimum temperature. This behaviour will be further analysed through several selected climate indices.

In order to facilitate the analysis of the simulated scenarios, the simulation was separated into three 20-year periods (2000-2019, 2020-2039, 2040-2059).

Figure 3 shows different selected indices from the Expert Team on Climate Change Detection Indices (ETCCDI). Peterson *et al*. (2001) recommended several indices relevant for temperature at different altitude during the simulation period compared with the base (observed) period (1980-1999).

For the agricultural Elqui area, two significant indices are the number of frost days (FD) and the number of icing days (ID). The number of frost days represents the average of days per year with a minimum temperature lower than 0°C. The number of icing days returns the yearly average of day with a maximum temperature lower than 0°C.

Figure 3 displays the calculated number of frost days in Rivadavia for the base and three future periods (panel A). Compared to the base period, the span 2000-2019 will encounter an increase of number of nights with a temperature below 0°C in winter (JJA). For the second (2020-2039) and third periods (2040-2059), the number of night temperatures values below 0°C will drastically diminish. In addition, the frost period will widen from April to September, with a sensitive shift to the end of summer for the last period (2040-2059). This may have consequence on the vineyard and orchard cultures in the region. As the diminishing of frost night may represent a consequent gain for the sector, the shift trend of frosting period shall have serious consequences on tree growth and fruits yields.

Panel B represents the calculated number of frost days in La Laguna for the base and three future periods. Compared to the base period, all future periods will encounter a decrease in winter (JJA) of number of nights with a temperature below 0°C. In addition, the frost period will be shifted to the right of approximately one month. It will have consequences on the snowmelt in the region, with a probable delay in availability of water in summer.

In high altitudes, the number of icing days will encounter a drastic diminution over the next 5 decades (Panel C). This diminution represents approximately a decrease of 73% of icing days. Consequently, a change in vegetation as well as in ecosystem may be expected in high altitude of the research area. Moreover, the diminution of glaciers surface will accelerate. Temperatures are expected to increase until 2059 within the Elqui watershed. The augmentation of temperatures will be stronger in high altitude areas than in middle altitude areas and valleys. For instance, in La Laguna station a mean increase of 2.05°C for maximum temperatures is expected by 2059 (SRES Scenario HadCM3-A2a and B2a) compared to 2001, while an increase of 0.78°C is expected in Rivadavia.

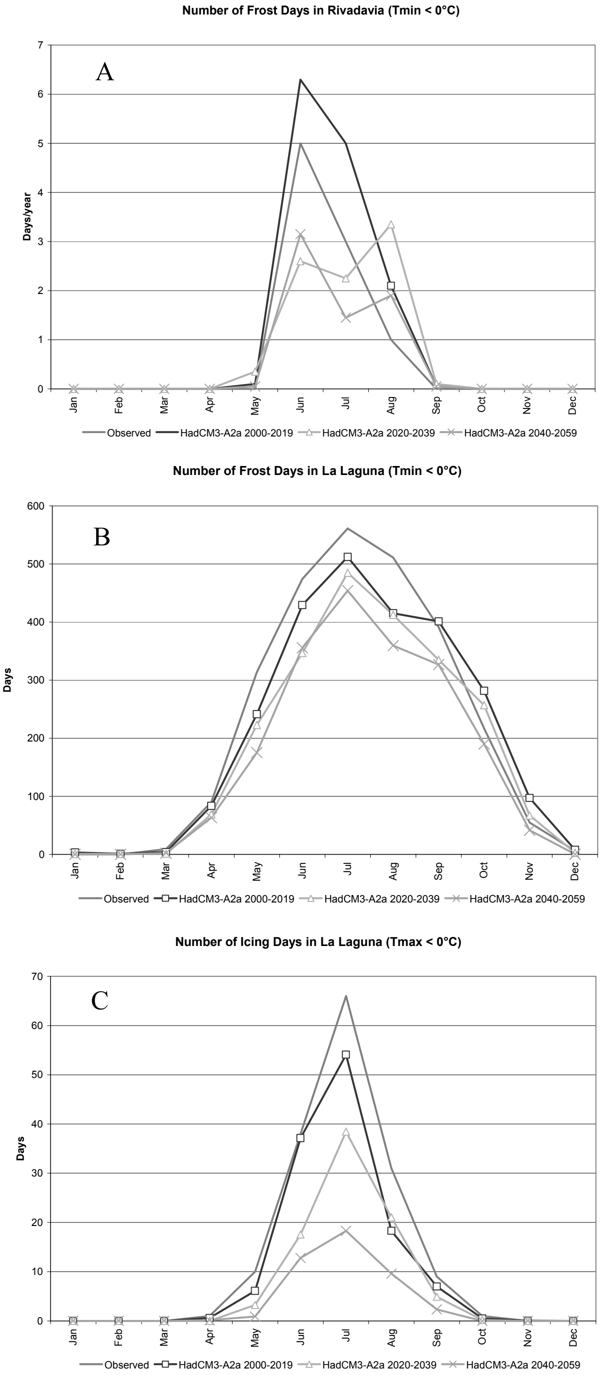

Figure 3*: Selected Climate Indicators for Rivadavia and la Laguna*

In addition, the HadCM3-A2a scenario returns higher increase rates than the B2a scenario. Besides the overall warming trends of both maximum and minimum temperature in middle and high altitude areas, more specific observations were done after the analysis of periods with climate indices.

Firstly, an overall trend for the basin appears to be the warming of winter season in middle and high altitude areas. This warming is explained by the diminution of frost nights (Tmin <0°C) and strong decrease (-73%) of icing days (Tmax<0°C) in high altitude regions.

Consequently, temperature patterns are expected to be strongly affected by climate change, and this will not only affect the overall increase of temperature but the whole behaviour of the watershed climate. This change in behaviour will have consequences on the water cycle, ecosystems and land use as well as the economy of the watershed.

General Precipitation Trends

The following section will comment on precipitation projection in Huanta, Juntas del Toro and La Laguna. Figure 4 shows future projections of precipitations in Juntas del Toro until 2059. Observed annual mean precipitations are displayed in grey. The ensemble mean of future projection was chosen to display general trends. The ensemble mean for precipitation is unable to reproduce extreme events occurring with the simulation period since all ensembles return different peaks of maximum intensity at different periods of the year or even different years.

However, as described during the frequency analysis, projected extreme events are expected to be underestimated by simulations. With regards to these considerations, only general trends, represented by a moving average of 25-year period are included.

Moreover, two trends could be observed. The first one is a general decrease in precipitation amounts. In Huanta, a decrease in precipitation ranges from 31.6% to 33.9% (losses between 17.5mm and 18.9mm) respectively for the HadCM3 A2a and B2a scenario. In Juntas del Toro, it is expected a decrease in precipitation from 20.6% to 28.9% (losses between 22.6mm and 35.1mm) respectively for the HadCM3 A2a and B2a scenario. In La Laguna, losses in precipitation are expected to be milder with a decrease ranging from 19.74% to 28.9% (losses between 23.5mm and 31.5mm) for HadCM3 A2a and B2a scenario.

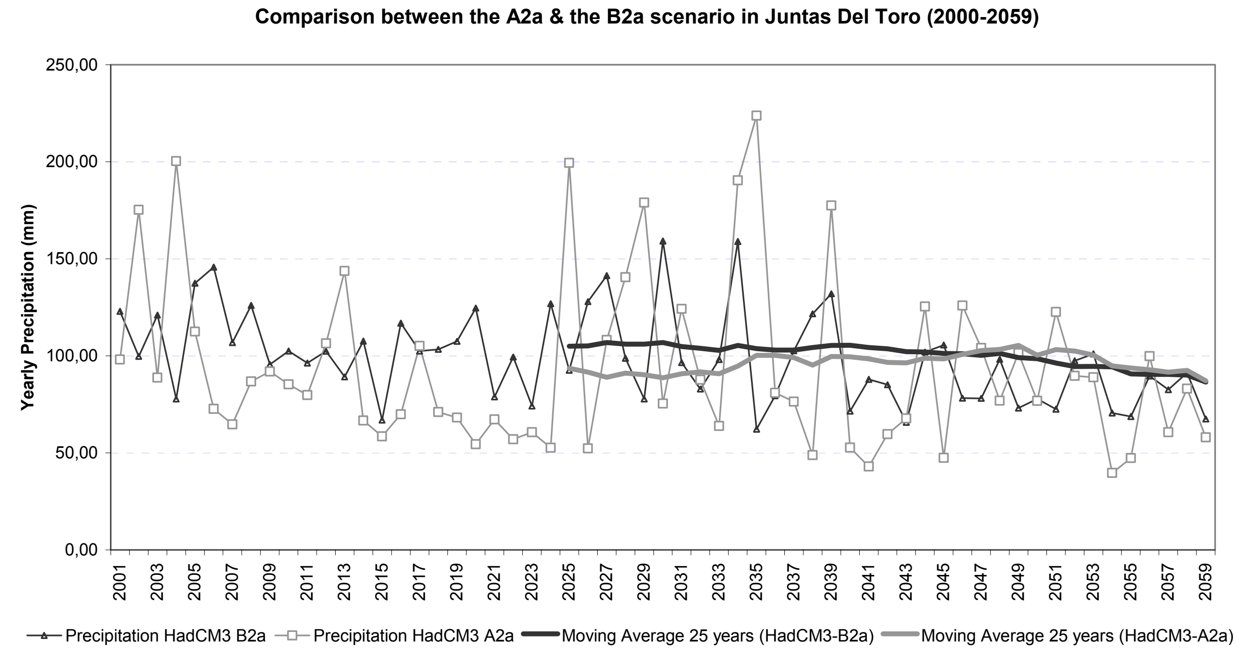

***Figure 4**: Precipitation Trends in Juntas de Toro (2150 m)*

The second tendency is the persistence of long run waves, illustrated by the moving average (25-year period) with large fluctuations of precipitation amounts every 20 to 30 years. Smaller undulations are appearing as well on shorter periods of one to three years. This illustrates very well the high variability of rainfall patterns the region.

Nevertheless, this projection does not have a value of meteorological forecast since precipitation are highly dependent on others factors that are not considered in this study. For instance, the ocean surface temperature offshore of the Chilean coasts plays a great role in the precipitation events on the continent and is proven to be one of the main factors in the ENSO phenomenon.

As for temperatures, selected indicators for precipitation were calculated for the three selected stations of the research area (Peterson *et al.*, 2001).

The R5D index measures the short term precipitation intensity. The CCDm is a measure for the mean length of dry spell, mean value of number of consecutive days with a rainfall amount inferior to 1 mm. Figure 5 displays the CCDm and the R5D index for the different stations in the Elqui basin (Hunta, Juntas del Toro, La Laguna) and for the HadCM3 A2a scenario. Each panel shows the evolution of the index through the time, according to the previously mentioned periods (2000-2019, 2020-2039, 2040-2059). The CCDm index returns the mean value of number of consecutive days with RR < 1mm. This index is a potential drought indicator, relevant for the semi-arid climate in the Norte Chico. This index may indicate also potential effects of climate on ecosystems and vegetation.

For all stations, the mean dry spell length is expected to increase by 2059 compared to the first simulation period (2000-2019). Middle altitude areas like Huanta and Juntas del Toro might experience a higher rate than higher altitude zones. However, a clear seasonal trend is hard to identify. This is explained by the high variability expected between the selected decades. A variation of rainfall events might be expected in the region, especially in high altitude areas. Even if these simulations include high uncertainties, a potential drying of the region is seriously to be considered.

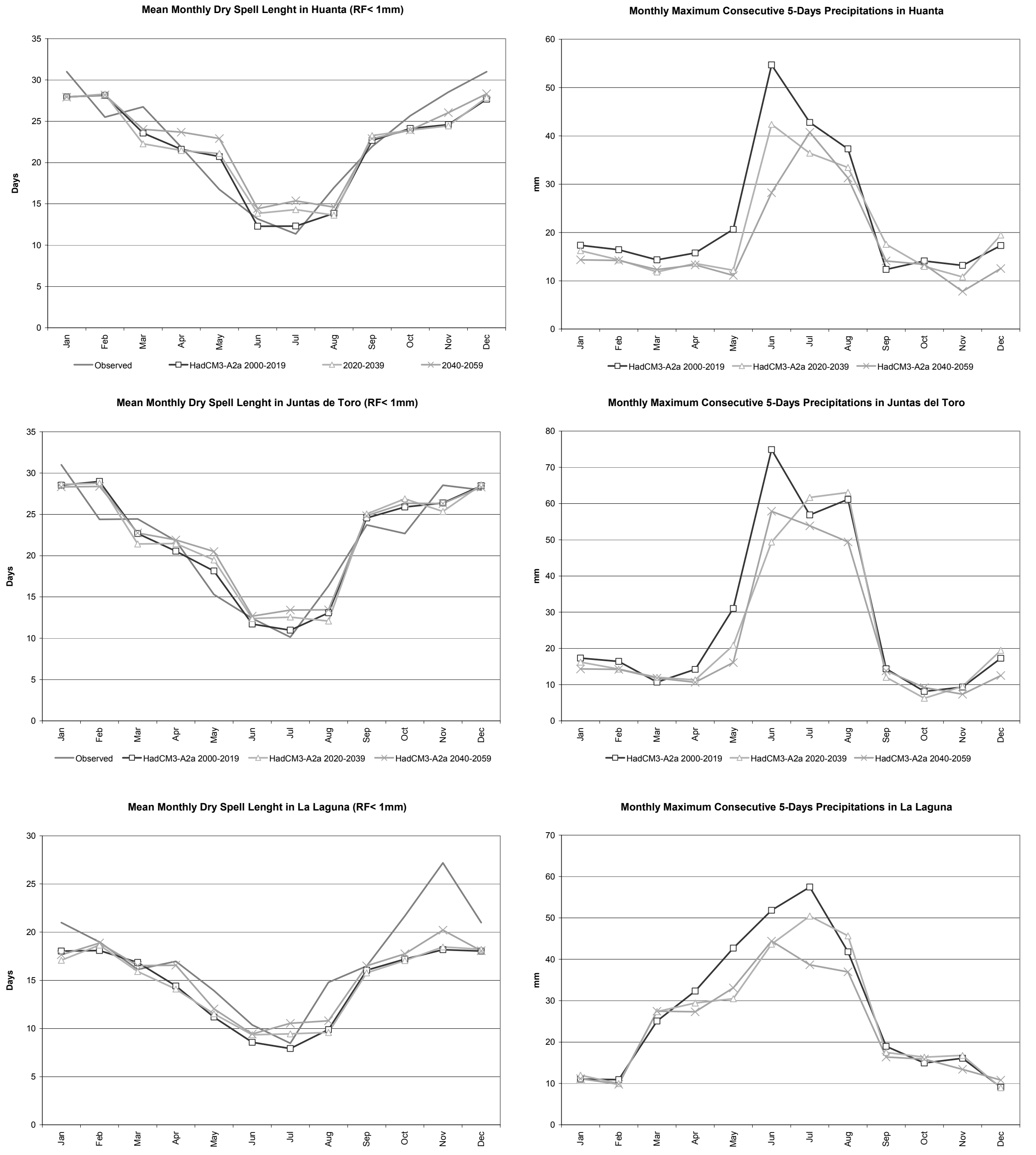

Figure 5. *CCDm and R5D Index in Hunta (820m), Juntas del Toro (2150 m), and La Laguna (3160 m)*

The R5D Index is a measure of short term precipitation intensity. It can be used as flood indicator. Figure 5 shows the evolution of the maximum precipitation accumulated each month for Huanta, Juntas de Toro and la Laguna. A clear general trend for all three stations is a shift of the rain season from June to July. In Parallel, the intensity of the rainfall events will diminish during the rain season. Since the number of consecutive days with precipitation will diminish throughout the year in lower altitudes, a phenomenon of dissemination of rainfall events could be interpreted. However, as the overall predicted amount of rainfall is expected to diminish it indicates that the intensity of the event as well as it occurrence will decrease in the region.

In conclusion, precipitations are expected to decrease in the Elqui Watershed. Both A2a and B2a scenarios return decreases in different altitudes. Nevertheless, the B2a scenario shows a faster rate with in average losses of ca. 30% of precipitations versus 21% for the A2a scenario. Moreover, climate index analysis allowed identifying a general decrease in extreme events for the whole watershed. Although interpretation concerning precipitation are subject to caution, given the high uncertainty that still remains about their simulation, a local trend of augmentation of dry season was identified in middle altitude areas.

This augmentation of drought periods length shows a relatively low growth rate, though. Nevertheless, the risks of desertification in the region are real even if these results should be considered as well as slight increase in precipitation volumes.

Case study in the Rio Claro Sub-watershed

Flow calibration was performed for a period of six years (1991-1996) for the whole watershed. However, seven years of simulation were necessary, since the first year was considered as warm-up period, intending to create a first snow coverage of the area. Three fluviometric gauged stations of the DGA were used for calibration purposes (Claro en Rivadavia, Cochiguaz en el Peñon and Est. Derecho en Alcohuaz), as displayed on Figure 6.

As previously discussed in the methodology section, the flow was calibrated manually using the observed flow of the gauged stations.

The coefficient of determination, which calculation is based on monthly values, is rather low (R^2=0.37). However, the standard error is acceptable (SE=1.06). Consequently, the simulation for the Claro watershed was performed for a three years period (1998-2000).

As for the calibration a warm-up period of one year was observed. The model proves to perform well during the validation periods with a satisfactory coefficient of determination for monthly values (R^2=0.61) and a small standard error (SE=1.55). However the total and averaged flow is still underestimated during the simulation. Possibly, the underestimation of monthly flows is due to the difficulty to calibrate the snow melt module in absence of accurate data in high altitudes.

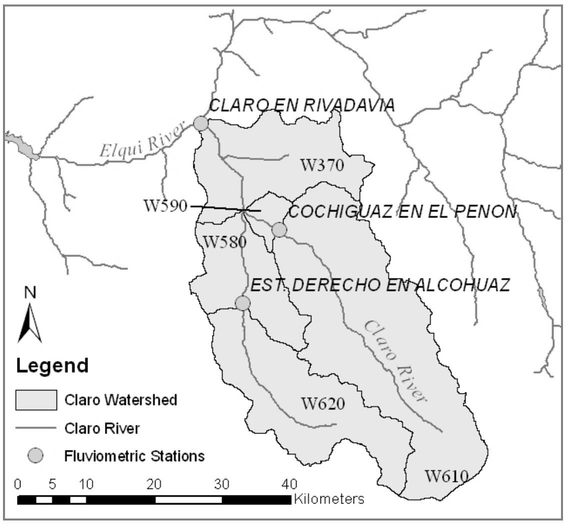

***Figure 6**. Fluviometric Stations in the Claro Watershed*

Impact on Monthly Streamflows

The streamflow simulation was performed with the downscaled results of the HadCM3 A2a and B2a scenarios and divided into three simulation periods (2000-2019, 2020-2039 and 2040-2059). Because the HEC-HMS simulation returned underestimated streamflows, results obtained with downscaled precipitation and temperatures were corrected following the model validation average flow statistics results. Figure 7 represents averaged monthly flows in Rivadavia for both A2a and B2a scenario. The peak flow in December is respected for the first (2000-2019) and last period (2040-2059), whereas the middle period (2020-2039) seems to reproduce a shift of the peak flow to January and February. This is mainly due to the shift in precipitation that occurred for the same period (2020-2039) from June to August. This occurred mainly in high altitude areas, so that a greater snow accumulation was predictable during the two decades. The total flow returns a relative increase of 8% for the 2020-2039 period. Only the average flow shows variations, which indicates a concentration of the flow during the peak period. This is true for both A2a and B2a scenarios. Where the A2a scenario returned a decrease in precipitation, stream flows seems to react with an increase compared to the B2a scenario. In addition, the A2a scenario returns nine (9) extreme years (Averaged yearly streamflow superior to 5,16m³/s), the B2a scenarios returns only four (4) noticeable extreme years. This might be explained by a greater influence of the ENSO phenomenon combined with a rise of temperature in high altitudes on snowmelt processes. The streamflow response tends to underline the overwhelming influence of temperature and inter-annual variability in the region.

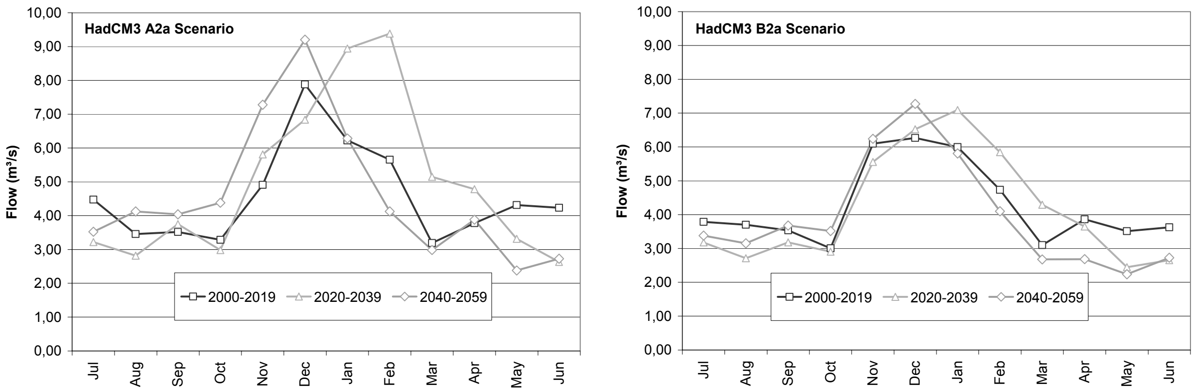

Figure 7*. Monthly Flow (m³/s) in Rivadavia for the HadCM3 A2a and B2a Scenarios*

Impact on Annual Streamflows

Extremes years tend to diminish during the last period (2040-2059) for the B2a scenario. In both cases, the 2020-2039 span will be the one with the highest hydrologic variability.

Accordingly, inter-annual variation is expected to be very high, especially for the A2a scenario and during the 20's and 30's. This high inter-annual variability might have serious consequences on the region. Figure 8 shows the percentage of variation for every decade for the A2a and the B2a scenarios.

The difference of intensity of variability between the A2a and the B2a scenario is clearly visible. In addition, a clear undulation tendency is present for both scenarios. These undulations already exist in the region and are mainly due to the influence of the ENSO phenomenon. However, as shown with the A2a simulation, climate change will strengthen this tendency in the Elqui valley. This increasing variability is to relate with a decreasing water security in the region. Between the 30's and the 40's decades, a change of 30% can be observed on a yearly basis. This is a huge difference considering that the model underestimated extreme variations.

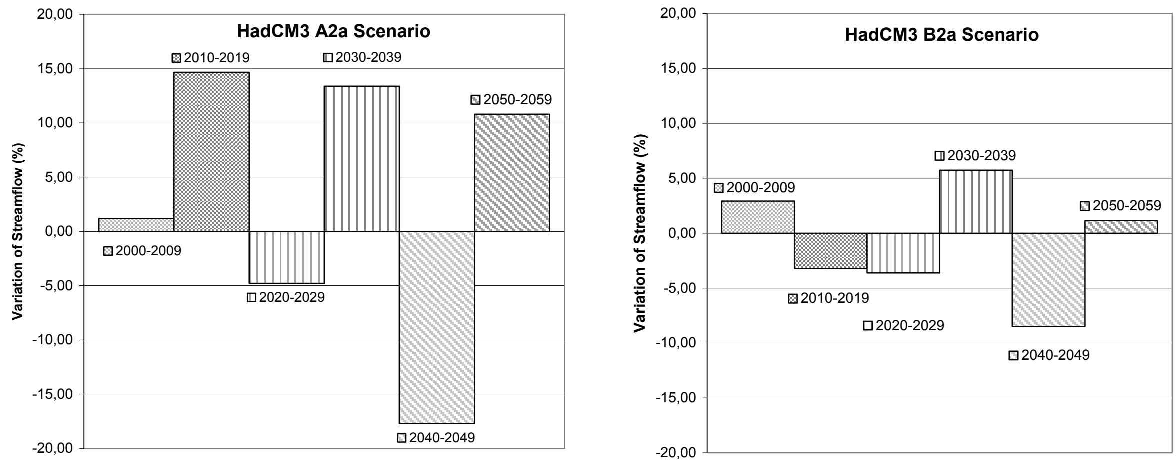

Figure 8*. Yearly Streamflow Variation for A2a and B2a Scenarios in Rivadavia (2000-2059)*

Final Remarks: Uncertainties consideration

Meteorological data coverage and related data, e.g. isohyetal curves, is relatively scarce. The Claro watershed benefits from only three meteorological stations, which lower the reliability of collected data. Especially high altitude areas, where snow hydrological processes take place, lack of reliable data. In this study, high altitude data was made available from a station located in another watershed under the assumption that meteorological condition were conserved. This generates in return uncertainties as to data quality and reliability. Nevertheless, research projects are currently implementing new stations in high altitudes areas of the Elqui watershed. This is a difficult, resource intensive and costly exercise given the hard conditions of the high Cordillera.

As already suggested, missing values and failing data quality induce a processing of uncompleted data through statistical operations. These operations, although based on scientific evidence are part of the global uncertainty in this study.

Beyond data scarcity and quality, most uncertainties emanate from the coupling of several models. Uncertainties of each model are likely added to the uncertainties linked to the next and so on. In this case two models (SDSM and HEC-HMS) were used in order to produce an impact assessment on climate change on streamflows in the research area.

To this, one should add uncertainties linked to the AOGCM model itself. According to Mearns *et al.* (2001), there are considerable uncertainties in the radiative forcing changes, especially aerosol forcing, associated with changes in atmospheric concentrations. AOGCMs show as well imperfections in replication of climate variability, which plays a non negligible role in the region. The uncertainty related with AOGCM compliance with local climate could be limited by using two or more AOGCMs. Unfortunately, in this study we were forced to use only the HadCM3 AOGCM, given data availability constraints for the research area.

Besides the AOGCMs themselves, climate forcing SRES scenarios used in impact studies are subject to uncertainties. Although of equal probability of appearance, those scenarios represent a set of assumptions on international geopolitics, economic and population growth rate as well as technical development.

Concerning the downscaling method, although it is a good and efficient manner to solve the regionalisation problem of AOGCMs coarse resolution results, it still has, as all weather generators, difficulties to model low frequency variations (Giorgi *et al.*, 2001). This problem is of first concern in a arid area where precipitations are very sparse. In addition, and because of the scarcity of precipitations, statistical downscaling was difficult and returned low calibration correlations. Another potential source of uncertainties is the fact that SDSM and statistical downscaling are generally based on the assumption that current conditions remain valid under climate change, which might not be always the case (Wilby and Dawnson, 2007).

Last but not least, both models used in this study needed calibration. For both models, calibration statistics were rather low, with an exception for the temperature models. These difficulties in calibration, as well as the different assumptions made given the limited amount of data available make the uncertainties increase as well. Moreover, land use, aquifer layers as well as permafrost behaviour were not taken into account in this study. Especially the low level of knowledge in the region concerning permafrost and the unclear relation between precipitation and streamflows patterns reduce the model accuracy and its ability to reproduce natural streamflows.

Thus, all these sources of error and uncertainties must be taken into account when analysing the modelling predictions obtained.

5. Conclusions

Climatic extreme events appear with a strengthened frequency all over the world. Climate change is expected to strengthen these effects, with heavy human and material costs. Hence, there is a real benefit to identify the local and regional effects induced by climate change. This will allow to determine the degree of vulnerability and to plan, in time, appropriate adaptation measures.

The arid Elqui valley is very sensitive to climate variations. As demonstrated in this study, simulated temperatures are expected to rise faster in high altitude areas with an increase in mean temperatures ranging from 1.0°C to 2.05°C by 2059. Further, lower altitudes areas may expect an increase up of 0.9°C for maximum temperatures. As for precipitations, both A2a and B2a SRES scenarios return a diminishing trend of ca. -30% in rainfall by 2059. Analyses carried out by the mean of the ETCCDI Climate Change Indices for three 20-year periods from 2000 to 2059, indicate strong inter-seasonal perturbations. Warmer winters will develop in the region and the dry season will lengthen in middle altitudes. In higher altitude areas, the number of icing days (Tmin<0°C) will encounter a drastic diminution; a diminution representing approximately a decrease of 70%. Consequently, a change in vegetation as well as in ecosystem may be expected in high altitude of the research area. Moreover, the diminution of glaciers is likely to fasten.

The Claro watershed, one of the main tributaries of the Elqui River, will see its streamflow strongly impacted with a resulting high variability on an inter-annual basis. This confirms the high sensitivity of the watershed and the complex processes at play. This underlines also the importance of flexible and adaptive measures to address hydrological problems in the Elqui valley. Unfortunately, the different models used in this study were not able to reproduce with accuracy all extreme events. Therefore, with consideration to the above mentioned uncertainties, few conclusions could be drawn on ENSO phenomena future occurrences. Nevertheless, the prediction ability as well as the understanding of uncertainties could be enhanced by using several AOGCMs. Development of SDSM predictors datasets from other AOGCMs for the Coquimbo region as well as simulation with other downscaling methods will deepen knowledge in the local future climate.

Complex climatic patterns, which result partially from interactions of atmospheric flow with topography, combined with land-use and land-cover changes, make it difficult to identify common patterns of vulnerability to climate change in the region. However, agriculture plays an overwhelming role in the region's economy. Downing *et al.* (1994) demonstrated how land-use changes are a major force causing ecosystem changes. Change in temperature, precipitation and inter-annual variability in water availability will put agricultural systems under stress in the region. Combined with an exportation driven economy, agriculture will have to face new challenges in a near future.

6. Aknowledgments

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