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RESEARCH REPORT

CLIMATEADAPTATIONSANTIAGO (CAS) PROJECT

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Abstract: This report describes the methodology and results from the analysis of climate scenarios and their impact on hydrometeorological variables in the Metropolitan Region of Santiago de Chile (MRS). Using a downscaling methodology for future scenarios A2 and B1, according to IPCC, temperature, precipitation and secondary variable trends were estimated for the time-window 2045-2065. The main results predict that Santiago will be a dryer and hotter city in the near future, with a high number of days with extreme temperatures. Due to lower precipitation rates, decreasing magnitudes in the streamflow of the two main rivers, Maipo and Mapocho, are expected. The presented data provide a basis for the ClimateAdaptationSantiago (CAS) project as the aim of that project is to elaborate, evaluate and prioritize adaptation measures to the climate change in the MRS.

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Foreword

This report was compiled within the ClimateAdaptationSantiago Project (CAS). The CAS project is a joint effort of the Helmholtz Centre for Environmental Research – UFZ (responsible for the coordination), the Karlsruhe Institute of Technology – KIT, the Universidad de Chile – UCH, the Pontificia Universidad Católica de Chile – PUC, and the Economic Commission for Latin America and the Caribbean (ECLAC–CEPAL) and acts at the science-policy interface. Its main objective is the development of adaptation strategies and measures to climate change in the Metropolitan Region of Santiago de Chile (MRS). The expected climate change impacts, on the one hand, and the extreme concentration of economic power and of decisive political and functional systems in the capital of Chile, on the other hand, require endeavours to plan and implement adaptive actions.

In different working packages, scientists from Chile and Germany assess future climate changes and their impacts in the MRS. The focus of the impact analysis lies on the core sectors energy, water and land use, based on a status quo and an explorative scenario analysis. In addition, current vulnerabilities of the population to flood and heat hazards are analysed and future vulnerabilities are estimated.

Stakeholders of relevant regional and national institutions, private enterprises and non-governmental organizations are included in the CAS project. Jointly with the researchers they develop, evaluate and prioritize adaptation measures to climate change in a participatory process that includes a series of ten Round Table meetings. These measures will be committed to political decision-makers in Santiago and shall be incorporated in regional development plans, e.g. the Regional Action Plan to Climate Change.

By establishing a Regional Learning Network the CAS project also involves scientists and decision-makers from five other Latin American cities: Mexico, Bogotá, Lima, Sao Paulo and Buenos Aires, in order to discuss issues of climate change adaptation and exchange knowledge.

The present report contains the results of the first working package of the CAS project. As a principal prerequisite for the subsequent elaboration of adaptation measures, this study focuses on the different processes of climate change and variability in the MRS. It entails the assessments of expected developments in temperature and precipitation as well as for some 'secondary' climate variables, e.g. wind and radiation, in the future.

The coordinators would like to thank the working group at the UCH for their intensive efforts to create a picture of climate change and climate variability in Santiago de Chile.

Prof. Dr. Bernd Hansjürgens
Helmholtz Centre for Environmental Research – UFZ
(for project coordination)

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Chapter 1 – Introduction

Climate change is one of the greatest challenges for human mankind. Since the release of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) it is very likely that global warming, caused primarily through anthropogenic activities, will occur. Cities are exposed to risks due to these climate changes, including rising sea levels, urban heat island, floods, and increased incidences of diseases. Until now, they have mainly taken efforts to implement mitigation activities and to depress greenhouse gas emissions (Betsill and Bulkeley 2003; Carbon Disclosure Project/CDP, C40 climate group). In response to actual or expected climatic stimuli or their effects, mitigation is not enough. City-regions will have to look for adaptation strategies to climate change.

Santiago is no exception in these processes. Being the capital of Chile and bearing a population of six million people, Santiago is the political, economic and institutional center of the country. Therefore, it is important for political decision makers to understand in which way the regional climate will change and which impacts are related to these changes, especially in core sectors like water, energy and land use. In view of the social coherence in the urban context, essential information refers to the consequences of climate change related hazards on social vulnerabilities.

The assessment of current climate and the prediction of future trends for temperature, precipitation and secondary data for the Metropolitan Region of Santiago (MRS) is the main objective of this paper. The research is motivated by the desire to establish a climate database for the region. It is going to close a research gap as there have been no detailed studies on that topic so far and most predictions are limited to qualitative statements. However, climate related adaptation measures for key sectors like water, energy and land use will need quantitative assessments of climate variables (e.g. temperature, days with extreme temperatures, shift of 0 degree line, precipitation) in the near future although uncertainty is still high.

The obtained results show for the near future (2045-2065 period) that the temperature in the Metropolitan Region of Santiago de Chile, both maximum and minimum, are expected to rise by approximately 1-2ºC. However, this – apparently – small change leads to a significant increase in days with extreme temperatures above 30°C, reaching in some cases 30%, and a significant decrease in days with temperatures below freezing point. Higher temperatures will also bring higher elevations in the zero isotherm line, thus increasing storm runoff from higher elevations of the city.

Precipitation will decrease in amounts for almost every month. In the worst case, reductions in precipitation range between 10% and 30% (20mm to 100mm less precipitation each year, depending on the station analyzed). Additionally, most models predict fewer days with precipitation, and lower precipitation rates in days with precipitation. Due to lower precipitation rates, a general decrease in magnitude of the streamflow is expected for the most important rivers in the MRS, the River Maipo and the River Mapocho. The overall conclusion is that in the near future Santiago will be a dryer and hotter city, with a high number of days with extreme temperatures and increased drought during the winter and summer.

This report is structured as follows: Chapter 2 provides information about the data used. Chapter 3 describes in detail the methodologies. Chapter 4 gives the main results for different variables for the historical analysis and for the future scenario analysis (2045-2045). Chapter 5 derives conclusions from the data analysis.

Chapter 2 – Data

As the objective of this study is to give the main results of the current climate and future climate changes in the Metropolitan Region of Santiago, first historical data for primary and secondary variables from different stations are collected. Then, historical trends are derived from these data. This procedure allows analyzing the current climate as well as climate trends in the RMS.

In order to predict future climate changes, Global Circulation Models (GCMs) that simulate the Earth's climatic system, are adapted, or *downscaled*, to the relevant spatial scales for this particular study. By this way, future climate changes for the variables are assessed using different models for the time window 2045-2065. The next step consists in averaging the across-model results and in computing standard deviations for the overall time window averages.

The historical and current climates as well as the expected future climate changes in the Metropolitan Region of Santiago are assessed through the analysis of main climate variables. This includes, in particular, temperature and precipitation as primary data. Secondary data comprise the development of glaciers, the shift of the isotherm 0°C, water run-off, wind velocity and insolation.

Parameter	Temporal specifications
Precipitation mm	Total, monthly and daily average, spitted in rain and snow, variability
Frequency of different types of rainfall intensity (mm/h)	Frequency distribution of precipitation classes (< 1mm, 1-10mm,…), variability
Temperature (maximum and minimum) for the different altitudes within the RMS	Annual, monthly and daily average, variability
Number of frost-free days for the different altitudes	Annual and monthly average, variability
Number of days with average temperature above 30ºC	Annual and seasonal average, variability

Table 1 – Primary data

Parameter	Temporal specifications
Development of glaciers	Annual average and for winter/summer half year average, variability
Shift of the isotherm 0°C	Annual and in winter and summer period, variability
Humidity (%) for the different altitudes	Annual average and seasonal average, variability
Water runoff (m^3/s)	Monthly average and minimum and maximum value for each month (frequency distribution), variability
Wind velocity (km/h)	Annual average and seasonal average, variability
Insolation (h/a)	Annual average and seasonal average, variability

Table 2 – Secondary data

The historical analysis is performed by analyzing data from existing meteorological stations. Records used were obtained from stations that are owned and operated by public agencies. Most of the existing stations within the Metropolitan Region of Santiago de Chile were used for this study. However, there are a number of stations that could not be considered as the number of years available from these stations was insufficient for the analysis, with records beginning only during the 1990s or 2000s. Most of the stations that were not used in the study are located within the rural areas of the region, and are intended for agricultural purposes rather than for climatological studies. Therefore, their data is less suitable for spatial interpolation and mostly valid for the close environment of the stations.

Data record of the used stations is limited to the last 40 years (1970-2010), and sometimes, there are major gaps of missing information on the records. Therefore, it should be taken into account that results provided in this report are uncertain. This is, especially, the case when viewing the meteorological network as a “whole” and not staying focused on one particular station, as the values shown by that station could be not representative for the whole region but only for a particular area that this station is located in (a rooftop, park, etc.). This was likewise one of the reasons that rendered spatial interpolation was impossible to realize as the variations of climatic data between each station due to altitude was not clear enough.

Precipitation

Concerning precipitation, the focus of the analysis lies on two different precipitation indexes, i.e. the precipitation amount (mm) with monthly and daily averages, indicating also the variability, and the frequency of different types of rainfall intensity (mm/h), classified in precipitation classes (<1mm, 1-10mm, etc.) and its variability.

Figure 1 presents the stations used for this analysis. Stations were selected by analyzing the temporal range of data and the consistency of measured values. The records provide available data for the last 30 to 40 years (for details see Table 3). This common time span is needed in order to correctly compare models and observed values. Nevertheless, most of the stations show random gaps in information, especially during the 1970-1974 period due to political unrest in Chile. However, the missing data do not affect in an important way the analysis as the gaps can be treated as “randomly” distributed. This property allows that the studied variable’s statistical distribution remains untouched. The time span used for the precipitation averages corresponds to the common time span between the GCM models and the observed data (1970 to 2000 when available).

ID	UTM N	UTM E	Elev. (m)	Ti	Tf	Temporal resolution
Central Florida	6286445	357350	770	1977	2010	Day and Month
Melipilla	6271064	296074	168	1972	2010	Day and Month
Pirque	6272845	352877	659	1968	2010	Day and Month
Quinta Normal	6298113	343588	527	1977	2007	Day and Month
San José de Maipo	6277311	374507	964	1972	2010	Day and Month
Tobalaba	6297259	356163	652	1979	2010	Day and Month
Cerro Calan	6303810	357081	848	1976	2010	Day and Month
El Yeso	6273104	399083	2475	1963	2010	Day and Month
San Gabriel	6261211	385240	1266	1978	2010	Day and Month

Table 3 – Precipitation data

Uncertainties related to station location (such as rooftops and parks) and measuring methodologies performed by the institutions in charge of the maintenance of the stations remain, but none of these possible errors were noticeable in the information, and no further correction of the data was performed. The light grey area in Figure 1 represents the limits of the Metropolitan Region of Santiago, and the grey area represents an approximation of the current approximate urban limits.

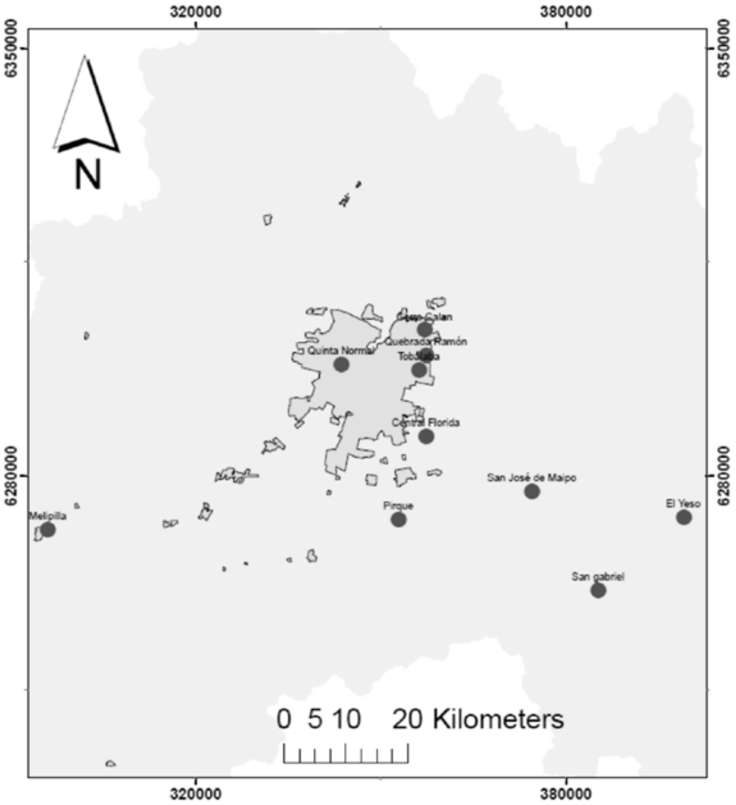

Figure 1 – Precipitation stations

Results of the analysis are not spatially interpolated as the network isn't dense enough, and the stations are not evenly distributed across the region; most stations exist toward the eastern part of the city and along the *Cajon del Maipo*, whereas within the urban limits and north of the central parts of the city the measuring network is scarce. A spatial interpolation of information would not add extra information; moreover, it would add false or possibly wrong information to the areas of the city where no information exists. In this report, the following names are used synonymously for the same station:

- SJM and San Jose de Maipo
- Quinta Normal and Santiago
- Central Florida and Florida

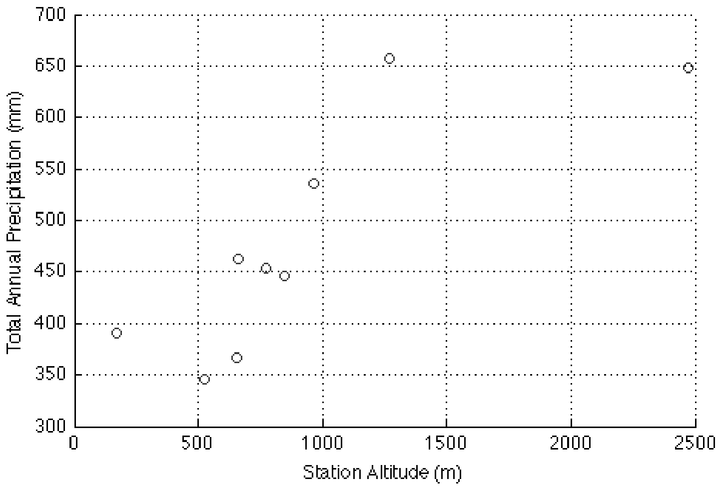

Figure 2 – Annual precipitation vs elevation

Unlike temperature gradients (discussed further in this report), precipitation gradients are clearly visible and precipitation changes are observed according to elevation changes (see Figure 2). Precipitation amounts generally follow an increasing trend according to altitude.

While precipitation may fall as snow above 2000 m.a.s.l. during winter, in the lower lying areas of the city of Santiago (below 1000 m.a.s.l.) only isolated events of solid precipitation occur every few years. These snow events are not recorded or differentiated by the stations, and snow that falls lasts in the ground for only few hours. Precipitation gradients observed are due to the orographic effect of the Andes Cordillera over cold fronts coming from the Pacific Ocean, and the result of this gradient is an important increase in precipitation when comparing stations away from the Cordillera with those located in foothills or on elevated sites.

Temperature

Regarding temperature, the report analyzes the daily extreme temperature (maximum and minimum) for different altitudes observed in the historical record. Deriving from these records, the number of days with temperatures above 30°C and the number of frost-free days are specified. Annual and monthly averages and variability are given for all variables.

The historical temperature analysis is based on data of different meteorological stations in the MRS. Nevertheless, there is a low number of stations in the region and a dense climatological network is not accomplished. Additionally, only few stations are located within the urban limits of Santiago, among them one station (Quinta Normal) is situated completely in the city, as Cerro Calan, Tobalaba and Central Florida are mostly suburbs and located in low density areas. Figure 3 presents the climatological stations used for the present analysis of temperatures. Stations were selected by analyzing temporal extend of data and consistency of measured values.

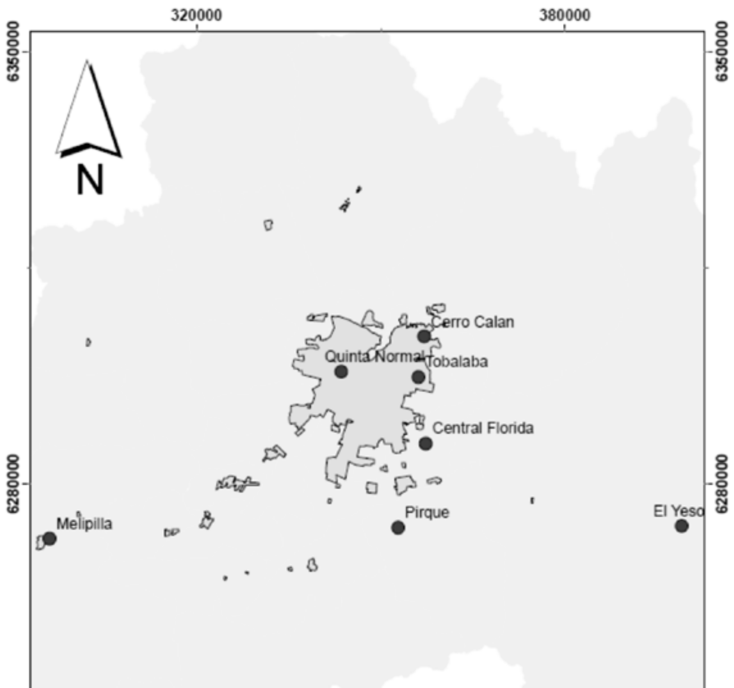

Figure 3 – Temperature stations

Spatial interpolation between the stations is not possible with such a low-density network, as false or misleading values will be assigned to portions of the interpolated region where no stations are available. For example, El Yeso station would influence the temperature interpolation in the whole Northeast region, as it is the only station situated in the high elevations. Location and elevation from these stations are presented below in Table 4.

ID	UTM N	UTM E	Elev. (m)	Ti	Tf	DT
Tobalaba	6297259	356163	652	1979	2010	Day and Month
Quinta Normal	6298113	343588	527	1970	2010	Day and Month
Cerro Calan	6303810	357081	848	1977	2009	Day and Month
El Yeso	6273104	399083	2475	1962	2010	Day and Month
Melipilla	6271064	296074	168	1972	2010	Day and Month
Pirque	6272845	352877	659	1970	2010	Day and Month
Central Florida	6286445	357350	770	1977	2010	Day and Month

Table 4 – Temperature data

The time span of the records varies from station to station but comprises most of the 1970-2000 period. The different time span from each station comes from the fact that some stations start the records on 1975, 1977 or 1973 for example, and do not pose a substantial source of error when comparing different stations as most of the records concur in the same time period, and changes, coming from a small number of disagreeing years will not affect the long term average.

These stations are in heterogeneous locations, so representativeness of the detailed meteorological conditions present in the area is determined by specific characteristics of the station's location. For example, Quinta Normal station is located in a park in the middle of Santiago, while Cerro Calan is located on an arid hill in the eastern suburbs. Although geographical location must play a relevant role in determining temperature spatial distribution, it is not clear that a single predictor such as elevation explains spatial variability (as it is the case with precipitation). The only station that has a clear temperature difference with the others due to elevation is El Yeso, located in the cordillera outside Santiago. The observed gradient for the stations is presented in Figure 4 and Figure 5, with average annual maximum daily temperature and average annual minimum daily temperature plotted against elevation.

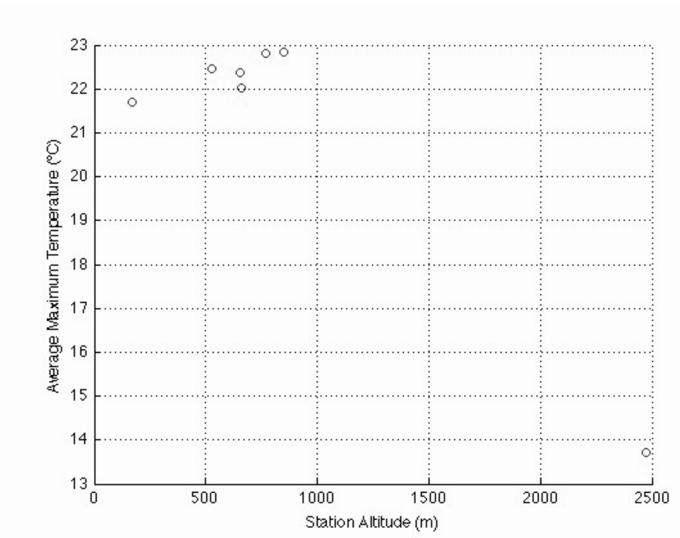

Figure 4 - Maximum temperatures (1970-2000) vs elevation

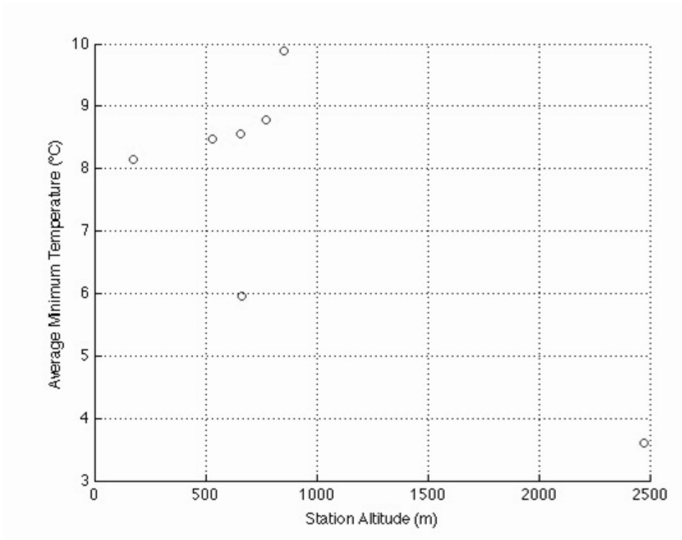

Figure 5 – Minimum temperatures (1970-2000) vs elevation

As shown in the previous figures, there is no clear gradient for average temperatures measured at stations within the lower areas of the region (<1000 m.a.s.l.), and while the gradient is clear if El Yeso station is considered, lower stations don’t exhibit a clear pattern of decreasing temperatures with increasing elevation.

0ºC Isotherm

The position of isotherm 0º lines is important as it determines the division between liquid and solid precipitation in the upper elevations. Although detailed records were not available for the isotherm 0 line, an isotherm 0 line was calculated using a standard method based on extrapolating temperature information from two stations located on the outskirts of Santiago, using a measured temperature lapse rate.

For the isotherm zero degree analysis, a temperature gradient is assessed analyzing temperature records from Vilcuya (1100 m.a.s.l., UTM N 6363187 m, UTM E 362268) and Portillo (2925 m.a.s.l., UTM N 6366070 m UTEM E 393900 m), two stations located north of Santiago, for the 1990-2010 period. The gradient will be used to estimate the change in the mean isotherm zero line, which represents the boundary that divides liquid from solid precipitation.

This assessed temperature gradient is applied to the Pirque station (Figure 6) that is an index temperature station. The reason for choosing this station instead of another one is the fact that it is located outside the urban limits of the city, thus, there should be no influence from external factors such as buildings or parks. Central Florida, El Yeso and Melipilla also seemed to be reasonable candidates for the analysis, but as Central Florida is located in the eastern side of Santiago there could still be an influence from the city as it is located very close to a densely populated area (La Florida). Melipilla represents a different climatic region for being more closely located to the ocean and to the central valley rather than to the cordillera, and El Yeso represents a much more colder, alpine climate.

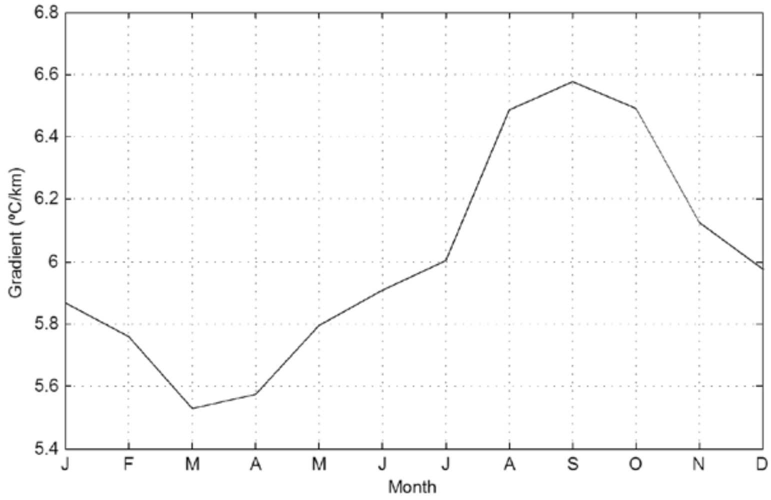

Figure 6 - Temperature gradients

Streamflow

Streamflow data is obtained from two stations: The water run-off of the Mapocho River is measured in Los Almendros, while the streamflow of the Maipo River is analyzed at the San Alfonso station. Originally, there has been another station for the analysis of the Maipo River at Las Melosas, but this streamflow measuring station was suspended in 1993, so available data was insufficient for this study.

The location and elevation from these stations are presented below in Table 5.

ID	UTM N	UTM E	Elev. (m.a.s.l.)	Ti	Tf	DT
Mapocho at Los Almendros	6307006	365534	1024	1961	2000	Day and Month
Maipo at San Alfonso	379641	6266823	1108	1961	2000	Day and Month

Table 5 – Streamflow data

For water runoff, monthly averages and minimum and maximum values for each month are given. Additionally, the analysis performed on the historical period consists of calculating exceedance probabilities (PEXC) based on the 1960-2000 period. For example, if a value of X m^3/s corresponds to an exceedance probability of 60% for a certain month, then 60% of the monthly average streamflow measured during that 40 year period are above X m^3/s. This approach is more accurate than just calculating minimum or maximum values, as it allows a proper analysis of streamflow distribution throughout the year. All of the data presented consists on monthly values, so extreme runoff events may not be represented.

Glaciers and other secondary variables

Even though glaciers in the region have been studied for the last decades, current data for the Metropolitan Region is limited to a recently updated inventory of glaciers that characterizes glacier covered area, but not volume or glacier dynamics. For the Metropolitan Region of Santiago, a monitoring network has been only recently developed, and no trends have been assessed for the evolution of these glaciers. Therefore, the analyses performed in this report consist on analyzing trends and the state of the art for regional ice masses based on available publications and local research efforts. Clearly, the topic of glaciers and their evolution under climate change for the central Andes holds many open and interesting questions, and more research is needed in order to better quantify their current contribution to water resources as well as their possible future evolution.

Records for secondary variables like wind velocity or insolation were obtained from the two existing meteorological stations that measure such variables: Pudahuel and Quinta Normal. Information for these two stations is presented below in Table 6. The average values for each of the variables are presented further in Table 7 to Table 11.

Due to the fact that only two stations are available for the analysis, no spatial interpolation was performed, as results from such an analysis would be insufficiently reliable.

ID	UTM N	UTM E	Elev. (m.a.s.l.)	Ti	Tf	DT
Pudahuel	6304000	333900	480	1980	2005	Seasonal
Quinta Normal	6298113	343588	527	1980	2005	Seasonal

Table 6– Secondary meteorological variables stations

Season	DJF	MAM	JJA	SON	ANNUAL
Wind Velocity (km/h)	13.4	7.9	5.6	10.2	9.7
Standard Deviation	1.5	1.2	2.1	1.8	1.5

Table 7– Wind Velocity for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Wind Velocity (km/h)	6.9	3.7	1.6	5.7	5.3
Standard Deviation	1.1	0.9	0.8	1.0	1.2

Table 8 – Wind Velocity for Quinta Normal station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Mean Radiation (Wh/m2)	315.5	163.2	96.6	237.7	201.9
Standard Deviation	9.3	21.1	6.8	11.9	11.1

Table 9 – Radiation for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%)	48.7	63.2	74.9	61.1	62.0
Standard Deviation	11.9	15.4	18.0	15.1	15.0

Table 10 – Relative Humidity for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%)	51.7	66.3	76.6	62.6	64.3
Standard Deviation	9.4	11.6	13.4	11.3	11.2

Table 11 – Relative Humidity for Quinta Normal station (1980-2005 period).

Chapter 3 – Methodology for future scenarios

The first elements of the construction of a climate change projection are future greenhouse gas (GHG) emissions that are known as the main driver of climate changes. Given that the future evolution of the world is not known, the IPCC developed different emission scenarios, all equally plausible to occur. These were published in the Special Report on Emission Scenarios (IPCC, 2000). Four different "storylines" were developed, named A1, A2, B1 and B2. Each storyline represents different demographic, social, economic, technological, and environmental developments. The present study for the Metropolitan Region of Santiago is analyzed with the climate change simulations that are forced by two different emission scenarios: B1 and A2.

The main characteristic of the B1 scenario is a future high level of environmental and social consciences, and a globally coherent sustainable development with close international cooperation. There are important technological changes leading to a fast-changing convergent world that has a smooth transition to alternative energy systems. The demographic transition is to low mortality and fertility.

In contrast the A2 scenario represents a world that has less international cooperation. People, ideas and capital are less mobile, and technological changes are slower. The A2 world is more heterogeneous, consolidating into a series of economic regions, with disparities in productivity, income, energy use, and economic growth in general. Hence, global environmental concerns are relatively weak. Fertility rates decline relatively slowly, which makes the A2 population the largest among the storylines (15 billion by 2100). This kind of development ends in the largest GHG emissions of all 4 scenarios by the end of the century.

Global Circulation Models, or GCMs, are mathematical models that simulate the Earth's climatic system. Land, ocean and atmosphere processes are represented through mathematical relationships between variables. These calculations are performed on grid divisions of Earth's surface, each of them of dozens or even hundreds of kilometers of resolution. For climate change impact studies, it is therefore necessary to adapt, or *downscale*, the GCM simulations to the spatial scales relevant for the particular study being conducted. There are several available methodologies for achieving this, and are explained in depth in subsequent sections of this report.

In this specific case study, the relevant spatial scale is the Metropolitan Region of Santiago de Chile, which spans the entire width of the country and may be of similar breadth than most GCM grid elements. Because of the grid cell spatial locations, the MRS may be straddled between grid cells simulating oceanic climate and neighboring cells simulating continental climates. In order to overcome this limitation, each downscaling or adaptation of the results of GCM simulations was reviewed looking for misrepresentation of stationarity in variables such as precipitation or temperature, as sometimes the result of the downscaling process was not enough.

For the present report, first, historical scenarios were analyzed according to historic trends. The second step comprises to move on to the future scenarios in order to understand what changes Santiago will overcome during the next 50 years (for the time window 2045-2065). The analysis of future scenarios is performed by analyzing the output of GCMs for the region. Unfortunately, this step is a major source of uncertainty. Different models produce different outputs for the same variable, and the size of most of the model's calculation grids is sometimes greater than Santiago itself. This means that each grid cell of the model, with a particular temperature, precipitation or meteorological variable, represents a region of hundreds of square kilometers.

Despite the fact that regional high resolution models exist (for example the PRECIS model: CONAMA, 2006), these are time and resource consuming, and global models tend to present similar responses to climate change in future scenarios. By taking in account several models it is possible to overcome the uncertainty related to model performance and structure. However, there are various sources of uncertainty that will be analyzed in the next section.

The process of the scenario analysis is accompanied by different sources of uncertainties. The first uncertainty is related to the socio-economic scenario, as it is difficult to anticipate what type of socioeconomic development human society will follow for the next century. The emission scenarios related to each socioeconomic assumption is another uncertainty that could be limited by analyzing different emissions scenarios as this study does for the worst case (A2 scenario) and the best case (B1 scenario).

Finally, the regionalization technique, in this case the *downscaling* techniques, which are presented in the following subsection is a further uncertainty related to the scenario results of the present study. All of these downscaling techniques are based on the assumption that the relationship between the observed values and the modeled values will remain unchanged in the future, which is a strong assumption but is the only possible way to address future climate change scenarios in a local scale without using regional climate models.

Summarizing all the sources of uncertainty, the following "uncertainty cascade" can be depicted (Figure 7, Giorgi, 2005).

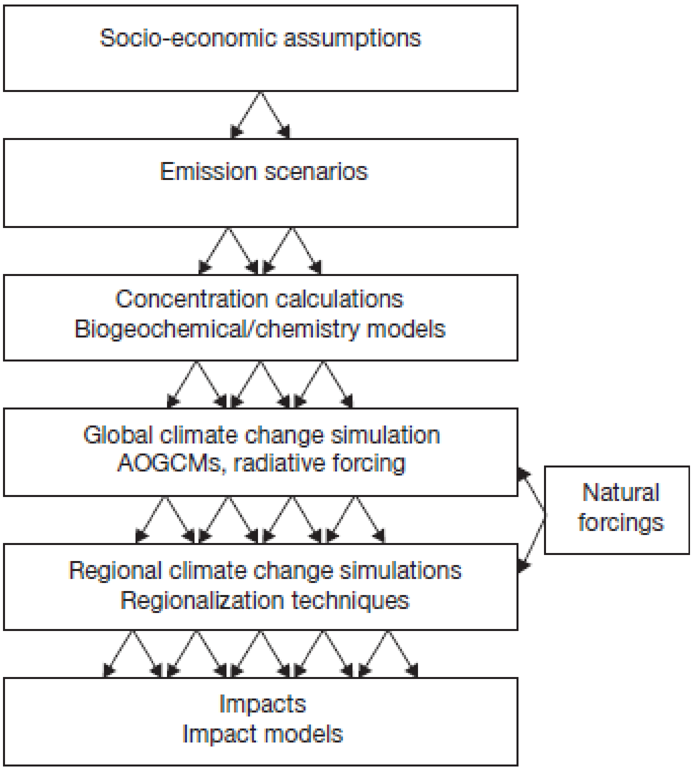

Figure 7 - Uncertainty cascade

Uncertainties related to each GCM can be assessed by studying the output of several models. By taking into account several GCMs it is possible to overcome the uncertainty related to model performance and structure. In the present study, ten to 15 different models for any particular variable or indicator of climate change (for example the average annual precipitation for the 2045-2065 time window) are used. Then, across-model averages are calculated, indicating the standard deviations. Standard deviations are computed for the overall time window averages, and not for year-to-year annual values, in order to distinguish between model uncertainty and interannual variability.

Although the study strives for the most representative conditions for the near future, the analysis of model uncertainty comprehends, however, a much larger dimension than the scope of this report.

Related to the analyzed variables, model uncertainty is present especially in the case of precipitation, e.g. in the number of days with a certain amount of precipitation. For example, csiro_mk3 is biased towards extremes, with most of the precipitation gathered towards the high end of the spectra (higher intensities), while the other models represent the lower end of the spectra: low intensities but a higher number of days with precipitation. This observation has implications on the uncertainty of predictions, as the standard deviation between models is increased, and the future results for extremes could present higher levels of uncertainty.

Another important source of uncertainty for the analysis of precipitation is the fact that models don't necessarily represent in a perfect way the Mediterranean characteristics of the climate of the MRS. In fact, this type of climate is characteristic for a very small portion of the Southern South American continent: if a transect is drawn at 33S from Chile to Argentina, the portion on which the Mediterranean type of climate (warm dry summers, cold wet winters) is predominant remains very small compared to the overall size of the continent. This characteristic implies that GCMs will not represent in an adequate way rainfall patterns for coastal and valley regions of Chile, as one grid cell will possibly represent oceanic climate (the cell closer to the sea), and the next cell will represent a continental climate (the one centered or closer to the Eastern side of the Andes). Climate change response of both types of climatic zones can be very different, so detailed studies with regional models must be performed in order to reduce this source of uncertainty.

Downscaling methodology applied to temperature

While assumptions regarding the representativeness of a GCM when analyzing large or medium scale regional climate can be made, the truth is that when compared to point data values (such as those observed in meteorological stations) these models fail to represent in an exact way the observed values. Downscaling techniques are needed in order to establish a relationship between the modeled and the observed value. For this project, the emphasis is on statistical downscaling techniques, as a dynamic downscaling is not feasible within the time frames of the project and climate projections for only a small region are required. Statistical downscaling is defined according to Wilby et al. (2004) as the "development of quantitative relationships between large-scale atmospheric variables (predictors) and local surface variables (predictands)". This method is based on the view that regional climatic conditions are influenced mainly by two variables: large-scale climatic patterns and regional features (von Storch, 1999; Wilby et al., 2004). The general methodology is to build a statistical model relating large-scale variations to local climatic patterns, and afterwards to apply the GCM model outputs for different scenarios with the relationship found. The main advantage of this technique is that it is fairly simple and it is computationally feasible for most studies. One of the main disadvantages of this methodology is that present day (or historical) relationships are assumed to be valid for the future scenarios. Using several historical periods to validate the relationship found can overpass this "time invariance", but this validation requires a long observational dataset, which in this study was not available. Also, another of the disadvantages is that extremes could be poorly represented as the equations or relationships used could be heavily influenced by mean or more common values in the time series. However, because this study mostly focuses on climatic, or long-term, behavior rather than on extreme events, we accept its validity for this work.

As an example, Figure 8 shows a two year comparison between the models data and the observed values at a particular station. While the models reproduce seasonal variability correctly (for example cold winters and hot summers) for the region, day-to-day averages and short-term variability don't agree with the observed data.

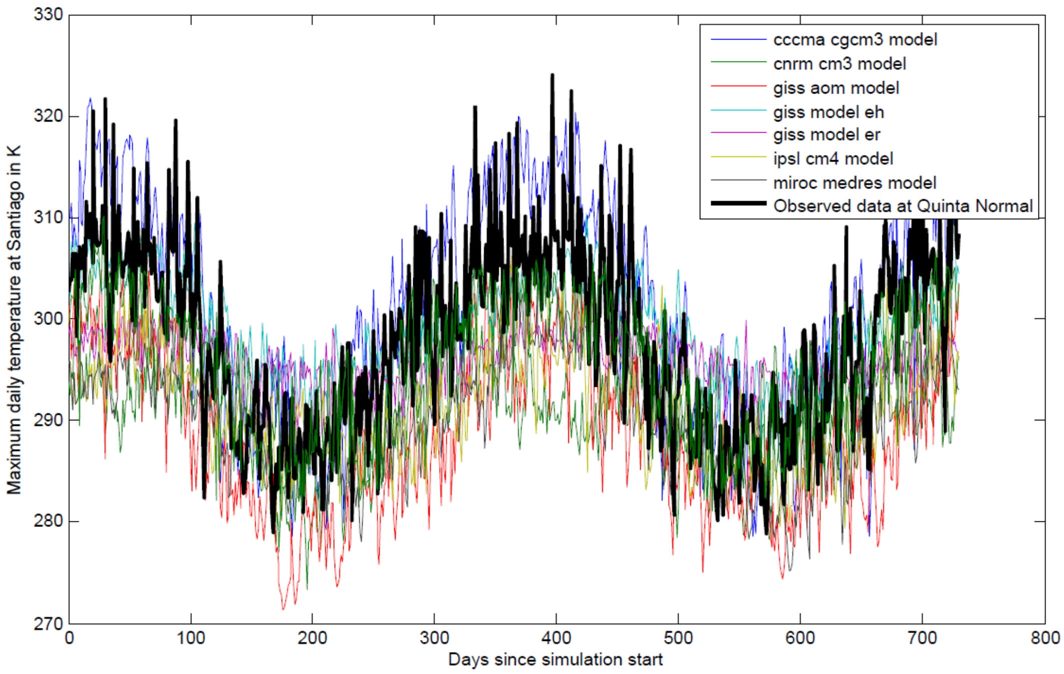

Figure 8 - Modelled and observed data comparison

While models and reality don't always agree on each daily temperature or other observed variables, it is possible to adjust model data to reproduce statistically the observed behavior (distribution) of the studied variable. This type of downscaling is performed by comparing the probability distribution of both the modeled variable and the observed variable, as it is shown on Figure 9.

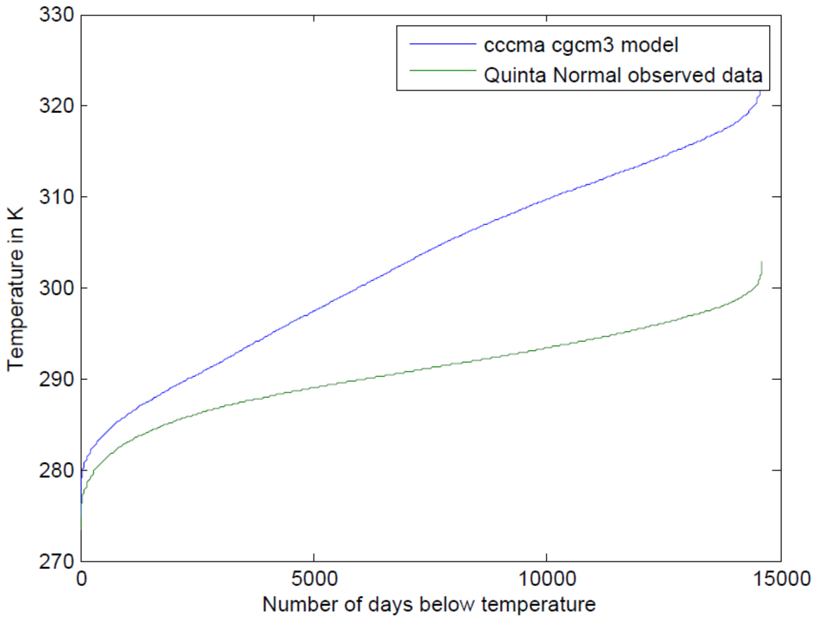

Figure 9 – Modeled and observed data comparison for Quinta Normal station and CCCMA model (1977-2000).

Both of these curves can be related through a regression, as it is shown in Figure 10. A relationship equation is established between both the modeled and observed variable. The relationship is assumed to be in the form Y = K*X + C, where Y is the downscaled or observed value and X is the modeled value by the GCM. The key point in this case is that no temporal correspondence is required among the observed and simulated values; only it is expected that frequency distributions are the same. A similar procedure was used by Wood et al. (2002) and Maurer and Duffy (2005) in hydrological applications. Both authors use a bias correction procedure for values of the model climatology based on probabilistic distributions. The methodology has been compared favorably to different other methods (Wood et al., 2004).

Each one of these relationships is different for each station and model, so if there are five stations and five models, a total of 25 relationships would be defined. For each station, the model-average value of a variable is obtained by calculating the mean of the five model outputs after the downscaling procedure. This average is obtained for each station and time period, so that the final result is a time series for each station and variable. These time series are then used to present station-specific statistics.

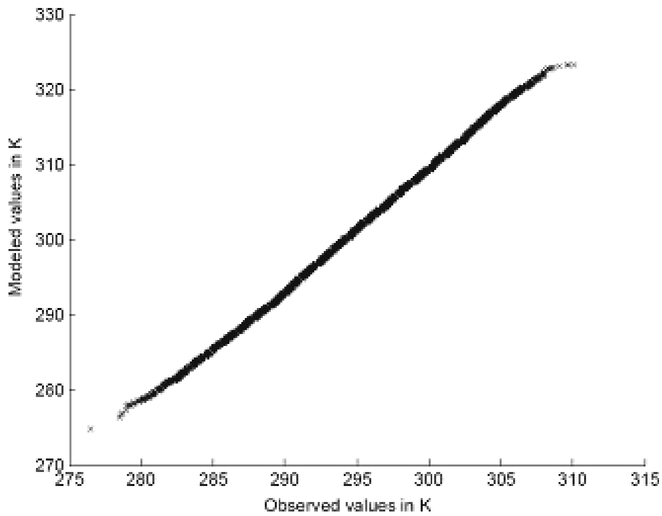

Figure 10 – Scatter plot of modelled and observed data for the mentioned example.

Unfortunately, not all stations count with 40 years of uninterrupted data. Most of the stations have missing gaps, so a direct comparison with the models is not possible without filtering the data. We filter the data by deleting both the observed missing data and the model data for the same day (even though it is still assumed that no chronological correspondence exists). Assuming that these gaps occur randomly in data, the relationship between observed values and modeled values should be the same despite the deletion of certain data. For instance, for a certain station (Quinta Normal, chosen because it is the station used by the DMC to represent the climate of Santiago), two relationships were tested. The first one with all the available data, the second one with randomly selected gaps consisting of nearly 20% of the information. When both relationships were applied to the modeled data (downscaling), a difference of only 0.04°C in average and 0.02°C in standard deviation was obtained for most of the models, showing that missing gaps in information don't affect in a significant way downscaled values.

The mathematical formulation of the downscaled methodology is as follows, with Xobs the value at the station and Xmod the value of the model. K and C are constants belonging to each model.

$$Xobs = K * Xmod + C$$

For the future values, the equation is applied directly:

$$Xobs_{future} = K * Xmod_{future} + C$$

For the example of figures 10 and 11, K = 0.6728 and C = 92.2626. A time series of downscaled values with the same average and standard deviation from the observed values is obtained (though there is still no temporal correspondence between values). An example of two years of downscaled and observed values is presented in Figure 11. This example is only illustrative and the chosen years have no significant value.

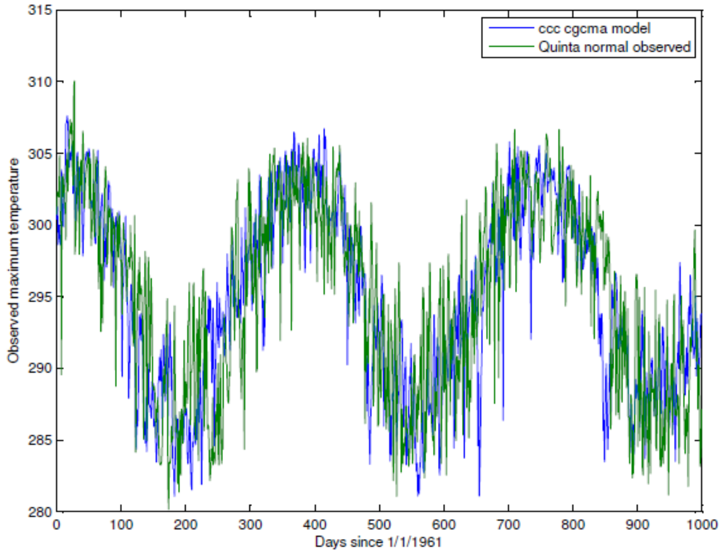

Figure 11 - Comparison of model and real data after downscaling

The downscaling relationship or equation is finally applied to future scenarios modeled by the GCMs and the projected value at the stations is obtained. It is assumed in this methodology that extreme temperatures in both the modeled and observed value occur due to the same climatic patterns and during the same approximate season.

This downscaling methodology is intended to adapt the mean and the variability of the modeled time series to the observed in the historical period. It assumes a lineal correspondence between both distribution curves (which in most cases is correct, as it is seen in Figure 10), and produces reliable results depending on the representativeness of the modeled values. If the model doesn't reproduce the observed climate patterns (for example, cold winter and hot summers), this downscaling methodology will not be reliable. For the present study there were several models that reproduced in a very exact way the temperature and precipitation distribution throughout the year for Santiago, and results obtained with the methodology were sufficient for analyzing temperature and precipitation changes in the region.

The following models were used for the downscaling procedure: the CGCM3 model by the Canadian Center for Climate Modeling (CCCMA, Canada), the CM3 model by the Centre National de Recherches Météorologiques (CNRM, France), the AOM, E_H and E_R model by the Goddard Institute for Space Studies (GISS, USA), the CM4 model by the Institut Pierre Simon Laplace (IPSL, France), the MIROC_MEDRES model by the National Institute for Environmental Studies (NIES, Japan), the MK model by the Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia), the ECHAM model by the Max-Planck-Institute for Meteorology (MPI, Germany) and the ECHAM model by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy).

Downscaling methodology applied to precipitation

Precipitation represented by GCM models could also be biased when compared to the observed values. While for temperature data the only variable is measured temperature, for precipitation data there are two variables that must be downscaled prior to future analysis: precipitation amount or intensity, and wet-day frequency. The downscaling procedure must consider both of these variables in order to achieve a realistic representation of the precipitation distribution registered in each measuring station.

Schmidli et al. (2006) proposed a benchmark for daily precipitation downscaling that was deemed sufficient for this analysis. The methodology considers modeled precipitation from the models directly as a predictor for observed precipitation, as proposed by Widmann et al. (2003) and it is used again by Schmidli et al. (2006) with good results in comparison with other downscaling methods. The method consists in downscaling both the wet-day frequency and the precipitation intensity for each day in a dependent way: first the wet-day frequency is downscaled and afterwards the precipitation intensity is adjusted so both the observed series and the modeled series have the same daily precipitation intensity distribution. This methodology is general and does not require of a specific climate for its application. Furthermore, it attempts at correcting possible biases in the distribution of climatic variables between models and observations, in order to preserve climatic patterns, although not absolute values. Because the methodology performs a sequential downscaling whereby wet-day frequencies are corrected separately from precipitation magnitudes, the singularities of daily precipitation distributions in Mediterranean climates (highly asymmetric density functions, large proportion of zero-rainfall days) are taken into account.

The methodology is as follows:

1) Determine how many wet days are present in the observed data series and in the model series. For example, a certain station can show 1000 wet days for the whole series, but the model output shows 1500 wet days. In all of the cases studied the model output showed a larger number of wet days than the observed record. In this case, step 2 is needed.

2) Establish a wet day threshold. This threshold is used to determine which GCM wet-days are really wet-days based on the observed data. In the example used above, the wet day threshold is established in order to reduce the number of wet days in the model to 1000. A real case example is Cerro Calan station along with the Csiro_mk model. The wet day threshold used is of 0.408 mm, which means that each day with precipitation below this amount will be reduced to 0 in the model. This factor is dependent on the model and on the station used, so different values are obtained for each station and each model. For each station, the results of the different models for a certain variable, such as annual precipitation, are averaged after the downscaling procedure and a “mean” value for the future is obtained.

3) Establish a scaling factor. This factor is used to downscale wet-day intensities to match the ones on the observed data series. In the Cerro Calan example, the scaling factor for csiro_mk model is of 2.07. This means that the model original output was biased by a 50% when compared to Cerro Calan records. The scaling factor is different for each model and station.

Some GCM precipitation estimations are extremely different, in their frequency distribution, to the observed climate in the Metropolitan Region. Attempting to correct or downscale these estimations would not provide any valuable information regarding future climate; therefore, only a subgroup of the available GCMs were used in the precipitation analysis. The models used were CNRM_CM3, CSIRO_MK, MIROC_MEDRES and MPI_ECHAM.

Streamflow and secondary data analysis

Streamflow data for future scenarios was obtained using a hydrological model, WEAP21, and downscaling future values for precipitation and temperature for a certain GCM (HadCM3). WEAP21 is a lumped model that is based on hydrological catchments, where each catchment can present different physical and climatic properties. The methodology for applying hydrological models to study future climate scenarios is as follows:

- First, the model is calibrated against historic streamflow data, using historic meteorological inputs. Data used consist on monthly average streamflow data at Maipo en San Alfonso station (the model is calibrated using a monthly scale), monthly precipitation at San Gabriel station and monthly mean temperature at Pirque station.

- In a parallel way, future scenarios derived from GCM data are downscaled to the meteorological stations used for the hydrologic model.

- Future downscaled values are used as the input for the hydrologic model, obtaining the model output for future scenarios.

It is important to mention that, unlike precipitation and temperature analysis, the streamflow data obtained, using the model, lacks of uncertainty analysis, as only one model (HadCM3) was used for future scenarios and the hydrologic model itself has uncertainty related to hydrological processes and calibration. At the moment of the work performed for the Maipo and Mapocho basins (CEPAL, 2009), the HadCM3 model was the only model with sufficient feedback and previous experience in Chile. Besides, it was the model used for setting the boundary conditions for the PRECIS model study (CONAMA, 2006). Even though only one model was used, the predicted changes by HadCM3 for this region is fairly consistent when compared to the results of the other models used in this study, and the results from the hydrologic model are consistent with the changes expected for the analyzed watersheds.

Data for future scenarios on streamflow was available only for the A2 and B2 scenarios. Even though the B2 scenario is not exactly the same as the B1, it is important to mention that both scenarios represent an “optimistic” point of view regarding future emissions, and up to the year 2050 are practically indistinguishable. Similar emission scenarios should result in similar changes for variables such as temperature and precipitation, so results of the hydrologic model considering B2 scenario instead of B1 should be coherent among each other. Detailed datasets of the results are available, but in this report average values for the future scenarios are presented in order to maintain clarity.

For variables such as wind velocity, radiation and relative humidity, downscaling is much more uncertain, as these variables are correlated not only to a regional climatic pattern but also to local singularities. For example, radiation measurements will be conditioned if the area on which the station is located is prone to fog formation, and the wind velocity measurements will be modified if there is a hill close by or a building on the way of the station. As GCMs don’t take in account these effects, it is probable that projected secondary variables by the models will not be representative at all of the measurements performed at a point level.

In order to comply with the requirements of the project, the same statistical approach applied to temperature was used taking in account monthly measurements of these variables. However, due to the large uncertainty derived from the fact that local effects are especially important on these variables, results for secondary variables (especially wind, relative humidity and radiation) must be used in a differential way; this is, taking in account the difference between the scenarios (historic, A2 and B1) and not the absolute value of the variable projected by the GCMs.

Chapter 4 – Historical context and future climate analysis results

Summary

Santiago's current climate, according to the results obtained from the observed values at different meteorological stations is characterized by hot, dry summers and cold, wet winters. This type of climate is consistent with the definition of Mediterranean climate present in the region. Average summer maximum temperatures range from 28 to 30 degrees Celsius, while minimum temperatures during winter range from 0 to 5 degrees Celsius. Precipitation falls mostly during the months of June, July and August, with total precipitation amounts ranging from 200 to 500 mm each year. Snow events are quite rare and happen mostly in the higher parts of the MRS. Trends for the last 30 years show increasing temperatures especially for the upper elevation stations, whereas precipitation amounts have been decreasing.

Regarding local spatial patterns of meteorological variables, temperature gradients are not evident within the urban limits of the city, as variability introduced by external factors such as buildings, parks or hills is greater than the expected variability resulting from elevation of the recording station. On the other hand, precipitation gradients are important and higher precipitation amounts are observed for higher stations. This orographic effect should be taken in account when analyzing future flood scenarios as rising temperatures could bring increasing flooding due to a greater liquid precipitation area.

Rivers from the region are characterized by presenting higher streamflow volumes during spring and summer due to their snowmelt dominated regime. During winter months, streamflow volumes in these rivers remains low due to the high altitude of their basins, with precipitation falling as snow during most of the rainy season and accumulating in a snowpack that melts later in spring and summer, generating most of the annual streamflow. Glaciers in the region have presented negative trends in volume and mass according to previous studies, and due to projected higher temperatures in the future these glaciers are expected to keep receding.

Climate projections for the region show some variability in value, but mostly agree in the trends being projected: warming temperatures and decreasing precipitation is expected for the region of southern South America according to the models. Figure 12 presents an ensemble mean of projected changes for the 2070-2100 period, from different GCMs (CONAMA, 2006).

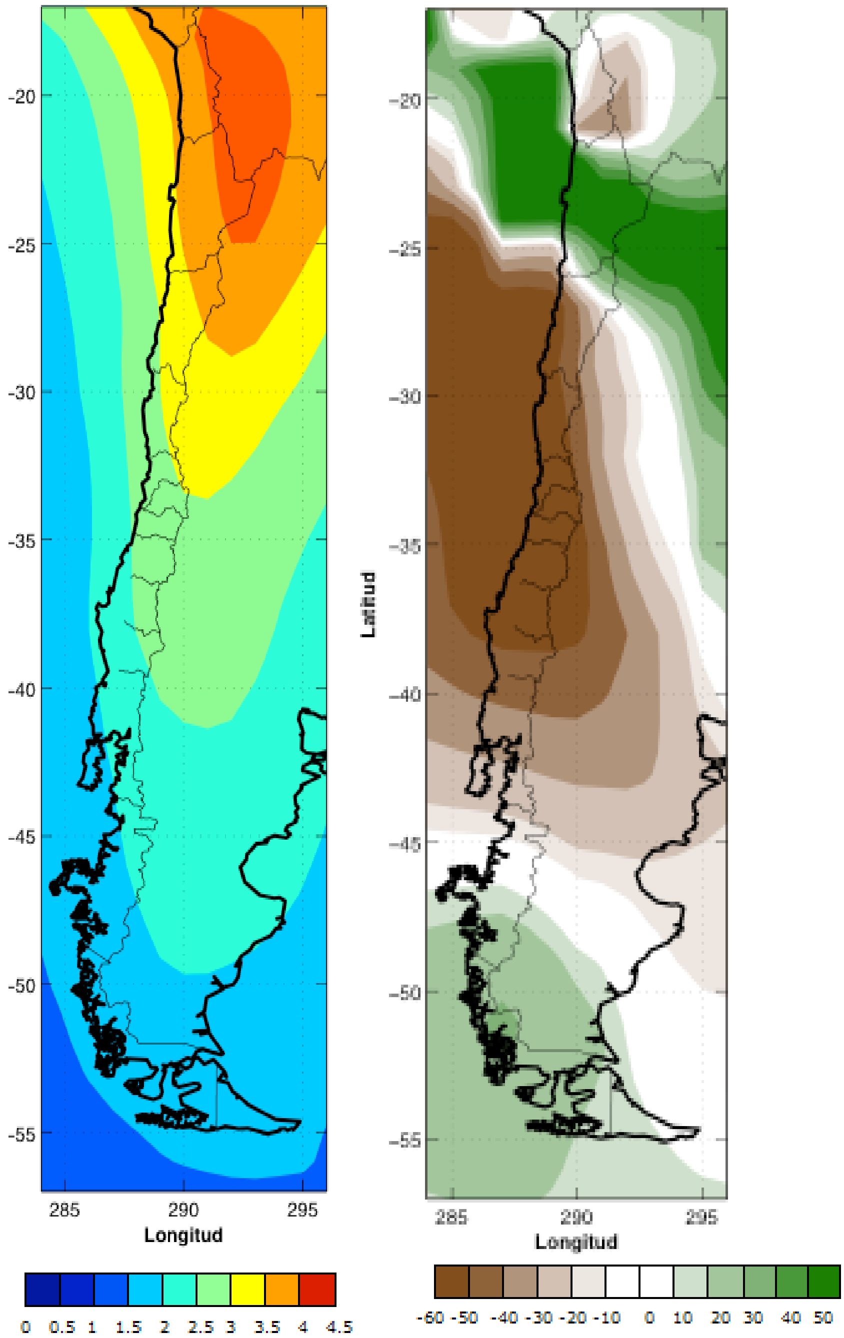

Figure 12- Projected changes in temperature (left, upper color bar in degrees Celsius) and precipitation (right, lower color bar in %) for Southern South America (period 2070-2100) according to an ensemble mean of different climatic models; scenario SRES A2.

In this chapter, all the results for the 2045-2065 period are presented. However, the results must be understood as an average for the whole period and not as a result representing each individual year. Results include a standard error bar wherever possible. This bar illustrates the standard deviation amongst the models for the future scenarios.

Temperature

As all of the meteorological stations incorporated in this study record maximum and minimum daily temperature, these data are used for the analysis. When available all observed data refer to the 1970-2000 time span.

Maximum annual temperatures for the stations in the Maipo Basin do not show big differences and range on the annual average from 21.71 degrees to 22.85 degrees. Only the station El Yeso, due to their higher elevation, differs significantly reaching an annual average of maximum temperatures of 13.72 degrees. The hottest months are in summer when maximum temperatures pass on average 25 degrees. Some stations even report average maximum temperatures of more than 30 degrees for January and February (e.g. Cerro Calan and Central Florida). In winter, maximum temperatures are about 15 degrees on average, being the exception El Yeso with only 5.85 degrees maximum temperature on average in August. The standard deviation is quite low for the stations in the Maipo Basin, but rises slightly for the higher elevated El Yeso station.

Detailed results for each station, indicating annual and monthly averages and standard deviation, are shown in Table 12.

ID	Melipilla	Quinta Normal	Tobalaba	Pirque	Central Florida	Cerro Calan	El Yeso
Elev.	168	527	652	659	770	848	2475
Annual	21.71	22.47	22.36	22.03	22.81	22.85	13.72
St. Dev.	1.53	0.51	0.52	1.49	0.93	1.54	1.62
Jan	27.72	29.70	29.59	28.98	30.41	30.66	20.76
St. Dev.	1.27	0.90	0.66	1.00	0.98	0.77	1.22
Feb	27.27	29.20	29.14	28.43	29.93	30.24	20.80
St. Dev.	0.98	0.93	0.98	1.04	1.23	1.02	1.43
Mar	25.75	26.96	26.94	26.62	27.65	28.06	19.35
St. Dev.	1.05	0.82	0.76	0.93	1.05	0.90	1.24
Apr	22.54	22.79	22.42	22.58	22.83	23.08	15.39
St. Dev.	1.13	1.56	1.35	1.50	1.45	1.45	1.96
May	18.40	18.32	18.06	18.37	18.08	18.48	10.76
St. Dev.	1.17	1.43	1.61	1.61	1.45	1.70	2.17
Jun	15.61	15.03	15.26	15.63	15.26	15.80	6.84
St. Dev.	1.15	1.46	1.74	1.48	1.68	1.75	2.12
Jul	15.09	14.90	15.17	15.08	15.05	15.26	5.85
St. Dev.	1.04	1.21	1.25	1.57	1.57	1.40	2.32
Aug	16.75	16.84	16.66	16.32	16.77	16.45	7.12
St. Dev.	0.77	1.15	1.21	1.30	1.43	1.15	2.19
Sep	18.79	19.11	18.70	18.22	19.22	18.47	9.51
St. Dev.	1.24	1.21	1.18	1.26	1.81	1.29	2.15
Oct	21.82	22.43	22.37	21.66	23.03	22.40	13.11
St. Dev.	1.27	1.33	1.55	1.37	1.53	1.51	1.71
Nov	24.04	25.92	25.69	24.85	26.38	26.07	16.07
St. Dev.	1.45	1.31	1.30	1.44	1.43	1.59	1.83
Dec	26.78	28.48	28.33	27.59	29.10	29.21	19.07
St. Dev.	0.83	1.01	1.00	1.05	1.20	1.14	1.61

Table 12 – Maximum temperature averages

The analysis of average minimum temperatures shows bigger differences among the stations than in the case of maximum temperatures. While Central Florida reports an annual minimum temperature of 12.62 degrees on average, the other stations of the Maipo Basis reach only about eight degrees on average, being Pirque with 5.96 degrees on average the lowest value for this group of stations and Cerro Calan with 9.89 degrees on average in between. Again, due to its elevations, el Yeso shows the lowest minimum temperature of all stations with 3.60 degrees on average.

Minimum temperatures in summer range from about eleven degrees on average to about 14 degrees for the stations in the Maipo Basin compared to 8.73 degrees for El Yeso. In winter, the minimum temperatures are about four to six degrees on average in Melipilla, Quinta Normal, Tobalaba, Central Florida and Cerro Calan, but is only 1.72 degrees on average in Pirque. In El Yeso, four months show minimum temperatures below zero degrees on average. Table 13 shows detailed data for each station, with the annual and monthly averages and standard deviation.

ID	Melipilla	Quinta Normal	Tobalaba	Pirque	Central Florida	Cerro Calan	El Yeso
Elev.	168	964	652	659	770	848	2475
Annual	8.14	8.47	8.55	5.96	12.62	9.89	3.60
St. Dev.	2.10	3.25	3.40	3.07	3.45	2.96	4.08
Jan	11.03	13.03	13.29	10.34	13.68	14.05	8.73
St. Dev.	1.32	0.78	0.95	0.75	0.76	0.73	1.11
Feb	10.97	12.51	12.79	9.75	13.05	13.63	8.83
St. Dev.	1.32	0.83	0.91	0.96	0.97	0.74	1.26
Mar	9.98	10.88	11.34	8.01	11.57	12.75	7.85
St. Dev.	1.54	0.94	0.90	1.23	0.66	0.80	1.20
Apr	8.30	8.20	8.58	5.23	8.64	10.56	5.17
St. Dev.	1.49	0.97	0.85	1.36	0.86	1.14	1.29
May	6.94	6.32	6.33	3.50	6.33	8.57	2.15
St. Dev.	1.26	1.09	1.24	1.76	1.31	1.87	1.66
Jun	6.00	4.60	4.64	2.48	4.90	7.05	-0.68
St. Dev.	1.69	1.54	1.39	1.78	1.33	1.69	2.15
Jul	5.18	3.91	3.76	1.72	4.04	5.99	-1.89
St. Dev.	1.30	1.33	1.13	1.53	0.94	1.05	1.87
Aug	5.72	4.96	4.82	2.91	5.03	6.19	-1.58
St. Dev.	1.44	1.08	1.21	1.71	1.15	1.05	2.07
Sep	6.68	6.49	6.26	4.16	6.49	7.28	-0.13
St. Dev.	1.22	1.02	1.10	1.43	1.04	1.03	1.76
Oct	7.66	8.37	8.27	5.94	8.52	8.93	2.40
St. Dev.	1.22	0.88	0.81	1.15	0.88	0.88	1.32
Nov	8.92	10.27	10.18	7.91	10.58	10.90	5.03
St. Dev.	1.14	0.73	0.83	1.05	0.80	0.94	1.17
Dec	10.35	12.13	12.33	9.58	12.62	12.83	7.36
St. Dev.	1.24	0.77	0.91	0.83	0.80	0.87	1.21

Table 13 - Minimum temperature averages

Besides mean maximum and minimum temperatures, extreme temperature analysis must be performed in order to fully understand the impact of rising temperatures. Small changes in average could bring important changes in extreme temperatures, as the average is just part of the whole temperature distribution. For instance, a small change in maximum temperatures (daily) of approximately 1 to 2 degrees Celsius can entail – in some cases – a rising number of days with extreme temperatures above 30 degrees, eventually resulting in a 100% change.

Tables 14 and 15 present the number of days for each year that show maximum temperatures above 30 degrees and minimum temperatures below 0 degrees, along with standard deviation computed from the time series of each variable.

	Cerro Calan	Quinta normal	Pirque	Melipilla	Tobalaba	Florida
Average N° of days per year	67.92	54.58	30.48	17.00	44.56	55.50
Standard Deviation	10.58	8.59	12.78	7.83	11.09	17.25

Table 14 - Number of days with maximum temperature above 30ºC

	Cerro Calan	Quinta normal	Pirque	Melipilla	Tobalaba	Florida
Average N° of days per year	67.92	54.58	30.48	17.00	44.56	55.50
Standard Deviation	10.58	8.59	12.78	7.83	11.09	17.25

Table 15 - Number of days with minimum temperatures below 0ºC

Analyzing the Pirque station in detail, an interesting result arises: it presents a relatively high number of days with minimum temperatures below freezing levels, and it also reports a low number of days with maximum temperatures above 30 degrees. This property of Pirque could be a clear sign of urban heat island (UHI) effect on the other stations. However, as only one station displays this effect, the result should be considered with caution as other factors such as wind or microclimates could affect the record. On the other hand, it can be seen that Cerro Calan shows a much lower number of days with minimum temperature below freezing point than the other stations, indicating the influence of local conditions around the former station (if we accept that data are accurate). Nevertheless, it is beyond the scope of this study to analysis UHI, especially because the meteorological network is not dense enough.

Regarding historical trends, Falvey and Garreaud (2009) analyzed historical temperature trends in central Chile (27.5°S – 37.5°S) for the 1960-2006 period, finding positive trends from 1975 to 2006 in stations located in the Andes and central valley, implicating a warming for the study period. Observed trends are presented in Figure 13 (Falvey and Garreaud, 2009). A more pronounced warming on the Andes region than in the coast is observed.

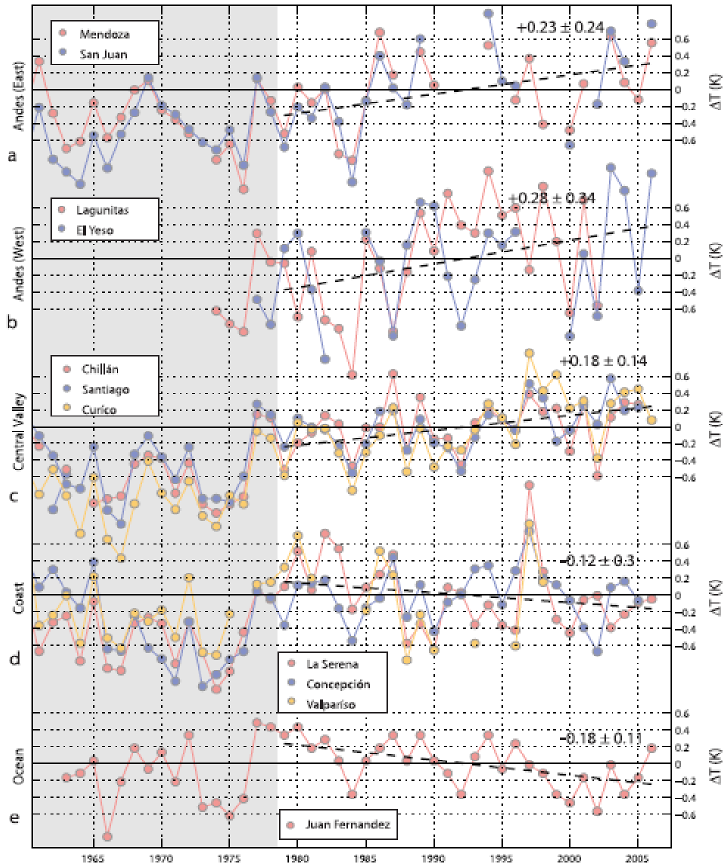

Figure 13 - Temperature trends for the years 1979-2006

Regarding observed extremes, different trends have been observed for maximum and minimum temperature, but results show warming on both indexes for stations located near Santiago. Results are presented in Figure 14. Cooling patterns observed for coastal and low lying stations are also reproduced on the daily maximum and minimum temperatures, which have increased proportionally and according to the elevation of the measuring station.

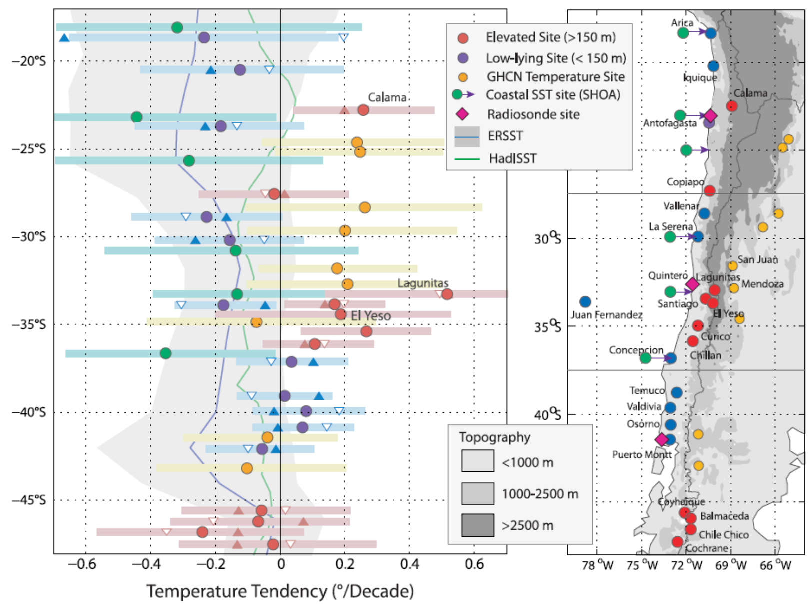

Figure 14 – Daily temperature trends

The main conclusion of the study is the presence of a warming trend in the Andean regions of central Chile, and a less significant – yet still observable – warming trend in the valley regions. As the Metropolitan Region of Santiago is mostly located within the central valleys and close to the mountain range, according to the results by Falvey and Garreaud, temperatures have been increasing during the last 40 years, as it is shown in Figure 13 and Figure 14 for the stations located within the limits of the MRS (Lagunitas, not used for the present study, El Yeso and Santiago or Quinta Normal). It is expected that the stations used for the present study have similar characteristics to those used by Falvey and Garreaud, and that similar changes will be observed for future scenarios, as the warming trends are expected to continue for the next years.

For the future scenarios, maximum and minimum temperatures were analyzed. Results are shown in Table 16 to Table 19 and Figure 15 to Figure 19.

Maximum Temperatures

Month	Cerro Calan	Tobalaba	El Yeso	Florida	Melipilla	Pirque	Quinta Normal
Jan	32.61	31.23	23.20	32.53	29.42	30.93	31.76
Feb	32.42	31.04	23.01	32.34	29.27	30.75	31.58
Mar	29.84	28.61	20.49	29.83	27.28	28.42	29.21
Apr	24.98	24.04	15.76	25.10	23.52	24.03	24.75
May	19.70	19.08	10.63	19.97	19.45	19.26	19.90
Jun	16.48	16.04	7.49	16.83	16.96	16.35	16.94
Jul	16.01	15.60	7.03	16.38	16.60	15.93	16.50
Aug	18.49	17.93	9.44	18.79	18.51	18.17	18.78
Sep	21.21	20.49	12.09	21.43	20.61	20.62	21.28
Oct	24.73	23.80	15.52	24.86	23.34	23.80	24.52
Nov	28.63	27.47	19.32	28.65	26.35	27.33	28.10
Dic	31.24	29.93	21.86	31.19	28.36	29.68	30.50
Annual	24.65	23.73	15.45	24.78	23.27	23.73	24.45

Table 16 - Maximum temperatures, A2 scenario

Month	Cerro Calan	Tobalaba	El Yeso	Florida	Melipilla	Pirque	Quinta Normal
Jan	32.04	31.02	22.64	31.98	29.00	30.42	31.24
Feb	31.33	30.35	21.94	31.28	28.44	29.77	30.58
Mar	28.76	27.94	19.44	28.78	26.45	27.45	28.22
Apr	24.01	23.48	14.81	24.16	22.77	23.16	23.86
May	19.23	18.99	10.16	19.51	19.07	18.84	19.46
Jun	16.49	16.42	7.49	16.84	16.95	16.37	16.94
Jul	16.05	16.00	7.06	16.41	16.61	15.96	16.53
Aug	18.05	17.88	9.01	18.35	18.16	17.77	18.37
Sep	21.36	20.99	12.23	21.58	20.73	20.76	21.42
Oct	24.62	24.05	15.41	24.75	23.25	23.71	24.42
Nov	28.33	27.53	19.02	28.36	26.12	27.06	27.82
Dic	31.03	30.07	21.65	30.99	28.21	29.50	30.31
Annual	24.24	23.69	15.03	24.38	22.95	23.36	24.06

Table 17 - Maximum temperatures, B1 scenario

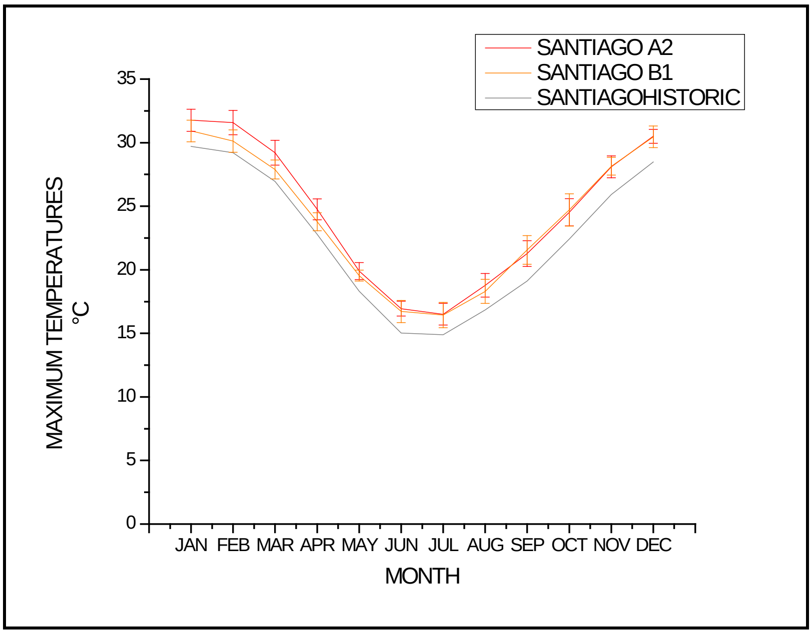

Figure 15 - Maximum average temperatures for Quinta Normal station (Santiago). In this case (and for all figures related to temperature) historic represents the average observed values for each meteorological station.

Every station experiences a rise in annual mean temperature in the order of 1.5 degrees for the two scenarios analyzed. This increase in temperature is consistent in every month, but for summer months it appears to be more important than winter months. The city will be affected especially during the months of November to March, as increasing higher temperatures will bring more heat waves and more extreme temperatures. This observation should be backed up with the total number of days with maximum temperatures above 30 degrees (results presented in Figure 16).

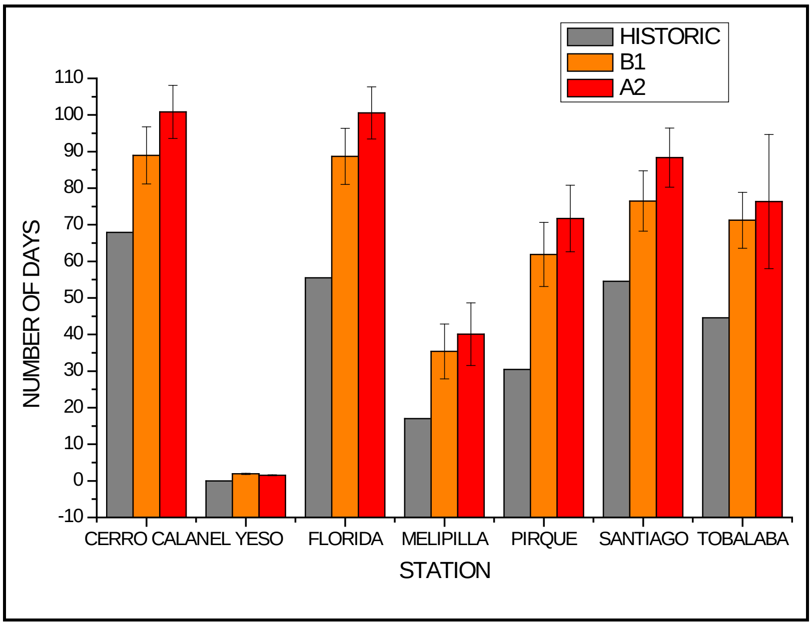

Figure 16 - Number of annual days with temperatures above 30°C for each station. Different increases in the number of days with maximum temperatures above 30°C are due to the different downscaling relationships derived for each station, the fact that some stations have different historical values and local effects on temperature.

All of the stations present a total annual increase in the number of days with maximum temperatures above 30 degrees, and some of these changes are significant. For example, the station of Santiago (or Quinta Normal) shows an increase of more than a month of total days with extreme high temperatures, so does the stations of Cerro Calan, Florida and Pirque for the more severe scenario. Even for the optimistic scenario, every station shows a significant increase in the number of days with extreme temperatures. This will severely affect the life quality of Santiago during summer. All of the GCM models analyzed show an increase in the number of days.

While maximum temperatures show a consistent and strong signal towards significant warming, minimum temperatures still must be assessed in order to comprehend the full extent of the climate change impact in the city of Santiago. The same methodology that was used with maximum temperature downscaling and analysis was applied to analyze minimum temperatures.

Minimum Temperatures

Considering the results obtained for maximum temperatures, it is expected to obtain similar increases for minimum temperatures for both scenarios, with A2 showing a more significant increase than B1. However, it is worth mentioning that some stations used in this study showed non-consistent minimum temperature measurements. For example, Cerro Calan station showed no days below 0 degrees, which is an error as during winter several days below freezing temperatures are experienced in the surroundings of this station. This type of error must not be disregarded for the other stations, and as downscaling methodologies include a comparison with historical values it is possible that some of the future values calculated for some stations are inconsistent. For example, some stations show decreases in temperatures for some months for both scenarios. In general, the longer the averaging period used for estimating changes, the lower the error that the measurement should present. For example, annual temperatures should show a more consistent signal than monthly temperatures. Figure 17 represents the average values for each month for a particular station.

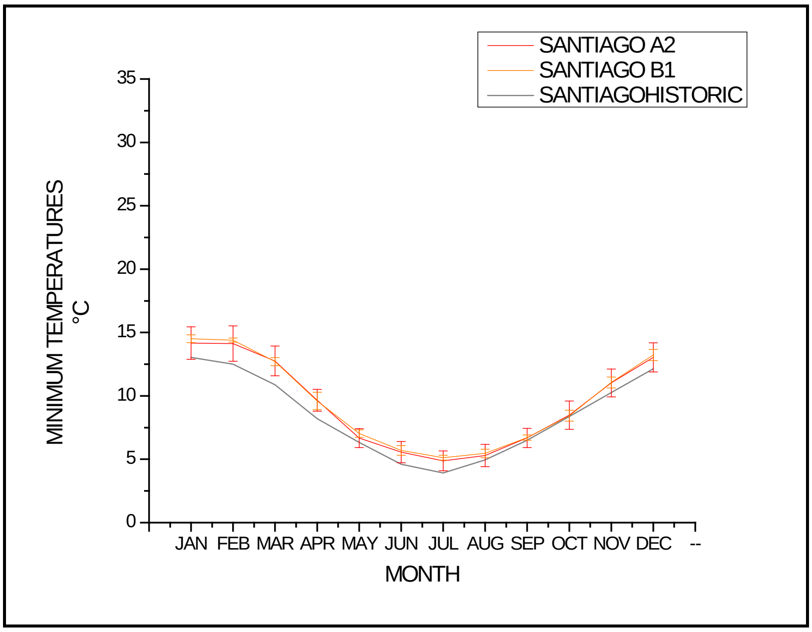

Figure 17 - Minimum temperatures for Quinta Normal (Santiago) station.

Minimum temperatures also show a consistent increase, however this increase in temperature is lower than the ones experienced by maximum temperatures. Without proper study it is difficult to assess why minimum temperatures experience a less drastic change when compared to maximum temperatures, although one reason could be the fact that minimum temperatures within the city limits are modulated by the UHI effect. As minimum temperatures are already high when compared to rural stations such as Pirque, climate change impact will not be clearly visualized in minimum temperatures within the city limits. However, the change in minimum temperatures is still positive: more than one degree for most of the studied stations for the two scenarios. This change is less important on spring months, and uncertainty is also larger during these months. However, for summer and winter the warming signal is strong.

Month	Cerro Calan	Tobalaba	El Yeso	Florida	Melipilla	Pirque	Quinta Normal
Jan	15.47	14.65	11.64	14.52	13.39	12.14	14.73
Feb	15.56	14.63	11.62	14.60	13.48	12.07	14.71
Mar	14.35	13.27	9.88	13.38	12.33	10.79	13.38
Apr	11.55	10.14	6.28	10.52	9.71	7.67	10.32
May	8.62	7.08	2.73	7.52	6.99	4.44	7.33
Jun	7.33	5.85	1.07	6.18	5.80	3.07	6.13
Jul	6.72	5.24	0.55	5.57	5.22	2.44	5.52
Aug	7.09	5.70	0.91	5.94	5.57	2.81	5.98
Sep	8.32	7.07	2.51	7.21	6.71	4.17	7.32
Oct	9.90	8.81	4.50	8.81	8.19	5.96	9.02
Nov	12.26	11.35	7.54	11.24	10.38	8.56	11.50
Dic	14.27	13.46	10.10	13.28	12.26	10.81	13.56
Annual	10.94	9.75	5.80	9.88	9.16	7.10	9.94

Table 18 - Minimum temperatures, A2 scenario

Month	Cerro Calan	Tobalaba	El Yeso	Florida	Melipilla	Pirque	Quinta Normal
Jan	15.50	14.64	11.77	14.31	13.64	12.09	14.73
Feb	15.34	14.46	11.58	14.15	13.48	11.89	14.56
Mar	13.77	12.78	9.66	12.59	11.97	10.05	12.92
Apr	10.94	9.74	6.13	9.75	9.28	6.80	9.97
May	8.62	7.26	3.21	7.41	7.09	4.16	7.51
Jun	7.35	5.90	1.60	5.85	5.89	2.73	6.22
Jul	6.95	5.47	1.11	5.72	5.51	2.25	5.76
Aug	7.31	5.86	1.57	6.09	5.85	2.67	6.12
Sep	8.49	7.12	3.04	7.27	6.97	4.02	7.35
Oct	9.98	8.72	4.97	8.77	8.38	5.71	8.93
Nov	12.26	11.16	7.78	10.88	10.53	8.31	11.30
Dic	14.27	13.32	10.27	13.09	12.45	10.64	13.43
Annual	10.87	9.68	6.02	9.67	9.23	6.75	9.88

Table 19 - Minimum temperatures, B1 scenario

The impact of rising minimum temperatures could be positive when days with temperatures below freezing are studied. Figure 18 presents the result for this analysis.

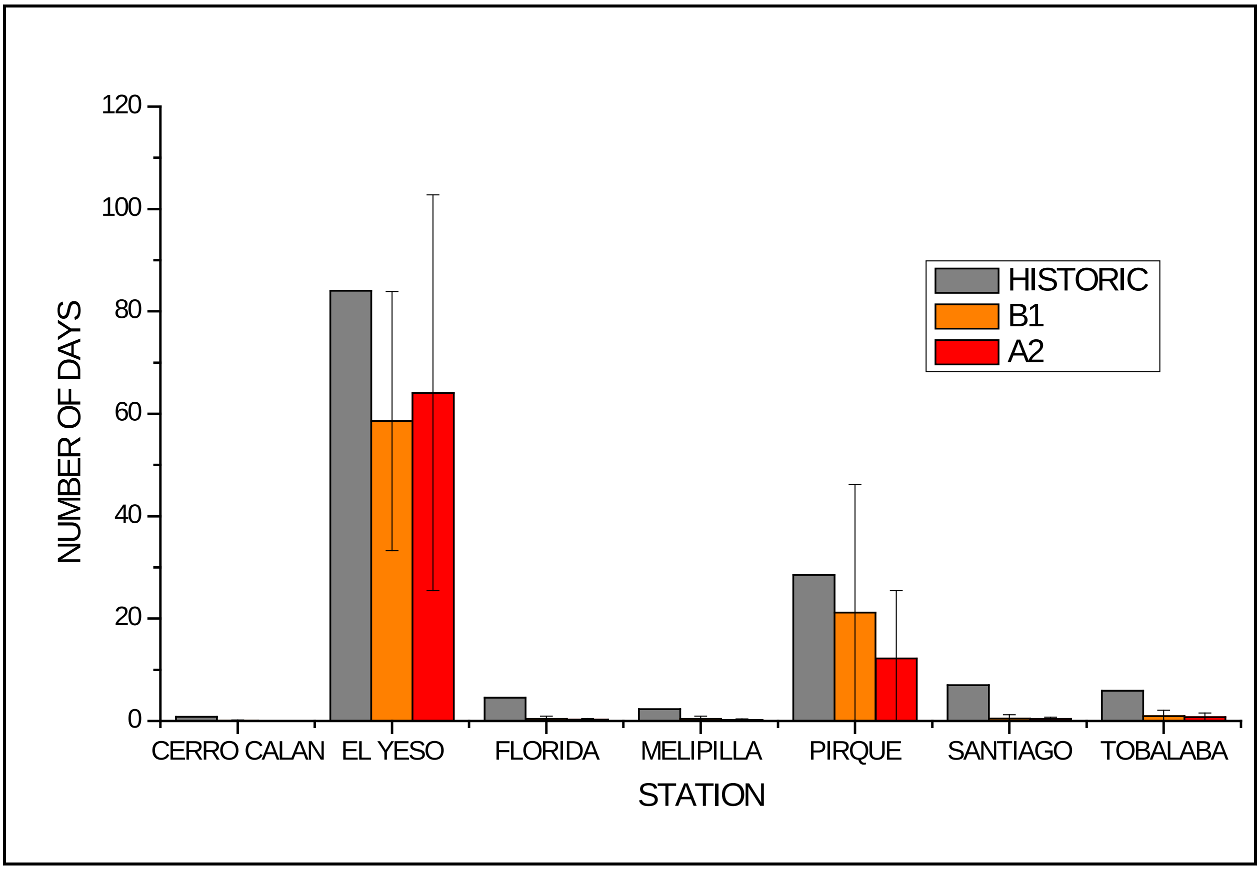

Figure 18 – Number of days with minimum temperatures below zero degrees.

All of the stations present a lower number of days with freezing temperatures. This change is especially significant for stations that used to present a higher number of days with freezing temperatures, such as Pirque and El Yeso stations.

0ºC Isotherm Altitude

According to a study performed by Carrasco et al. (2005), a change of approximately 150 m (positive increase) has been observed for the isotherm 0 line between 1975 and 2001, and subsequent changes in snowline and equilibrium line have also been observed. Data from this study was obtained using radiosonde measurements (not available for the public). For a station located near the Pacific Ocean, at the same latitude of Santiago, mean annual isotherm line was located at 3500 m.a.s.l. approximately, varying with values of 4250 m.a.s.l. during summer and 3000 m.a.s.l. during winter. Considering that a station close to the ocean should exhibit warmer temperatures than those observed inland during winter, the values obtained based on the Pirque temperature record and the mean gradient are deemed to be close to the ones observed, thus future temperature scenarios will consider Pirque and the same gradient as a baseline for understanding isotherm 0 line changes due to warming. The analysis of the isotherm 0 position is important as it shows when heavy precipitation events will have a greater impact on the city. Storm events during March or April sometimes led to increased flooding due to the higher position of the isotherm 0 line, thus a higher amount of liquid precipitation is available. In the future scenarios, the change in the position of this line according to values obtained for maximum and minimum temperatures will be assessed. However, due to the uncertainty in the temperature gradients, the low number of stations and the fact that each independent storm has its own isotherm 0 line position, changes addressed in this report must be taken into account in a qualitative way rather than in absolute terms. The position of the isotherm 0 lines is important as it determines the division between liquid and solid precipitation in the upper elevations. A higher isotherm 0 line would bring increased liquid precipitation areas for each storm, with increased flooding and a higher amount of sediments carried during each event. Table 20 presents the calculated isotherm derived from the temperature gradients for the future scenarios. These results were calculated indirectly from mean monthly temperature projections for Pirque station. These monthly values were at the same time calculated from mean maximum and minimum temperature projections for each month.

0ºC Isotherm Altitude (m.a.s.l)			
Month	**Historic**	**A2**	**B1**
January	4235	4576	4525
February	4197	4627	4520
March	4001	4442	4278
April	3322	3695	3527
May	2673	2841	2777
June	2295	2413	2384
July	2153	2292	2278
August	2241	2384	2340
September	2475	2671	2670
October	2929	3106	3078
November	3514	3787	3741
December	3978	4276	4244
YEAR	3146	3398	3334

Table 20 – 0ºC Isotherm variations due to climate change.

These values must be taken in a relative way (i.e., comparing the differences between historic and future scenarios, and not the absolute values) as they are approximate and based in only one station. For example, for A2 and B1 scenario El Yeso shows a mean temperature above freezing level, but isotherm results show that at El Yeso elevation freezing temperatures could still be present.

The calculated isotherm for the region experiences rises of between 200 and 400 meters for each month in the more severe scenario (A2). This rise will have an impact on storms occurring during warmer periods such as spring and autumn, with increased flooding, increased sediment transport and important effects in the Santiago water supply, as turbid waters will be more frequent due to an increased amount of runoff coming from the steeper, higher zones of the Andes, affecting the capacity of water treatment plants.

Precipitation

Considering the precipitation gradients, the stations for this study show different precipitation values, ranging on average from 345 mm p.a. at Quinta Normal to 657 mm p.a. at San Gabriel. Precipitation patterns are similar for all stations with higher precipitations in the months May until August and lower precipitation in summer (from December until February). Nevertheless, standard deviation is high, indicating that precipitation is characterized by high variability. One reason for the irregular precipitation could be the influence of ENSO phenomena in the MRS.

Table 21 shows more detailed data for each station, with the annual and monthly averages and standard deviation.

ID	Melipilla	Quinta Normal	Tobalaba	Pirque	Central Florida	Cerro Calan	San José de Maipo	San Gabriel	El Yeso
Elev.	168	527	652	659	770	848	964	1266	2475
Annual	391	345	366	463	453	446	536	658	648
St. Dev.	204	177	175	233	232	214	276	358	374
Jan	0	1	1	0	1	1	3	2	6
St. Dev.	1	2	4	2	2	3	6	8	12
Feb	1	2	2	3	2	4	4	4	10
St. Dev.	3	5	7	9	7	11	9	9	14
Mar	4	5	6	5	7	6	7	5	9
St. Dev.	7	8	10	8	11	9	14	10	12
Apr	17	22	24	31	29	28	37	55	53
St. Dev.	21	25	26	35	32	30	37	62	52
May	72	56	54	71	68	65	87	102	94
St. Dev.	67	49	49	53	57	52	73	79	80
Jun	105	81	85	114	109	100	137	179	170
St. Dev.	106	87	99	119	128	108	170	204	216
Jul	85	77	73	101	98	99	106	118	133
St. Dev.	100	82	64	106	99	100	107	119	164
Aug	59	49	59	67	66	65	74	85	82
St. Dev.	51	46	55	68	63	54	77	100	95
Sep	33	33	38	44	44	47	50	67	58
St. Dev.	38	33	35	45	36	33	37	69	57
Oct	11	13	17	17	21	22	21	23	18
St. Dev.	16	18	19	21	25	23	25	34	22
Nov	4	3	3	5	5	5	5	11	10
St. Dev.	10	7	4	8	7	7	8	19	12
Dec	1	2	4	4	3	5	5	5	5
St. Dev.	3	6	12	11	7	13	15	12	13

Table 21 – Precipitation data for each station. Precipitation is measured in mm, while elevation is measured in m.a.s.l. Time span corresponds to the historical scenario.

Trends in precipitation have been examined in different studies (CONAMA 2006, Quintana and Aceituno 2006) and the common observation is that there is a slight decreasing trend for the region, with lower total precipitation amounts. Quintana and Aceituno (2006) evaluated data for the last 30 years for central and southern Chile (30-55°S, see Figure 19), finding negative (although not significant) trends for 33 - 37S, and significant negative trends between 37 - 45°S.

Even though the study by Quintana and Aceituno shows no significant trends for the Metropolitan Region of Santiago de Chile, the strong negative signal between 33S and 45S, with almost all records showing negative (albeit mostly not significant) trends suggests that the central-south region of Chile is experimenting drier conditions each year.

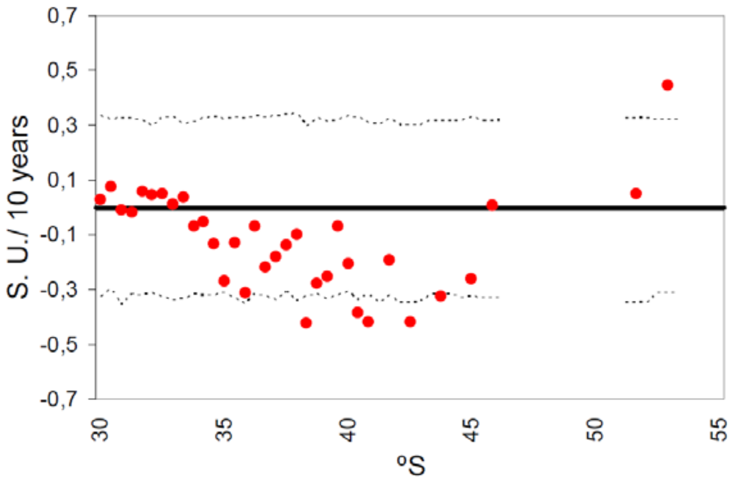

Figure 19 - Precipitation changes evaluated by Quintana and Aceituno (2006)

Regarding precipitation frequency distributions, all of the analyzed stations present a similar regime, with a high number of "dry" or less than 1 mm precipitation days, and a decreasing number of days with precipitation according to the intensity of precipitation. Figure 20 presents the different number of days with a certain precipitation class derived from the historical observed values. It is clear that El Yeso presents a higher number of days with precipitation compared to the other stations due to a higher location. The remaining stations present similar regimes, with each totaling approximately 30 days with precipitation per year. For this analysis, the 1980-2000 period was used as it was the common period with the smallest number of gaps.

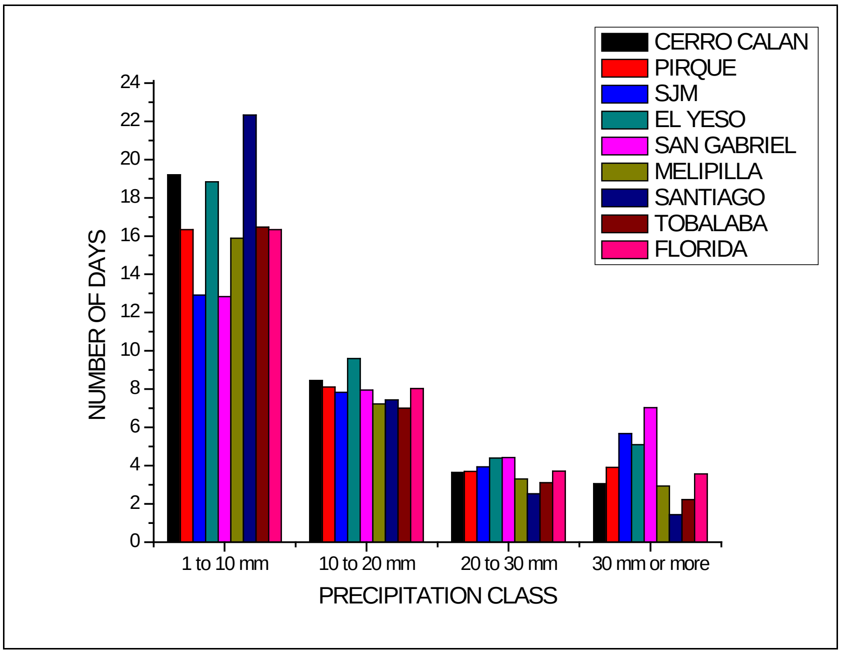

Figure 20 - Daily precipitation distribution for each studied station (1980-2000).

Precipitation was obtained and downscaled from the different GCMs available to each station in the historical scenario, and then compared to the values downscaled for the future A2 and B1 scenarios for the time period 2045-65. A graph for each of the scenarios from downscaled historical and observed data for each station is compared in this section of the report. Extra figures with the results for a particular station are presented in order to clarify uncertainty related to the different models. Figure 21 presents the results for annual precipitation.

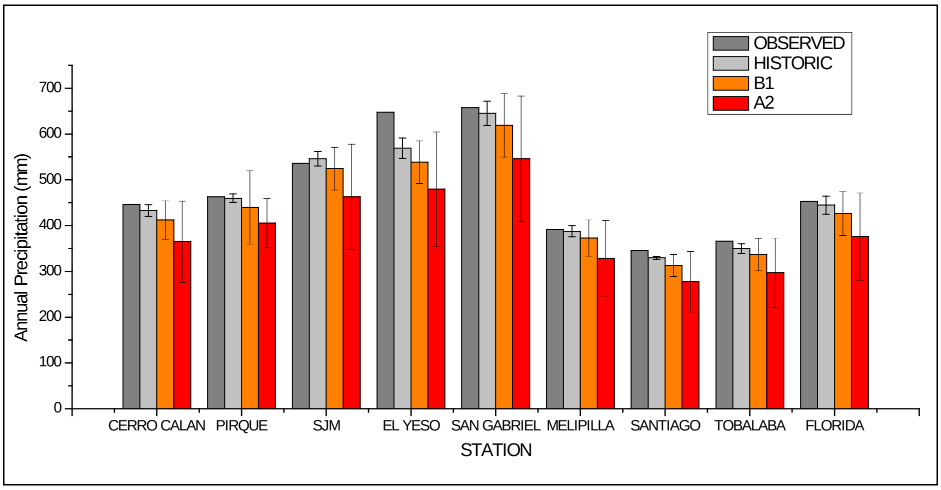

Figure 21 – Total annual precipitation. Historic precipitation is derived from models, whereas observed precipitation is derived from meteorological stations (observed climatology). Differences between "historic" and "observed" come from the fact that the downscaling methodology is unable to reproduce in an exact way the observed precipitation and that the models may have difficulties reproducing local effects on total annual precipitation. Bars represent standard deviation between the models.

For precipitation, both scenarios show a clear decrease in amounts for almost every month. This decrease is particularly important for the A2 Scenario, on which reductions in precipitation of between 10% and 30% (20mm to 100mm less precipitation each year, depending on the station analyzed) are predicted through the model ensemble mean. It is important to clarify that these differences are relative to the downscaled ensemble mean, this is, the historical values downscaled from the climate models, not the historical values observed at each station. The uncertainty related to the downscaling methodology is presented in Figure 22.

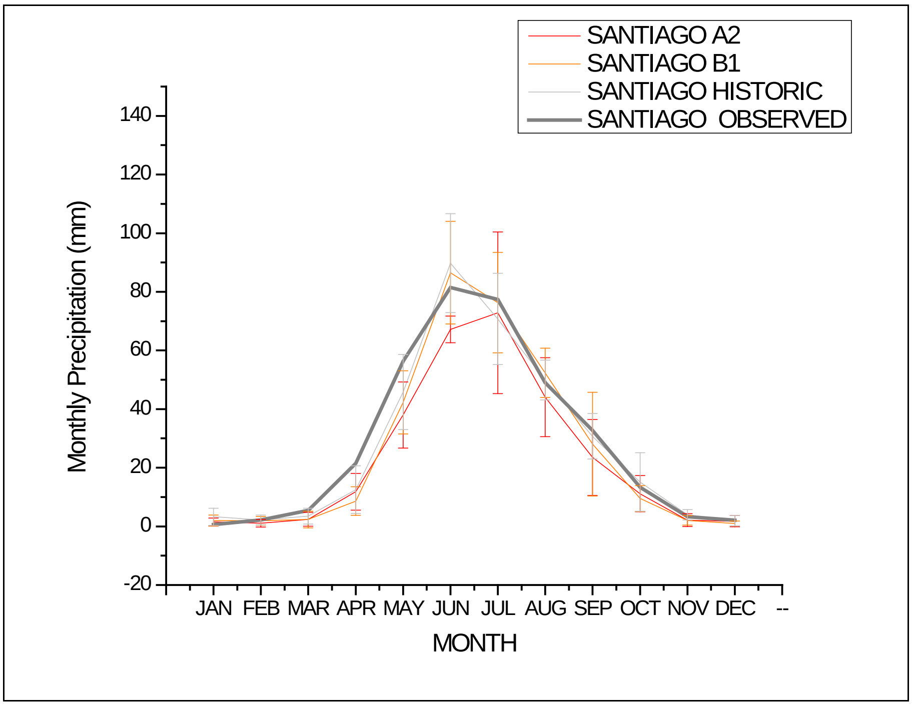

Figure 22 - Different precipitation model outputs for all scenarios (A2 , B1, observed and historic). Models presented are the ones that better represented the Mediterranean characteristic of Central Chile. Bars represent standard deviation from the models. Historic and Observed are defined as based on downscaled data and observed data respectively.

The uncertainty related to the models can be as high as 40% for some months (this value is estimative), but the overall conclusion is that most of them predict drying conditions for the metropolitan region, with lower precipitations for almost every month of the year.

Regarding precipitation intensity, Figure 23 presents the different precipitation classes for each station derived from the ensemble mean.

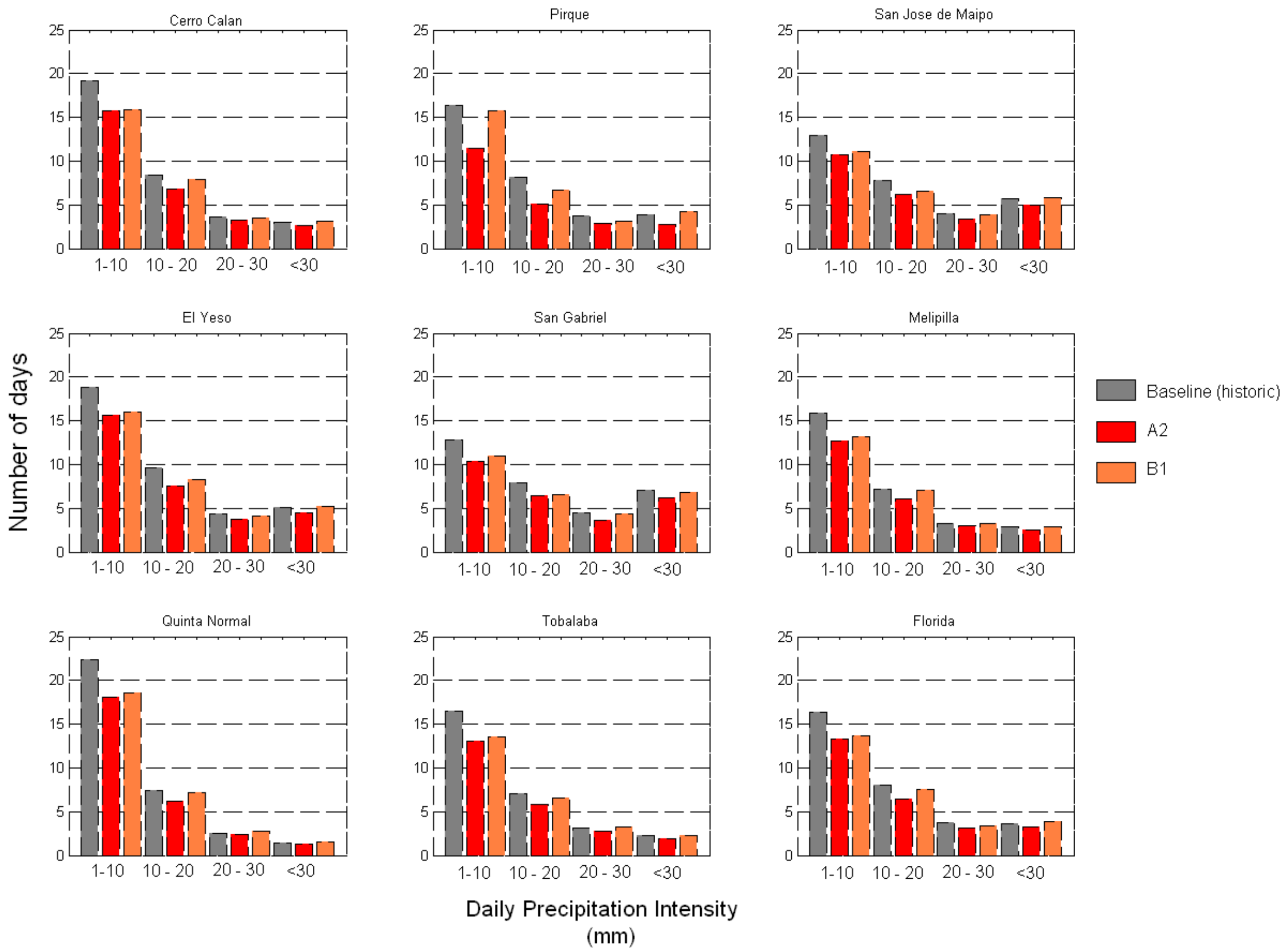

Figure 23 –Historic and future (2045-2065) precipitation for each analyzed station grouped by scenario and daily intensity. Each group of the three columns represents a particular daily precipitation intensity

As Figure 23 shows, there is a decrease in the number of days for every type of precipitation, which is consequent with the general decline in precipitation expected for the region. Yet, for the higher intensities, the decrease is not so clear: it is expected that most of the precipitation that falls in the region will come from the higher intensity storms, as the decline in total precipitation is mostly represented by a decrease in the number of days with low to medium precipitation amounts. This doesn't mean that there will be higher intensity events during the future, but that most of the precipitation will come from the higher events rather than the usual light rain events, with an important decrease in the number of days with 1 to 10 mm of precipitation instead of an important decrease in the number of days with higher precipitation.

Despite the different sources of uncertainty, most of the models agree that in the future Santiago will be a dryer city, with lower amounts of annual precipitation, a lower number of days with precipitation but higher intensities during these fewer days of rain.

Streamflow

Santiago's water supply comes mostly from the runoff derived from snow and ice melting during the spring and summer season. This runoff depends directly on the amount of precipitation that has fallen during the winter or wet season, the temperature at which snow accumulated and the temperatures during the melting season. All of these elements interact together to produce a final output: liquid water runoff. The availability of the resource, including volume and timing, is of key importance to the region, as more than 6 million people live in the area and rely on this resource. Also, groundwater sources are directly recharged by the surface sources, so the implications of climate change on the Maipo and Mapocho rivers can be directly related to the availability of groundwater.

The analysis performed shows a big variability in the values of water runoff for the historical period. For instance, the amount of streamflow of the Maipo River at the San Alfonso station was in January as high as 413.5 m^3/s, but also as low as 35.5 m^3/s. Nevertheless, these are extremes. Using exceedance probabilities, the results indicate that in January normally 90 percent of the monthly average streamflow exceeds 74.0 m^3/s while the water runoff is above 272.6 m^3/s only for a 10 percent probability. For the winter months, streamflow values are generally lower. Although water runoff exceeds 22.3 m^3/s in 90 percent during June, for example, it only passes 52.5 m^3/s in 10 percent of the cases. The minimum for this specific month is of 11.3 m^3/s and the maximum 118.7 m^3/s.

Data for all months with the different exceedance probabilities for the Maipo River are shown in Table 22.

PEXC	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
90%	31.1	21.8	22.3	21.6	19.6	28.6	38.4	61.8	74.0	69.4	54.3	45.3
80%	36.7	28.9	26.7	26.0	25.4	31.8	46.8	76.7	93.6	75.5	64.4	49.8
70%	38.0	31.1	28.8	28.6	27.4	33.6	54.7	87.7	110.4	85.2	66.4	50.8
60%	39.6	34.4	31.9	30.1	30.5	36.3	58.5	98.8	126.5	88.8	71.3	57.0
50%	42.8	35.6	34.4	33.4	32.2	37.9	61.0	108.6	140.8	105.1	81.6	59.7
40%	47.5	40.3	40.5	35.4	36.6	43.4	67.6	127.7	152.0	145.8	94.9	69.0
30%	49.3	44.4	42.3	40.9	42.4	48.4	76.5	133.6	178.6	167.6	115.2	72.4
20%	59.9	50.1	48.9	48.8	46.9	56.4	87.3	139.8	222.4	207.3	134.3	78.8
10%	74.2	60.3	52.5	55.3	55.8	71.1	93.7	158.3	281.5	272.6	154.9	106.6
Min	19.6	12.0	11.3	18.7	15.4	9.4	31.1	39.5	28.6	35.5	43.5	24.2
Max	94.3	199.4	118.7	71.2	65.0	89.7	123.3	206.4	373.3	413.5	278.8	163.1

Table 22– Streamflow values of the Maipo River at the San Alfonso station in m^3/s based on monthly average data for the 1961-2000 period.

The high variability of the streamflow values of the Maipo River is even more illustrative when it is transferred into a graphic chart. Figure 24 shows the observed values for water runoff of the Maipo River according to exceedance probabilities.

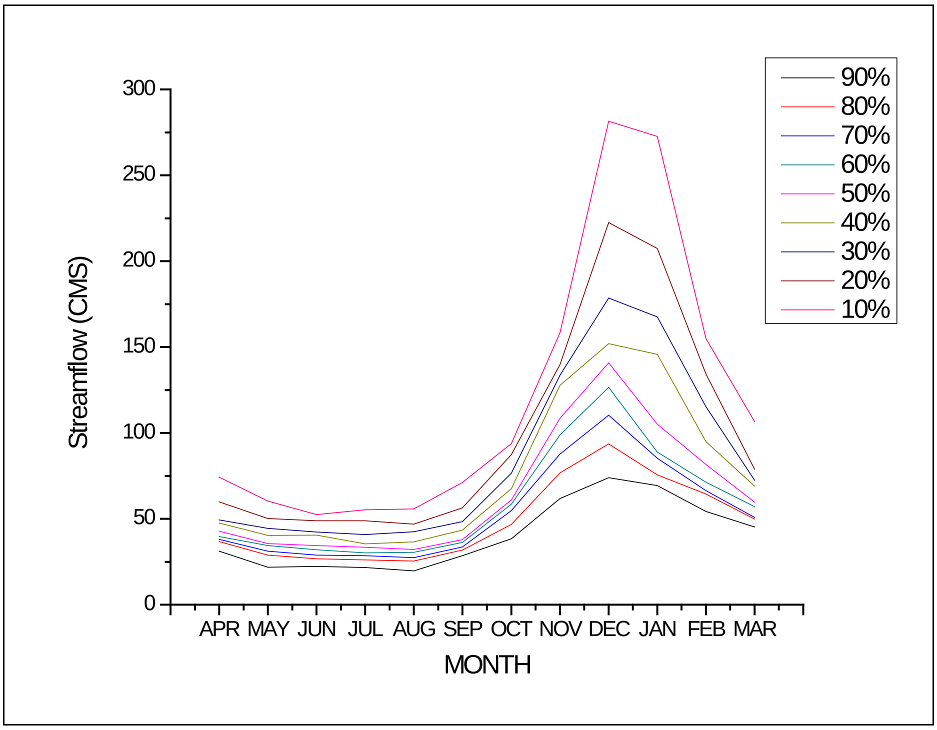

Figure 24 - Observed values of the Maipo River at the San Alfonso station based on monthly average data for the 1961-2000 period. Upper curves represent lower exceedance probability values.

The analyzed San Alfonso station for the Maipo River shows a significant prevalence of spring and summer high flows. This type of regime, known as “snow dominated”, indicates that most of the streamflow comes from the melt of snow and ice accumulated during the winter months. This type of regime is important for a Mediterranean climate type, as most of the water flows during the dry months, allowing irrigation and water supply during the hot and dry season. Under a climate change scenario, changes in streamflow timing and amount should be expected according to what types of changes are predicted. For example, hotter temperatures during winter and spring would cause a shift in the peak flow, causing peak streamflow to occur earlier in the year, and lower precipitation amounts would cause to have lower volumes of water during the whole season.

The second river studied is the Mapocho River. Results for this station are presented below in Table 23.

PEXC	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
90%	1.0	1.0	0.5	0.7	0.8	0.9	2.0	1.9	2.8	2.7	2.3	1.5
80%	1.3	1.4	0.8	1.1	1.2	2.2	3.3	3.3	3.1	3.3	2.5	1.9
70%	1.5	1.5	1.6	1.9	2.1	3.0	4.8	5.7	4.7	4.3	3.1	2.1
60%	1.7	1.7	1.8	2.3	3.4	4.8	6.5	7.1	6.4	5.0	3.6	2.2
50%	2.0	2.0	2.3	3.2	3.7	5.4	7.5	8.3	8.9	6.2	4.0	2.6
40%	2.3	2.2	2.9	3.8	5.0	7.5	12.2	13.1	11.2	7.1	4.8	3.2
30%	2.7	2.6	3.6	4.7	6.0	9.0	15.4	15.5	13.6	8.0	5.6	3.7
20%	2.8	3.2	5.2	5.9	7.1	11.7	18.7	19.0	16.5	9.9	6.2	4.5
10%	3.6	3.7	8.3	9.3	8.6	14.0	21.1	22.8	28.9	17.5	7.6	5.3
Min	0.8	0.7	0.4	0.2	0.3	0.3	1.0	1.0	1.5	2.3	1.5	1.1
Max	8.0	18.5	22.7	22.3	19.8	23.3	25.1	41.8	38.7	26.0	15.2	6.1

Table 23 – Streamflow values of the Mapocho River at the Los Almendros station in m^3/s based on monthly average data.

Unlike the Maipo River, the Mapocho River shows some significant flows in spring and late winter (see Figure 25), and also some important flows during the wet season in early winter. This river may eventually be more sensitive to warming temperatures as its whole watershed is lower than the Maipo River. Increasing temperatures will expose a larger area of the watershed to liquid precipitation instead of snow. This entails a significant effect in streamflow, with even earlier peak streamflows, on the one side, and decreasing thickness and extent of the snow covered area within the basin, on the other side. The impact of a rising isotherm 0 line is also important, as the presence of lower elevations in the basin implies that a higher percentage of the basin is contributing with liquid precipitation during each storm.

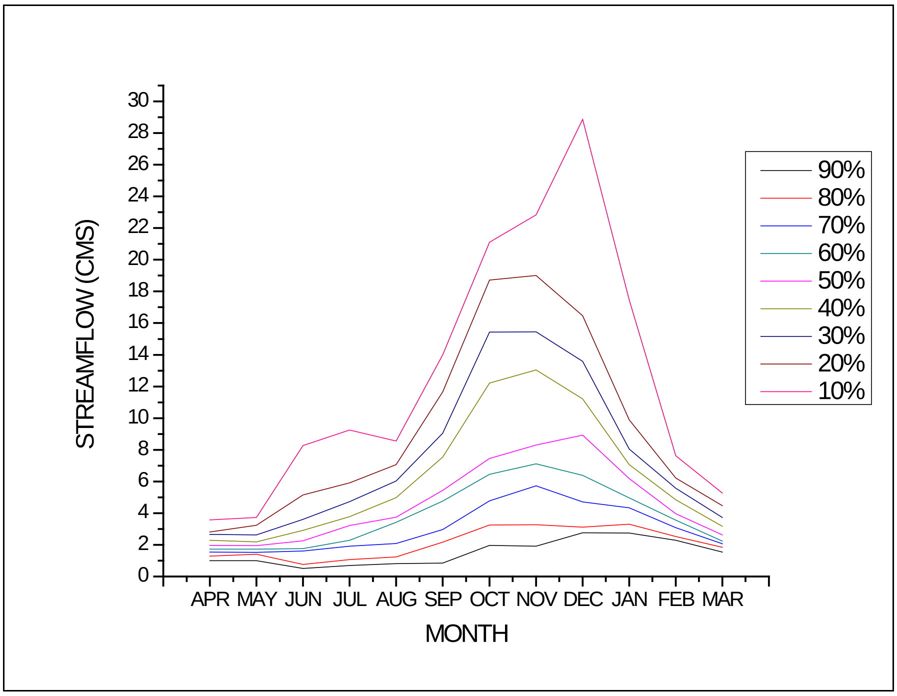

Figure 25 - Observed values of the Mapocho River at the Los Almendros station based on monthly average data for the 1961-2000 period. Upper curves represent lower exceedance probability values.

Drastic changes can be observed in the hydrologic regime of the analyzed rivers. Peak streamflow dates will shift to earlier months, and decreases up to 40% are observed for some summer months. Peak flow during winter will increase, as higher temperatures will bring earlier melting of snow and ice. During winter, lower precipitation rates and higher temperatures will reduce the amount of snow that is accumulated in the high Andes, further reducing runoff during the spring and summer. Another important impact that the hydrological model shows is that during winter and autumn higher streamflow values will be present. Considering that according to model results a lower precipitation will be present during the future, this increase in runoff comes only from an increase in melt during these months and a higher elevation of the isotherm 0 line.

Results are presented as averages for the 2045-2065 period. Table 24 and Table 25 present the results for this analysis.

SCENARIO	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
HIST	47.6	43.1	40.7	37.1	36.0	43.9	66.7	113.5	158.2	145.7	100.3	69.0
A2	44.3	43.4	41.5	38.8	39.5	51.8	69.0	88.7	110.9	102.7	77.0	59.9
B2	45.2	42.7	39.6	34.8	33.8	43.6	61.9	86.1	123.6	110.8	81.8	63.2

Table 24 - Average monthly values for Maipo at the San Alfonso station. Values correspond to m^3/s and 2045-2065 period.

SCENARIO	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
HIST	2.3	2.8	4.2	4.8	5.0	7.1	10.8	12.3	11.6	7.9	4.7	3.1
A2	2.0	2.7	4.3	5.0	5.8	8.8	10.8	8.9	6.9	4.8	3.3	2.6
B2	2.0	2.7	4.1	3.9	4.3	6.9	9.3	8.6	8.0	5.3	3.5	2.7

Table 25- Average monthly values for Mapocho at the Los Almendros station. Values correspond to m^3/s and 2045-2065 period.

Even though it is not possible to assess any conclusions regarding high intensity or extreme events, as the model is based on monthly data, it can be anticipated that floods will be a problem as each storm will have a greater risk of bringing high flows from the mountains, as areas that today are covered by snow in winter will suffer from liquid precipitation. The Mapocho river watershed, much lower in elevation than the Maipo river, will have a greater vulnerability to climate change as its lower elevation make the watershed more prone to receive liquid precipitation during storm events.

The results are shown in Figure 26 and Figure 27.

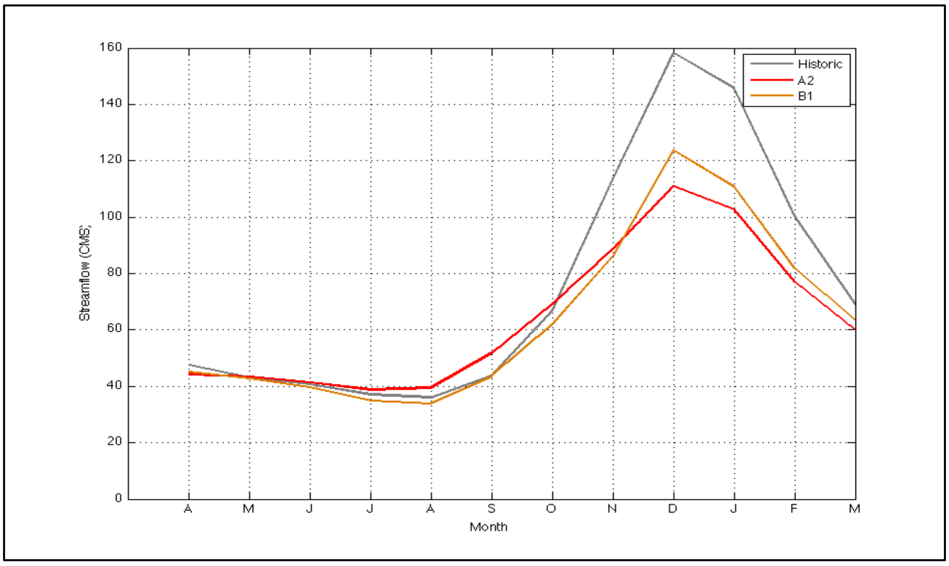

Figure 26 - Maipo at the San Alfonso station – average streamflow data

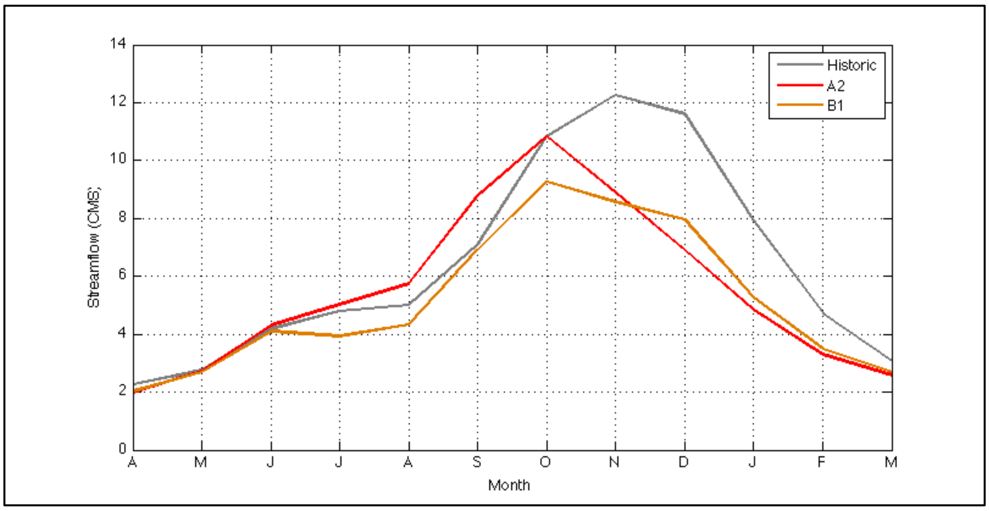

Figure 27 - Mapocho at the Los Almendros station – streamflow data

Glaciers and Secondary Data

Glaciers and permanent snow fields in the Andes cordillera store big quantities of freshwater. It is estimated that they contain a total water equivalent volume of about 30.6 Km^3 (Garin, 1986). Therefore, glaciers are of great importance for the hydrological cycle and the water supply for the Metropolitan Region of Santiago.

According to a glacier cadaster performed by the Dirección General de Aguas (DGA), there are 647 glaciers in the central part of Chile (Marangunic, 1979). Their surface sums up for nearly 422 Km^2, with the mean glacier area equal to 0.65 km^2 (Garin, 1986). Recent studies performed for the region show consistent trends in glacier receding for the Andean mountains. Le Quesne et al. (2009) calculate that the whole glacier surface in the central Andean region dropped by approximately three percent between 1955 and 2000. However, for some glaciers, detailed studies report an even more pronounced loss. The Aconcagua river basin glaciers, for example, have experienced a 20% area reduction on average since 1955 (Bown et al., 2008). The Juncal Norte glacier, located in the headwaters of the Aconcagua River, approximately 70 km northeast from Santiago, shows a retreat of about 50 m per year (Rivera et al., 2002). For the same glacier, Figure 28 shows an example of the area reduction that has receded in approximately 14% since 1955 (Bown et al., 2008). According to this study, the decrease in glacier area is coherent with the rising temperature trends observed for the area.

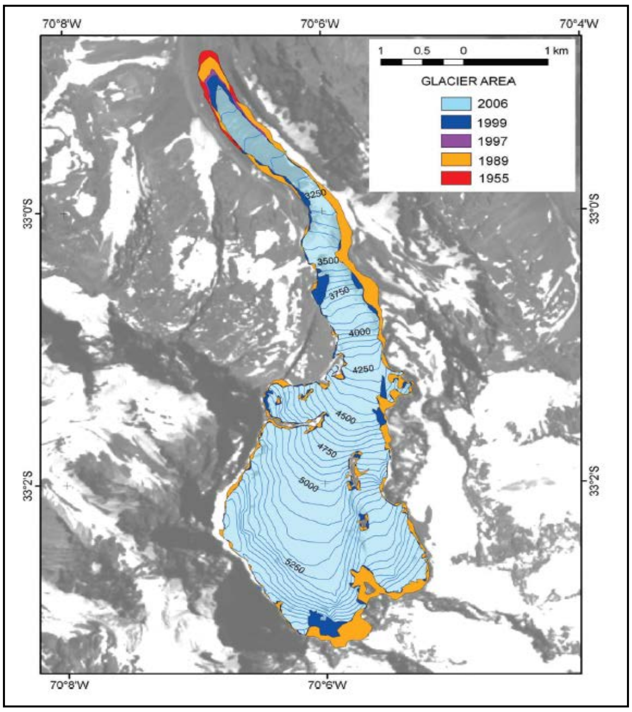

Figure 28 - Juncal Norte glacier area comparison, 1955 - 2006 (Bown et al., 2008).

Even though the Juncal Norte glacier has its principal impacts on the V. Region, similar developments are reported also for the Andean region of the MRS. Bodin et al. (2010) analyze the status of glaciers in the MRS. This study focus on the glaciers in the Laguna Negra watershed east of Santiago, a key area that supplies an important part of the water reserves for Santiago. The study states that permafrost and rock glaciers are spread within the region, and that these glaciers are of key importance to the hydrological balance of the region. However, a monitoring network has been only recently developed, and no trends have been assessed for the evolution of these glaciers. On the other hand, the Dirección General de Aguas (DGA) has recently published a report on the historical trends of mass balance in the Echaurren Norte glacier. The Echaurren

Norte drains to the Laguna Negra, in the headwaters of the Volcán River, a tributary itself of the Maipo River. The glacier's surface area is just 0.226 km^2 (DGA, 2010). The Echaurren Norte is one of the most intensively studied glaciers in the region. Several field campaigns show that the net accumulated mass balance of the glacier was relatively stable until approximately 1991. Then it experienced a sudden and steep drop in mass balance that lasted until the year 2000, after which it has somewhat recovered and stabilized again. For the whole period 1975 until 2008, there is a total accumulated loss in the glacier mass balance of nearly 8 meter water equivalent[1] (DGA, 2010).

As glaciers account for a significant percentage of streamflow volumes during the months of February and March, the reduction in volume could have possible implications for water resources availability for the region during the summer months. However, the specific contribution of glacier melt to overall water availability in the Metropolitan Region is as yet unknown, with possible estimates ranging from 30 to 67% for rivers such as the Maipo (Peña and Nazarala, 1987). The surveyed glacier area of approximately 400 km^2 is small compared with the upper Maipo and Mapocho river basins (defined by the Manzano and Los Almendros stream gauges), a combined area of 5600 km^2. Although it can be argued that the bulk water input flowing into the metropolitan region comes from the melting of seasonal snowpack, the relative contribution of glacier melt to river flow may be higher in dry years and during drier months of the year, when most snowmelt has already flowed out of the basin. The exact amount of this contribution has to be quantified yet, and the dynamics of most glaciers in the region must be examined in much greater detail in order to provide meaningful estimates of future glacier evolution and its impact on water resources availability. For instance, it has been shown that glaciers in this region respond strongly to precipitation extremes. In El Niño years, the Echaurren Norte glacier typically gains mass. For instance, during the El Niño year 1991/1992, mass balance of the Echaurren Norte increased by 1740 mm water equivalent, but lost considerable amounts in the following years. The loss was between 290 mm water equivalent in 1992/1993 and 2890 mm water equivalent in 1996/1997. In the following El Niño year 1997/1998 the glacier gained 2890 mm water equivalent, but lost 4070 mm in the years 1998/1999 (Rivera et. al, 2000).

It is worth mentioning the special status those glaciers in the central parts of Chile posses. According to Borquez et al. (2006), glaciers in the central Andes cordillera can be classified as "polithermal" glaciers. These glaciers are located at relatively low elevations (5000 m.a.s.l. and below), with the ablation zone located sometimes at very low elevations. During summer, these glaciers experience higher than fusion temperatures at their lower sections, thus producing runoff especially during hot months. It is possible that in a climate change context, these glaciers could be more affected than others due to the fact that significant parts of their mass are vulnerable to high temperatures. Nevertheless, there is a high uncertainty related to Chile's central region glaciers. Much is yet to be quantified in terms of total existing glacier mass, together with improved estimations of melt contributions to river systems. For further details, the reader is encouraged to review works by Pellicciotti et al. (2007, 2008), Petersen and Pellicciotti (2011) among others.

The central Chilean glaciers are directly affected by temperature and precipitation changes. The response of the glaciers to changing climate conditions is not immediate. The time lags vary from years to several decades (Paterson, 1994). The basic knowledge about glacier extent, dynamics and location is still incomplete in Chile, and therefore it is yet not possible to formulate quantitative projections of the effect of future climate change on glacier mass balance, areal evolution and contribution to water resources in the Metropolitan Region. However, a few insights can be gleaned from the combination of mass balance measurements at the Echaurren glacier and the most recent climate projections: because the Echaurren glacier has responded heavily to climatic variability (ENSO and interdecadal variability) in the past, and because this kind of variability will dominate short-term climate rather than eventual long-term trends at least until the second half of the 21st century, it is very likely that short term variability will keep dominating glacier evolution before the year 2050. In other words, El Niño (La Niña) years should continue

1 For calculation of water-equivalent, the density is assumed to be 0.9 g/cm³, therefore 1 m ice is of about 90 cm water equivalent.

resulting in net mass gains (losses), and decadal cycles of dry/wet years should result in cycles of glacier retreat/advance. However, as climatic signals depart from historical averages, trends in glacier behavior could emerge. In particular, the combination of drying and warming that current GCMs project for the Metropolitan Region should obviously have the effect of reducing ice accumulation and increasing ablation rates. When, and to what extent this changes should be noticeable, is still unknown. It is expected that no climatic trends will be noticeable before 2030, and uncertainty is still large regarding the 2030-2050 period. Furthermore, the lack of climatic stations at high elevation increases the downscaling uncertainty for those areas where glaciers are currently present (typically above 3000 m.a.s.l. for the Metropolitan Region). With respect to effects on water resources, increased glacier melt should, for a few years at least, increase summer flows; however, because melt flow is also related to glacier surface area, as glaciers shrink their contribution to total runoff should decrease.

Secondary variables follow a strong seasonal pattern. Wind experiences its maximum during the spring and summer months, while its minimum is during the winter months. Both stations show a significant difference in magnitude during the whole year, probably due to local effects: the station of Pudahuel is located on the airport area, an open space with no buildings and hills close by, showing stronger winds, while Quinta Normal is located in the middle of the city, and probably buildings and other man-made structures interfere with the natural wind patterns.

Data for secondary variables are presented below in Table 26 and in subsequent tables on wind velocity, mean radiation and relative humidity.

Season	DJF	MAM	JJA	SON	ANNUAL
Wind Velocity (km/h)	13.4	7.9	5.6	10.2	9.7
Standard Deviation	1.5	1.2	2.1	1.8	1.5

Table 26– Wind Velocity for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Wind Velocity (km/h)	6.9	3.7	1.6	5.7	5.3
Standard Deviation	1.1	0.9	0.8	1.0	1.2

Table 27 – Wind Velocity for Quinta Normal station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Mean Radiation (Wh/m2)	315.5	163.2	96.6	237.7	201.9
Standard Deviation	9.3	21.1	6.8	11.9	11.1

Table 28 – Radiation for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%)	48.7	63.2	74.9	61.1	62.0
Standard Deviation	11.9	15.4	18.0	15.1	15.0

Table 29 – Relative Humidity for Pudahuel station (1980-2005 period).

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%)	51.7	66.3	76.6	62.6	64.3
Standard Deviation	9.4	11.6	13.4	11.3	11.2

Table 30 – Relative Humidity for Quinta Normal station (1980-2005 period).

Radiation also has a strong seasonal component, with higher radiation levels during summer and lower during winter. This seasonal variation is due to lower radiation levels in the southern hemisphere during winter, and in Santiago an increased cloud cover is also responsible for lower radiation levels.

Future scenario analysis was undertaken for some further secondary data, i.e. radiation, wind and relative humidity. Table 31 presents the results for radiation, Table 32 and Table 33 for wind and Table 34 and Table 35.

Radiation

Month	**Historic**	**Historic (models)**	**A2**	**B1**
Jan	329.10	318.75	327.11	313.03
Feb	290.54	280.55	275.71	275.68
Mar	228.92	216.77	216.51	222.12
Apr	151.30	145.46	146.85	152.74
May	113.09	94.91	97.28	98.33
Jun	77.11	78.72	74.81	72.17
Jul	92.40	93.95	96.47	86.64
Aug	122.66	141.99	141.45	133.31
Sep	170.96	194.58	200.27	197.55
Oct	209.53	245.17	252.45	262.39
Nov	303.59	302.38	299.71	311.26
Dec	328.95	328.12	323.82	330.72

Table 31 – Radiation values at Pudahuel (Wh/m2)

There isn't a clear change in radiation values for the station available, in both scenarios. Quinta Normal, the other station with historical data, wasn't used in this analysis as the amount of data available was insufficient for the downscaling methodology. Despite the uncertainty related to radiation change, it is expected that overall radiation will increase in the future, as lower precipitation is a sign of lower cloud cover for the region.

Wind

For both scenarios there is an increase in overall wind velocity according to the model ensemble mean. This change is greater during the winter months, and a possible reason for this is that drier, close to summer conditions could affect the overall wind regime for the region. The impact of increased wind in the livability conditions of the city is yet to be studied, as this analysis is a rough estimate of the conditions in Santiago as wind velocities are not correctly represented by GCMs for a point value at ground level, as local conditions affect in an important way recorded values at the station.

Month	Historic	Historic (models)	A2	B1
Jan	14.37	12.21	12.25	12.32
Feb	11.98	11.02	10.71	10.76
Mar	9.51	9.78	9.66	9.67
Apr	7.93	7.99	8.24	7.75
May	5.77	6.01	6.45	6.34
Jun	4.57	4.22	5.01	4.60
Jul	4.82	4.31	4.95	4.36
Aug	6.54	6.23	6.70	6.25
Sep	7.97	8.85	8.85	8.90
Oct	9.92	11.23	11.13	11.45
Nov	12.39	12.42	12.23	12.61
Dec	13.68	12.62	12.76	12.35

Table 32 – Wind values at Pudahuel (km/h)

Month	Historic	Historic (models)	A2	B1
Jan	7.35	6.60	6.65	6.68
Feb	6.80	5.85	5.66	5.68
Mar	5.07	5.06	4.99	4.99
Apr	3.18	3.94	4.09	3.77
May	2.25	2.66	2.93	2.86
Jun	2.06	1.49	2.00	1.74
Jul	2.46	1.55	1.95	1.58
Aug	3.05	2.80	3.08	2.81
Sep	3.73	4.48	4.48	4.51
Oct	5.10	6.01	5.95	6.15
Nov	6.23	6.77	6.65	6.89
Dec	7.06	6.88	6.98	6.70

Table 33 – Wind values at Quinta Normal (km/h)

Relative humidity

Relative humidity was compared only to historical model outputs, as the downscaling procedure didn't provide results good enough to allow a direct comparison between future values and observed values. Tables 34 and 35 show the results of this analysis. The overall result is that relative humidity will experience a light decline, in the order of 2% for each season. This decline is consistent with the drier and hotter conditions that should be present in Santiago according to the climatic models, however the large standard deviation observed between the models renders any conclusion for this variable uncertain. The observed change is significantly smaller than the intermodel deviation.

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%) A2 Scenario	63.44	70.94	66.64	59.04	65.01
Standard Deviation	8.59	3.19	8.04	5.24	1.17
Relative Humidity (%) B1 Scenario	63.69	70.55	65.55	60.21	65.00
Standard Deviation	8.90	4.42	7.10	5.21	1.33
Relative Humidity (%) Historic	64.33	71.64	68.15	61.18	66.32
Standard Deviation	9.12	4.59	7.75	4.37	0.53

Table 34 – Relative humidity at Pudahuel station, future scenarios. Historical values represent model output for the 1970-2000 period and not observed values at the station.

Season	DJF	MAM	JJA	SON	ANNUAL
Relative Humidity (%) A2 Scenario	63.98	70.98	66.91	59.78	65.41
Standard Deviation	7.95	2.79	7.70	4.98	1.18
Relative Humidity (%) B1 Scenario	64.16	70.62	65.89	60.89	65.39
Standard Deviation	8.27	3.87	6.84	4.82	1.01
Relative Humidity (%) Historic	64.76	71.64	68.33	61.80	66.63
Standard Deviation	8.51	4.05	7.46	4.09	0.26

Table 35 – Relative humidity at Quinta Normal station, future scenarios. Historical values represent model output for the 1970-2000 period and not observed values at the station.

Summary of the Results

Results for the 2045-2065 time window show that temperatures in the Metropolitan Region of Santiago de Chile, both maximum and minimum, are predicted to rise by approximately 2º C in comparison with historical records for the 1970-2000 period. However, this small change brings a significant increase in days with extreme high temperatures, with some stations showing a 30% increase in the number of days with maximum temperatures above 30º C, and days with temperatures below freezing point will significantly decrease for most of the stations. Higher temperatures will also bring higher elevations in the zero isotherm line, thus increasing storm runoff from higher elevations of the city. Streamflow however shows a general decrease in magnitude compared with historical data due to lower precipitation rates and increased melting during winter and spring.

For precipitation, a general decrease in all indexes is observed whereby the future scenarios show a clear decrease in amounts for almost every month. This decrease is particularly important for the A2 scenario, for which reductions in precipitation between 10% and 30% (20mm to 100mm less precipitation each year, depending on the station analyzed) are predicted through the model ensemble mean. It is important to clarify that these differences are relative to the average of GCM ensemble simulations for the historical or baseline period, not with respect to the historical values observed at each station. In this way, any outstanding biases between models and observed station data are not relevant for the interpretation of results. Precipitation under the B1 scenario decreases less significantly than under A2-type climate, and GCMs show less dispersion among themselves. The result is a projection that although lesser than the historical period, is indistinguishable –statistically speaking – from that period due to the high variability of results among different models. Additionally, most models project fewer days with precipitation, and lower precipitation rates in days with precipitation.

The overall conclusion is that in the near future (2045-2065 period) Santiago will be a dryer, hotter city, with a high number of days with extreme temperatures, increased drought during the winter and summer. This result is independent of the scenario chosen, as both A2 (worst case) and B1 (best case) scenarios give similar responses.

Table 36 to Table 38 show the comparison between historical (simulated and downscaled) precipitation and temperatures, and their counterpart projections for the two scenarios (A2 and B1) in the time window 2045-2065. In view of all the uncertainties involved in these estimations, the quantitative assessments of changes in magnitude should be considered with caution and may provide, in the first instance, a basis for qualitative conclusions, especially in comparison with historical trends.

Station	Historical	A2	B1
	(1960-2000)	2045-2065	2045-2065
Cerro Calan	433	365	412
Pirque	460	405	440
San Jose de Maipo	546	463	525
El Yeso	569	480	539
San Gabriel	645	546	619
Melipilla	388	329	373
Quinta Normal / Santiago	330	277	313
Tobalaba	350	297	337
Florida	445	376	426

Table 36 – Historical and projected average annual precipitation (mm/year).

Station	Historical	A2	B1
	(1960-2000)	2045-2065	2045-2065
Cerro Calan	22.9	24.7	24.2
Pirque	22.0	23.8	23.4
El Yeso	13.7	15.5	15.0
Melipilla	21.7	23.3	23.0
Quinta Normal / Santiago	22.5	24.5	24.0
Tobalaba	22.4	23.8	23.6
Florida	22.8	24.8	24.4

Table 37 – Mean average monthly maximum temperature (in °C)

Station	Historical	A2	B1
	(1960-2000)	2045-2065	2045-2065
Cerro Calan	9.9	10.4	10.5
Pirque	6.0	6.4	6.6
El Yeso	3.6	5.1	5.4
Melipilla	8.1	8.7	8.8
Quinta Normal / Santiago	8.5	9.4	9.5
Tobalaba	8.6	9.2	9.3
Florida	8.8	9.3	9.4

Table 38 – Mean average monthly minimum temperature values (in°C)

Chapter 5 – Conclusions

This report presents estimates of future climate and hydrologic conditions at the Metropolitan Region of Santiago for the period 2045-2065 based on direct downscaling of GCM projections (daily values) to local conditions measured at meteorological stations. Output from multiple GCMs was included in this analysis, in order to obtain an estimate of the uncertainty affecting these projections.

Local meteorological data was obtained from stations operated by DGA and DMC. Few stations have a period of record of sufficient extension for establishing downscaling relations with simulated values, so spatial interpolation of the data was not analyzed, except for precipitation and temperature. In the case of precipitation data, orographic effects expressed through an elevation gradient were observed from values compiled from stations in adjacent watersheds, plus the differences observed within the Metropolitan Region. For temperature, no clear spatial pattern was found, and an approximate elevation gradient was adopted in order to estimate future zero isotherm line positions.

Downscaled climate projections show approximately a 1 - 2 ºC warming for the future period 2045-2065 at most stations in the region. Additionally, days with maximum temperatures above 30 ºC increase in the order of 25 – 45 days per year (A2 scenario) depending on the station being analyzed. Minimum temperatures also increase, but unlike the maximum temperature results, they increase more significantly at Pirque and El Yeso stations, which are located towards the mountain region of the area.

Precipitation projections are based on two indicators: average monthly values (climatology) and the distribution of number of days with precipitation in certain ranges. On average, precipitation decreases throughout the region. Models display a great deal of variability regarding the temporal patterns associated with this change, with specific months sometimes showing an increase in precipitation whereas most months evolve decreasingly.

The work presented here attempts to organize in a coherent way a number of different data sources in a product that is useful for decision making in the sense of presenting likely changes in climate for one future time window and two scenarios that allow for further estimations on climate change related impacts and later the development of specific adaptation measures. However, some limitations persist, which should be taken into account for future investigations:

- GCM data: the current generation of GCMs (IPCC IV) does a good job in capturing the local climatologies at the oceanic cells off the coast of Chile, but no cells fall exactly at the location of the MRS. Furthermore, this generation of models does not capture the low frequency climate variations that influence a great deal of the MRS weather, such as ENSO and the Pacific Decadal Oscillation (PDO). It is expected that the next GCM generation (IPCC V) will represent in a better way these circulation patterns; therefore, projections of related phenomena, such as maximum daily precipitation, and extreme seasonal events (e.g. droughts) should be updated as these data become available.

- The projection of secondary variables such as relative humidity, radiation, wind and the like suffers from a higher level of uncertainty than that of precipitation and temperature, because these variables are much more dependent of local conditions; therefore regional extrapolation from observed data might not represent accurately the predominant conditions at all locations.

- Glacier characterization is incomplete in much of Chile, and this is also true for the MRS. Thus, streamflow projections should improve (particularly during dry periods) when hydrologic models are able to represent this component more properly. This research is currently ongoing.

- Overall, regional extrapolation of point (meteorological station) information is rather uncertain, because the spatial coverage of meteorological stations is insufficient. Compared to developed countries, the MRS has very few data points available, and a large geographical region (the upper Mapocho and Maipo river basins) remains unmonitored. Vertical gradients of precipitation and temperature could and should be verified with dedicated monitoring campaigns, and in general a better understanding of meteorological and hydrological processes in the Andes is required for assessing future water resource availability.

This report builds upon previous studies performed at a national level, attempting to provide much more in-detail analysis. A significant improvement over previous studies is the time window being analyzed, which is closer in time; furthermore, an ensemble model approach was used to quantify the uncertainty associated to the results. Estimations of uncertainty should become the standard in future studies regarding climate change impacts and adaptation, because of the special position of Chile, between Oceanic and Continental climates.

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