2 Downscaling Climate Changes for Santiago: What Effects can be Expected?

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Abstract

This chapter describes the methodology used to analyse climate scenarios and their impact on hydro-meteorological variables in the Metropolitan Region of Santiago de Chile (MRS) and the results thereof. Using a downscaling methodology for future IPCC A2 and B1 scenarios (and B2 for stream flow), temperature, precipitation and secondary variable trends are estimated for the 2045–2065 time frame. The findings suggest that Santiago will be a drier and hotter city in the near future and have a high number of days with extreme temperatures. Lower precipitation rates are expected to lead to decreasing magnitudes in the stream flow of the two main rivers, Maipo and Mapocho, particularly in the summer months. Based on the data presented below, expected climate change impacts are analysed and adaptation needs identified for the MRS.

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2.1 Introduction

The current climate in the Metropolitan Region of Santiago de Chile (MRS) is characterized by warm dry summers and cold winters that concentrate most of the annual rainfall during the latter period. Average maximum temperatures in the summer range from 28 to 30 °C, while minimum temperatures during winter vary from 0 to 5 °C. Precipitation occurs primarily during the winter months of June, July and August, with annual precipitation ranging from 200 to 500 mm. Snow events, which are quite rare in the low elevation areas where the city of Santiago is located, dominate in high elevation Andean watersheds and serve as temporary water reservoirs for human, agricultural and industrial use. Trends in the last 30 years have indicated an increase in temperature for the upper elevation stations in particular, and a decline in precipitation amounts (Cortés et al. 2012). Although climate projections derived from models for the Latin American region show some variability in values, these trends correspond among the different simulations: warming temperatures and a reduction in winter precipitation throughout the continent, and less precipitation during all seasons along the southern Andes (Vera et al. 2006).

So far, climate change projections for the MRS have either been a component of large-scale studies (e.g., CEPAL 2009) or tailored made to sectorial needs (agriculture, water resources). This type of comprehensive information, however, is ill suited to analysing climate change impacts at urban-regional level (cf. Chaps. 4–7) or identifying adaptation needs. Hence the aim of this chapter is to present downscaled information for the MRS at a level of detail appropriate to outlining adaptation measures relevant to the urban environment. The chief benefits include the availability of daily scale projections to study the future variation of meteorological events, such as intense precipitation and extreme temperatures. At the same time, the absence of a dense network of spatially distributed meteorological data prevents a more detailed spatial analysis of the projected climate for the region.

This chapter builds upon previous studies performed at a national level in order to provide an in-depth analysis. The findings refer to the 2045–2065 period, enhancing previous works dealing with climate change projections for the end of the twenty-first century. These should be understood as an average for the entire period and not a prediction for each individual year. Where possible, they include a standard error bar. The latter represents the standard deviation that quantifies to a certain extent the uncertainty involved in future scenario models. Chile's unusual position between oceanic and continental climates demands that uncertainty estimates become standard in future studies on climate change impacts and adaptation.

The chapter is structured as follows: Sect. 2.2 provides information on the data used to analyse climate change projections for the MRS. Section 2.3 gives a detailed description of the methodologies applied to downscale climate projections to scales appropriate for adaptation studies. Section 2.4 presents the principal results for individual variables in the future scenario analysis (2045–2065) in the context of the historical records on which the climate change impact analysis is based. Section 2.5 derives key conclusions and discusses the methodological constraints and uncertainty issues involved in using these figures for further analysis on climate change impact and adaptation needs.

2.2 Data Sources and Methodological Steps

In order to project future climate changes for the MRS, Global Circulation Models (GCMs) simulating the Earth's climatic system are adapted or downscaled to the appropriate spatial scale (for further detail, see Sect. 2.3). This allows for the assessment of future climate changes for climate-relevant variables such as temperature, number of hot days or precipitation for the 2045–2065 time frame, the earliest period for which GCM data is available after the baseline time frame (1960–1999). Future GCM-based climate projections are based on scenarios describing the evolution of greenhouse gas emissions. Two main scenarios, i.e., SRES A2 and B1, are assessed in this contribution, while the B2 scenario is explored for stream flow projections (for details, see IPCC 2000, 2001, 2007). The next step is to average cross-model results and compute standard deviations for overall time-frame averages. This provides uncertainty estimates due to GCM variability. In addition to the statistical downscaling of global models, analysis of the principal climate variables allows the assessment of historical and current climate conditions, as well as expected future climate changes in the Metropolitan Region of Santiago de Chile. These include temperature and precipitation as primary data. Secondary data is comprised of glacier development, the shift in the isotherm 0 °C, water run-off, wind velocity and insolation. The historical analysis is based on data obtained from meteorological stations owned and operated by public agencies. Many of the stations in the MRS used for the purpose of this study have records that date back 40 years (1970–2010). There are, however, major information gaps in the records of some stations.

Figure 2.1 shows the stations used for precipitation and temperature analysis. The light grey area indicates the limits of the MRS, while the darker area is an approximation of current urban limits. Stations were selected by analysing the temporal range of the data and the consistency of measured values. Table 2.1 provides further information on the stations.

2.2.1 Precipitation

The time span used to analyse historical precipitation averages corresponds to the concurrent period between the GCM models and the observed data (1970–2000 where available) (Table 2.1). Uncertainties remain with regard to spatial representativeness of point measurements and measuring methodologies adopted by the institutions in charge of station maintenance. Since no evident errors were observed, no data correction was performed.

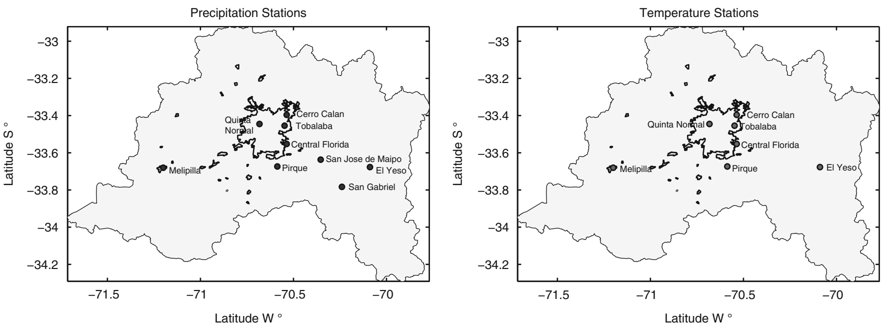

Fig. 2.1 Climatological stations (**a**) Precipitation data, (**b**) Temperature data (*Source*: Authors' own presentation)

Table 2.1 Meteorological stations (*Source*: Authors' own presentation)

ID	UTM N	UTM E	Elev. (m)	Beginning of record	End of record	Variables recorded
Central Florida	6286445	357350	770	1977	2010	Daily precip., mean daily temp., max/min daily temp.
Melipilla	6271064	296074	168	1972	2010	Daily precip., mean daily temp., max/min daily temp.
Pirque	6272845	352877	659	1968	2010	Daily precip., mean daily temp., max/min daily temp.
Quinta Normal	6298113	343588	527	1977	2007	Daily precip., mean daily temp., max/min daily temp., radiation, relative humidity, wind
San José de Maipo	6277311	374507	964	1972	2010	Daily precip.
Tobalaba	6297259	356163	652	1979	2010	Daily precip., mean daily temp., max/min daily temp.
Cerro Calan	6303810	357081	848	1976	2010	Daily precip., mean daily temp., max/min daily temp.
El Yeso	6273104	399083	2475	1963	2010	Daily precip., mean daily temp., max/min daily temp.
San Gabriel	6261211	385240	1266	1978	2010	Daily precip.
Pudahuel	6304000	333900	480	1980	2005	Radiation, relative humidity, wind

Precipitation values generally tend to increase according to altitude (Cortés et al. 2011). While precipitation may fall as snow above 2,000 m.a.s.l. during winter, in the lower lying areas of the city of Santiago (below 1,000 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 due to instrumental constraints, and snow usually remains on the ground for a few hours only. Precipitation gradients observed are due to the orographic effect of the Andes Cordillera on frontal systems coming from the Pacific Ocean, the result of which is a major increase in precipitation when stations away from the Cordillera are compared with those located in the foothills or on elevated sites (Cortés et al. 2011).

All of the stations analysed present a similar regime in terms of precipitation frequency distribution, with a high number of "dry" days or days with less than 1 mm precipitation, and—depending on its intensity—a decline in the number of days with higher precipitation. Due to its location at a higher altitude, the El Yeso station shows evidence of a greater number of days with precipitation than other stations. The remaining stations present similar regimes, each with an annual total of approximately 30 days with precipitation. For the present analysis, the 1980–2000 period was used, as it was the common period with the smallest number of gaps.

Trends in precipitation have been examined in various studies (CONAMA 2006; Quintana and Aceituno 2006) and their common observation is a slight decreasing trend for central Chile, with lower total precipitation amounts. Considering the precipitation gradients, the stations for this study show varying 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 from May until August and lower precipitation in the summer (December to February). Standard deviation is high, however, indicating that precipitation is characterized by high variability. One reason for irregular precipitation could be the influence of ENSO phenomena in the MRS, which introduces high variability during warm events in the shape of higher precipitation amounts ("El Niño") and low precipitation amounts during cold events ("La Niña") (Cortés et al. 2011).

2.2.2 Temperature

The historical temperature analysis is based on data from seven meteorological stations presented in Table 2.1. The number of stations available is small: a dense climatological network has not been established, and only one station, Quinta Normal, is located within the urban limits of Santiago. Cerro Calan, Tobalaba and Central Florida are suburbs in low-density areas. Spatial interpolation between the stations, which could serve to generate area-wide information for further analysis, was avoided, since the interpolation of point measurement values has severe limitations and adds no significant information to this particular study. The El Yeso station located in the higher Andean area, for example, would affect temperature interpolation in the entire northeast region as a result of its altitude (Table 2.1).

The time span of temperature records varies from station to station but covers most years between 1970 and 2000. The seven station locations are heterogeneous. Their individual features determine the representativeness of their detailed meteorological conditions. Quinta Normal station is located in a park in the centre of Santiago, for example, while Cerro Calan is situated on a hill in the eastern suburbs. Although geographical location should play a role in determining the spatial distribution of temperature, there is not enough evidence to show that any single predictor (such as elevation, as in the case of precipitation) can explain its spatial variability. The only station with obvious temperature differences as a result of elevation is El Yeso, which is located in the Andean Cordillera (Cortés et al. 2012).

Maximum annual temperatures for the stations in the Maipo Basin vary only slightly, and range on average from 21.7 to 22.9 °C. The sole exception here is the El Yeso station, diverging significantly with an annual average maximum temperature of 13.7 °C. For all stations, maximum temperatures during summer months normally exceed 25 °C. Some stations even report average maximum temperatures of more than 30 °C for January and February (e.g., Cerro Calan and Central Florida). Maximum winter temperatures reach an average of 15 °C, with the exception of El Yeso with a mere 5.9 °C maximum average temperature in July. The standard deviation is quite low for the stations in the Maipo Basin, with a slight increase for the more elevated El Yeso station.

Minimum temperatures during summer months range on average from 11 to 14 °C for stations in the Maipo Basin, compared to 8.7 °C for El Yeso. Minimum temperatures during the winter drop to an average of 4 to 6 °C in Melipilla, Quinta Normal, Tobalaba, Central Florida and Cerro Calan, with an average of merely 1.7 °C in Pirque. El Yeso has 4 months of average minimum temperatures below zero.

Tables 2.2 and 2.3 indicate the number of days for each year that show maximum temperatures above 30 °C and minimum temperatures below 0 °C, along with standard deviation computed from the time series of each variable.

Falvey and Garreaud (2009) analysed historical temperature data in central Chile (27.5–37.5°S) for the 1960–2006 period and found positive trends from 1975 to 2006 in stations located in the Andes and in the central valley, the location of the MRS. Cooling patterns were observed for coastal and low-lying stations. Daily maximum and minimum temperatures increased proportionally and in accordance with the elevation of the measuring station. The key conclusion of their study is the presence of a warming trend in the Andean regions of central Chile and—somewhat less significant but still observable—a similar trend in the valley regions.

2.2.3 Stream Flow

Stream flow data for the two main rivers in the MRS is obtained from two stations: Los Almendros measures the Mapocho river runoff, while the San Alfonso station measures the Maipo River stream flow. The location and elevation of these stations is presented in Table 2.4. Average, minimum and maximum monthly run-off values are given for each month. The analysis of the historical period included calculating exceedance probabilities (PEXC) based on the 1960–2000 period, which is more accurate than merely calculating minimum or maximum values, as it allows for a proper analysis of stream flow distribution throughout the year. If a value of X m^3/s corresponds to an exceedance probability of 60 % for a certain month, for example, then 60 % of the monthly average stream flow measured during that 40-year period

Table 2.2 Number of days with maximum temperatures above 30 °C (*Source*: Statistical data from meteorological stations)

	Cerro Calan	Quinta Normal	Pirque	Melipilla	Tobalaba	Florida
Average no. 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 2.3 Number of days with minimum temperatures below 0 °C (*Source*: Statistical data from meteorological stations)

	Cerro Calan	Quinta Normal	Pirque	Melipilla	Tobalaba	Florida
Average N° of days per year	0.81	7.04	28.54	2.31	5.92	4.54
Standard deviation	1.23	4.23	14.53	2.59	4.32	3.22

Table 2.4 Stations recording stream flow data (*Source*: Dirección General de Aguas)

ID	UTM N	UTM E	Elev. (m.a.s.l.)	Ti	Tf*	DT
Mapocho in los Almendros	6307006	365534	1,024	1961	–	Day and month
Maipo in San Alfonso	379641	6266823	1,108	1961	–	Day and month

*Final or ending time of the time series

is above X m^3/s. All of the data presented consists of monthly values, so that extreme run-off events may not be represented.

The analysis of stream flow projections shows considerable variability in run-off values for the historical period. Stream flow in the Maipo River measured as high as 413.5 m^3/s in January at the San Alfonso station, for instance, but also as low as 35.5 m^3/s. However, these are extremes. Using exceedance probabilities, the results indicate that it can be expected that 90 % of the time monthly average stream flow exceeds 74.0 m^3/s in January, while run-off values over 272.6 m^3/s occur with a probability of only 10 %. Stream flow values are generally lower in the winter. Although monthly flow exceeds 22.3 m^3/s 90 % of the time in June, for example, it exceeds 52.5 m^3/s in only 10 % of cases. The minimum for this month is 11.3 m^3/s, the maximum 118.7 m^3/s. Data for all 12 months of the year with the specific exceedance probabilities for the Maipo River are shown in Table 2.5.

The high variability of stream flow values for the Maipo River is even more striking when transferred to a graphic chart (Fig. 2.2). The San Alfonso station for the Maipo River shows a prevalence of spring and summer high flows. Known as "snow dominated", this type of regime indicates that most of the stream flow comes from the melt of snow and ice accumulated during the winter months. It is important for a Mediterranean climate type, as most of the water flows during the dry months, allowing for irrigation and water supplies during the hot and dry season. In a climate change scenario, changes in the amount and timing of stream flow should be expected depending on the type of change predicted. Hotter temperatures in winter and spring, for example, would result in a shift in the peak flow and thus an

Table 2.5 Stream flow values of the Maipo River in San Alfonso in m^3/s based on monthly average data for the 1961–2000 period (*Source*: Dirección General de Aguas)

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
Minimum	19.6	12.0	11.3	18.7	15.4	9.4	31.1	39.5	28.6	35.5	43.5	24.2
Maximum	94.3	199.4	118.7	71.2	65.0	89.7	123.3	206.4	373.3	413.5	278.8	163.1

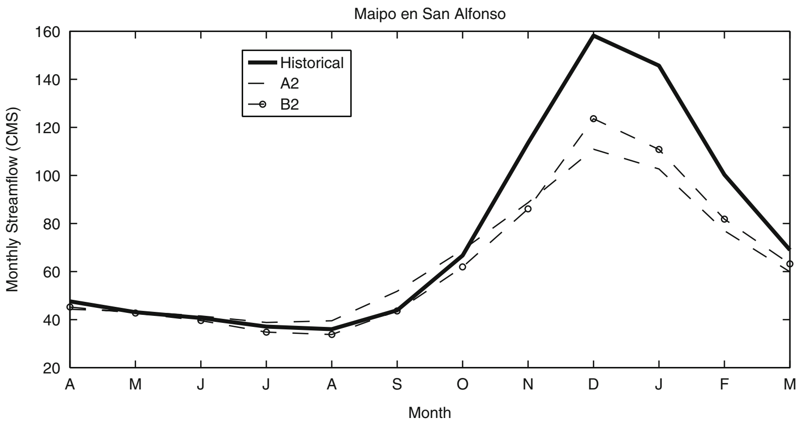

Fig. 2.2 Mean monthly stream flow projections for the Maipo River at San Alfonso watershed (*Source*: Authors' own presentation)

earlier occurrence of peak stream flow, while lower precipitation amounts would lead to lower volumes of water during the entire season.

The second river under review is the Mapocho River. Results for this station are presented in Table 2.6.

Unlike the Maipo River, the Mapocho River shows significant flows in spring and late winter (Table 2.6), as well as during wet periods in early winter. It could eventually be more sensitive to warming temperatures, as its watershed is lower than that of the Maipo River. Increasing temperatures will expose a larger area of the watershed to liquid precipitation rather than snow, and subsequently have a heavy impact on stream flow. It implies, on one hand, earlier peak stream flow values and, on the other hand, a decrease in the thickness and extent of the snow-covered area in the basin. The impact of a rising isotherm 0 line is also significant,

Table 2.6 Stream flow values for the Mapocho River in los Almendros in m^3/s based on monthly average data (*Source*: Dirección General de Aguas)

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
Minimum	0.8	0.7	0.4	0.2	0.3	0.3	1.0	1.0	1.5	2.3	1.5	1.1
Maximum	8.0	18.5	22.7	22.3	19.8	23.3	25.1	41.8	38.7	26.0	15.2	6.1

since the presence of lower elevations in the basin implies that a greater area contributes to runoff in the course of each storm event.

2.2.4 Glaciers

Although glaciers in the region (e.g., the Echaurren Glacier) have been studied for the past decades (e.g., Casassa 1995), current data for the MRS is confined to an updated glacier inventory that characterizes the glacier-covered area, but not the glacier volume or its dynamics (Rivera et al. 2000, 2002). Neither does a recently developed monitoring network for the MRS reveal trends for the evolution of these glaciers. Hence this chapter will analyse 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 in the central Andes poses several—as yet unanswered—interesting questions, and more research is needed to improve quantification of their current contribution to water resources and their possible future evolution.

Glaciers and permanent snowfields in the Andes Cordillera store large quantities of fresh water. It is estimated that they contain a total water equivalent volume of about 30.6 km^3 (Garín 1986). Glaciers are therefore crucial to 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 area of Chile (Marangunic 1979). Their surface adds up to almost 422 km^2, with the mean glacier area equal to 0.65 km^2 (Garín 1986). Recent studies performed for the region show consistent trends in glacier retreat for the Andean mountains. Le Quesne et al. (2009) calculate that the complete glacier surface in the central Andean region dropped by approximately 3 % between 1955 and 2000. Detailed studies report for some glaciers 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 of Santiago, shows a retreat of about 50 m per year (Rivera et al. 2002). 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, itself a tributary of the Maipo River. With a surface area of merely 0.226 km^2 (DGA 2010), it is one of the most thoroughly studied glaciers in the region. Several field campaigns show that the net accumulated mass balance of the glacier was relatively stable until approximately 1991, when it experienced a sudden and steep drop that lasted until 2000. Having recovered to a certain extent, it is now stable. The entire period 1975–2008 shows evidence of a total accumulated loss in glacier mass balance of almost 8 m water equivalent[1] (DGA 2010).

2.2.5 Other Secondary Variables

Records for secondary variables such as wind velocity or insolation were obtained from the two meteorological stations that measure them: Pudahuel and Quinta Normal. Table 2.7 presents information on these two stations. The seasonal averages and standard deviation values for each of the variables are presented in Table 2.8. With only two stations available for analysis, no spatial interpolation was performed, as results would prove unreliable.

2.3 Downscaling of Future Climate Scenarios: Methodological Explanations

Global Circulation Models (GCMs) are mathematical models that simulate the Earth's climatic system. Land, ocean and atmospheric processes are represented by calculations performed on grid divisions of the Earth's surface, each with resolutions of up to hundreds of kilometres. For climate change impact studies, GCM simulations must therefore be downscaled to the spatial scale relevant to the study concerned. In this specific case, the relevant spatial scale is the MRS, which spans the entire width of the country (approximately 200 km) and may be of similar scope to most GCM grid elements. The uncertainty related to model performance and structure can be overcome by taking several GCMs into account. In this study we use 10–15 different models for any one variable or indicator of climate change (e.g., the average annual precipitation for the 2045–2065 time frame). Cross-model averages are then calculated, indicating standard deviations computed for overall

[1] In water equivalent calculation, the density is assumed to be 0.9 g/cm^3. One meter of ice is therefore approx. 90 cm water equivalent.

Table 2.7 Secondary variables at two meteorological stations (*Source*: Authors' own presentation)

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 2.8 Secondary variable climatology at selected stations (1980–2005 period) (*Source*: Dirección Meteorológica de Chile)

			Season (months)				
Variable	Units	Station	DJF	MAM	JJA	SON	Annual
Wind velocity	(km/h)	Pudahuel	13.4 (1.5)	7.9 (1.2)	5.6 (2.1)	10.2 (1.8)	9.7 (1.5)
		Quinta normal	6.9 (1.1)	3.7 (0.9)	1.6 (0.8)	5.7 (1.0)	5.3 (1.2)
Mean radiation	(Wh/m^2)	Pudahuel	315.5 (9.3)	163.2 (21.1)	96.6 6.8)	237.7 (11.9)	201.9 (11.1)
Relative humidity	(%)	Pudahuel	48.7 (11.9)	63.2 15.4)	74.9 (18.0)	61.1 (15.1)	62.0 (15.0)
		Quinta normal	51.7 (9.4)	66.3 (11.6)	76.6 (13.4)	62.6 (11.3)	64.3 (11.2)

Standard deviation from the mean is shown in parenthesis

time-frame averages rather than for year-to-year annual values. This allows for distinction between model uncertainty and inter-annual variability. The following models were used for the downscaling procedure: the CGCM3 model from the Canadian Center for Climate Modeling (CCCMA, Canada), the CM3 model from the Centre National de Recherches Météorologiques (CNRM, France), the AOM, E_H and E_R model from the Goddard Institute for Space Studies (GISS, USA), the CM4 model from the Institute Pierre Simon Laplace (IPSL, France), the MIROC_MEDRES model from the National Institute for Environmental Studies (NIES, Japan), the MK model from Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) , the ECHAM model from the Max Planck Institute for Meteorology (MPI, Germany) and the ECHAM model from the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy).

2.3.1 Downscaling Temperature Projections

Downscaling techniques are required to establish a relationship between the data acquired from GCMs and the values observed at meteorological stations, since large-scale climatic patterns and regional features both influence regional climatic conditions (von Storch 1999; Wilby et al. 2004). Statistical downscaling is the "development of quantitative relationships between large-scale atmospheric variables and local surface variables" (Wilby et al. 2004). First, we create a statistical model that relates large-scale variations to local meteorological observations. The GCM model outputs are subsequently applied to a number of scenarios with the relationship found. The major advantage of this technique is its relative simplicity, making it "computationally feasible" for most studies. One obvious disadvantage, however, is the assumption that present day (or historical) relationships are valid for future scenarios. This can lead to invariances when the models reproduce seasonal variability for the region correctly (e.g., cold winters and hot summers), but day-to-day averages and short-term variability do not coincide with the observed data. This "time invariance" could have been ignored if several historical periods had been used to validate the relationship found; since the long-term observational data set required for validation would exceed the scope of this study, it was not applied.

2.3.2 Downscaling Precipitation Projections

Precipitation values in GCM models could be biased when compared to those observed for the MRS. In terms of frequency distribution, several GCM precipitation estimates show strong differences with respect to the observed climate. An attempt to correct or downscale these estimates would not produce valuable information on future climate since the differences come from limitations such as sub-adequate representation of the Andes Cordillera or ocean land coupled within the model pixel that represents the study region. Hence, the precipitation analysis made use of a subgroup of the available GCMs: CNRM_CM3, CSIRO_MK, MIROC_MEDRES and MPI_ECHAM.

While temperature data calls for measurement of only one variable, i.e., temperature, two variables must be downscaled for precipitation data prior to analysis: the amount or intensity of precipitation and wet-day frequency. The downscaling procedure must consider both variables to achieve a realistic representation of the precipitation distribution registered in each measuring station. Schmidli et al. (2006) propose a method for daily precipitation downscaling that was deemed adequate for this analysis. The methodology considers GCM modelled precipitation data as a predictor for observed precipitation data, as proposed by Widmann et al. (2003). The method consists in downscaling wet-day frequency and the precipitation intensity for each day: wet-day frequency is downscaled and the precipitation intensity subsequently adjusted so that the observed and the modeled series have the same daily precipitation intensity distribution. Application of this methodology does not require a specific climate. The idea is to correct potential biases in the distribution of climatic variables between models and observations and thus to preserve climatic patterns as distinct from absolute values. Since the methodology entails sequential downscaling—the separate adjustment of wet-day frequencies and precipitation magnitudes—the singularities of daily precipitation distribution in Mediterranean climates (highly asymmetric density functions, large proportion of zero-rainfall) are taken into account. Schmidli et al. (2006) obtained good results with this methodology in comparison to other downscaling methods.

2.3.3 Stream Flow and Secondary Data Projections

Stream flow data for future scenarios was obtained with a hydrological model, WEAP21. Based on hydrological catchments, this is a semidistributed model where each catchment may contain different physical and climatic properties. For the purpose of exploring future values of stream flow, the model was first calibrated against historic data from meteorological stations: monthly average stream flow data at Maipo in San Alfonso station (the model is calibrated using a monthly scale), monthly precipitation at San Gabriel station and the monthly mean temperature at Pirque station. Future scenarios derived from GCM data were downscaled to these stations. Projected future downscaled precipitation and temperature values were used as input for the hydrological model to obtain output for future scenarios. Data for future scenarios on stream flow was available for the IPCC A2 and B2 scenarios only. Although the B2 scenario is not identical to the B1 scenario, both scenarios present an "optimistic" point of view on future emissions and up to the year 2050 are practically indistinguishable. Although detailed data sets of the results are available, for clarity purposes this chapter will only present the average values for future scenarios.

For variables such as wind velocity, radiation and relative humidity, downscaling is much more uncertain, as these variables are correlated to a regional climatic pattern as well as to local singularities. Radiation measurements will be affected, for example, if the location of the station is prone to fog formation, and wind velocity measurements modified if there exist hills or buildings in the immediate vicinity of the station. As GCM resolutions cannot resolve these effects, model projections of secondary variables will probably be far from representative of measurements performed at a point level. The statistical approach adopted for temperature was nevertheless used for the secondary data, taking monthly measurements of these variables into account. However, since the uncertainty derived from the importance of local effects on these variables is high, results for secondary variables (especially wind, relative humidity and radiation) must be seen differentially; in other words, the difference between the scenarios (historic, A2 and B1) must be taken into account, not the absolute value of the variable projected by the GCMs.

2.4 Future Climate Analysis Results

This section presents the key findings on future predictions for the 2045–2065 time frame and discusses them for each climate variable.

2.4.1 Temperature

Figures 2.3 and 2.4 show future projections of maximum and minimum daily temperatures for each month of the year and for each meteorological station. Where available, observed (i.e., historical) data refers to the 1970–2000 time

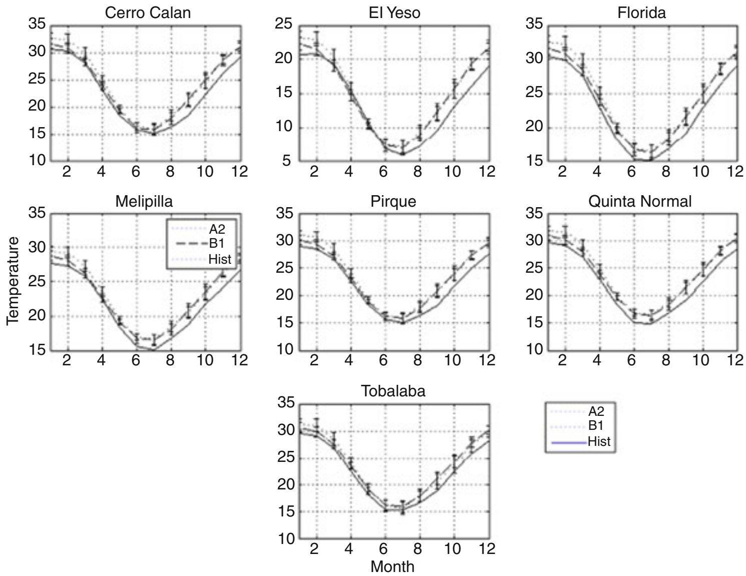

Fig. 2.3 Monthly maximum daily temperature (historical and projected (2045–2065) values) (*Source*: Authors' own presentation)
Note: Error bars show the annual standard deviation in projected future values due to GCM differences

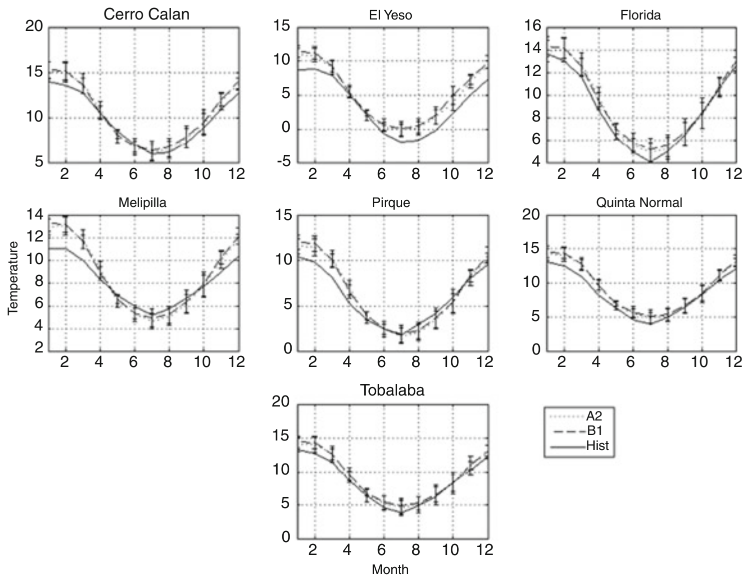

Fig. 2.4 Monthly minimum daily temperature (historical and projected (2045–2065) values) (*Source*: Authors' own presentation)
Note: Error bars show the annual standard deviation in projected future values due to GCM differences

span. Future projection averages are based on the A2 and B1 greenhouse gas emission scenarios for the 2045–2065 time period.

Each of the seven stations experiences a rise in annual mean temperature in the order of 1.5 °C in the two scenarios analysed for the 2045–2065 period. The increase in temperature is consistent for every month but appears to be more significant for summer than winter months, i.e., the MRS will be particularly affected between November and March, as higher temperatures will produce more heat waves and greater extremes in temperature (Fig. 2.3). This observation should be backed up with the total number of days with maximum temperatures above 30 °C (results presented in Fig. 2.5).

The analysis of average minimum temperatures shows that differences between the stations are far greater here than in the case of maximum temperatures. While Central Florida reports an annual minimum temperature of 12.6 °C on average, the other stations of the Maipo Basin reach an average of no more than 8 °C: Pirque with an average 6.0 °C—the lowest value for this group of stations—and Cerro Calan averaging 9.9 °C in between. Again, due to its elevation, El Yeso shows the lowest minimum temperature of all stations with an average 3.6 °C (Fig. 2.4).

Minimum temperatures also show a consistent increase, albeit less than that encountered for maximum temperatures. Since the former are high compared to those in rural stations such as Pirque, climate change impact will not be clearly visualized in minimum temperatures within the limits of the city. The change in minimum temperatures is still positive: more than one degree for most of the stations under review for the two scenarios. This shift is less significant in the spring months, and uncertainty is also on the increase during this period. For summer and winter, however, the warming signal is strong (Fig. 2.5).

Under climate change projections, all stations would experience a total annual increase in the number of days with maximum temperatures above 30.0 °C. Some of these changes are significant. The Santiago station (Quinta Normal), for example, shows an increase of more than 30 days with extremely high temperatures; this also applies to the Cerro Calan, Florida and Pirque stations for the more severe A2 scenario. Even the optimistic B1 scenario indicates a significant increase in the number of days with extreme temperatures for all stations. This could seriously affect the quality of life in Santiago in the summer time. The result is consistent across all GCMs included in the analysis.

Without exception the stations present a smaller number of days with freezing temperatures. This is especially significant for those that presented a higher number of days with freezing temperatures in the past, such as the Pirque and El Yeso stations.

2.4.2 0 °C Isotherm Altitude

According to a study performed by Carrasco et al. (2005), a change of approximately 150 m (positive increase) was observed for the isotherm-0 line between 1975 and 2001 in central Chile, and subsequently a shift in the snow line and

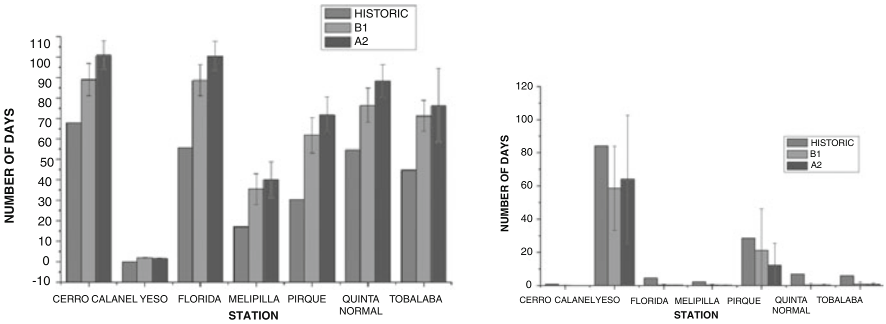

Fig. 2.5 Annual number of days with temperatures above 30°C (*left*) and below 0°C (*right*) for each station (for the historical scenario and the two future scenarios (A2 and B1 for 2045–2065)) (*Source*: Authors' own presentation)
Note: Variations in the number of days with maximum temperatures above 30°C are due to the different downscaling relationships derived for each station; some stations have different historical values and local effects on temperature

equilibrium line. Data for this study was obtained with radiosonde measurements (not available to the public). For a station located near the Pacific Ocean at the same latitude as Santiago, the mean annual isotherm line was located at 3,500 m.a.s.l. approximately, varying between values of 4,250 m.a.s.l. in the summer and 3,000 m.a.s.l. in the winter. Given that a station located near 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 those observed. Hence future temperature scenarios will consider Pirque and the same gradient as a baseline for understanding isotherm 0 line changes caused by warming. The analysis of the isotherm 0 position is vital as it indicates when heavy precipitation events will have a strong impact on the city. Due to the high position of the isotherm 0 line, storm events in March or April can lead to increased flooding, because of greater amounts of liquid precipitation available.

Due to uncertainty in the temperature gradients, however, the low number of stations and the fact that each storm has its own isotherm 0 line position, changes addressed in this chapter must be taken into account in qualitative rather than absolute terms. The position of 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 greater flooding and a higher amount of sediments carried during each event. Table 2.9 presents the calculated isotherm derived from temperature gradients for the future scenarios. These results were calculated indirectly from mean monthly temperature projections for Pirque station. These monthly values were calculated at the same time from mean maximum and minimum temperature projections for each month.

Table 2.9 0 °C isotherm variations due to climate change (*Source*: Authors' own presentation)

0 °C Isotherm Altitude (m.a.s.l)			
Month	Historic	A2	B1
January	4,235	4,576	4,525
February	4,197	4,627	4,520
March	4,001	4,442	4,278
April	3,322	3,695	3,527
May	2,673	2,841	2,777
June	2,295	2,413	2,384
July	2,153	2,292	2,278
August	2,241	2,384	2,340
September	2,475	2,671	2,670
October	2,929	3,106	3,078
November	3,514	3,787	3,741
December	3,978	4,276	4,244
Annual	3,146	3,398	3,334

As they are approximate and based on one station only, these values must be seen in perspective (i.e., a comparison of the differences in historic and future scenarios, and not their absolute values). El Yeso, for example, shows a mean temperature above freezing point for the A2 and BI scenarios, but isotherm results indicate that freezing temperatures could still prevail at the altitude of El Yeso

2.4.3 Precipitation

Future precipitation projections were obtained by downscaling data from the different GCMs available to each station in the historical scenario. These were compared to values downscaled for the A2 and B1 future scenarios for the time period 2045–2065. Precipitation model outputs differ for all scenarios (A2, B1, observed and historic). The models used were those closest to the Mediterranean characteristic of the climate in central Chile. Figure 2.6 presents the results for annual precipitation at each station and for each scenario.

Both scenarios show a distinct reduction in precipitation amounts for almost all months of the year. This is particularly significant for the A2 scenario, where reductions of between 10 and 30 % are predicted by the model ensemble mean (20–100 mm less precipitation each year, depending on the station in question). It is important to clarify that these differences are relative to the downscaled ensemble mean, i.e., the historical values downscaled from the climate models, not those observed at individual stations.

With regard to precipitation intensity, Fig. 2.7 presents the precipitation categories for each station, derived from the ensemble mean. The decline in the number of days with precipitation for each category coincides with the general decline in precipitation expected for the region. Yet, this decrease is not as clear for the higher intensities: most precipitation in the region is expected to come from

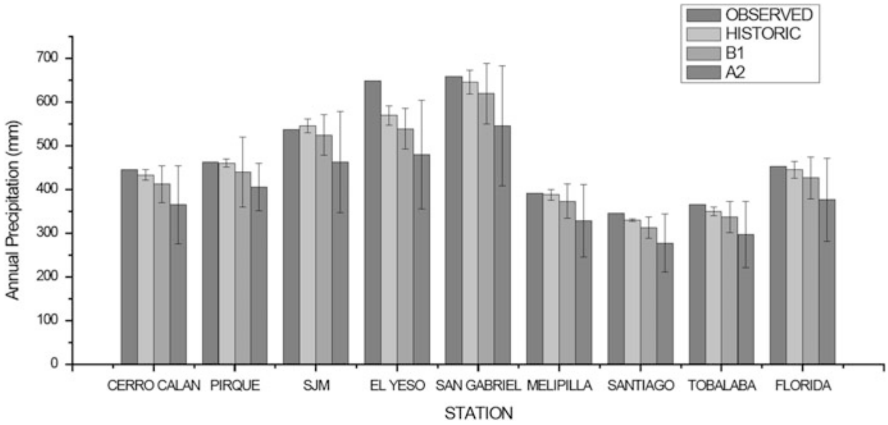

Fig. 2.6 Total annual precipitation changes (*Source*: Authors' own presentation)
Note: Historic precipitation is derived from models, whereas observed precipitation is obtained from meteorological stations (observed climatology). Two factors explain the differences between "historic" and "observed": the downscaling methodology is unable to reproduce observed precipitation faithfully and models may have difficulty in reproducing local effects on total annual precipitation. The bars represent standard deviations found in the models

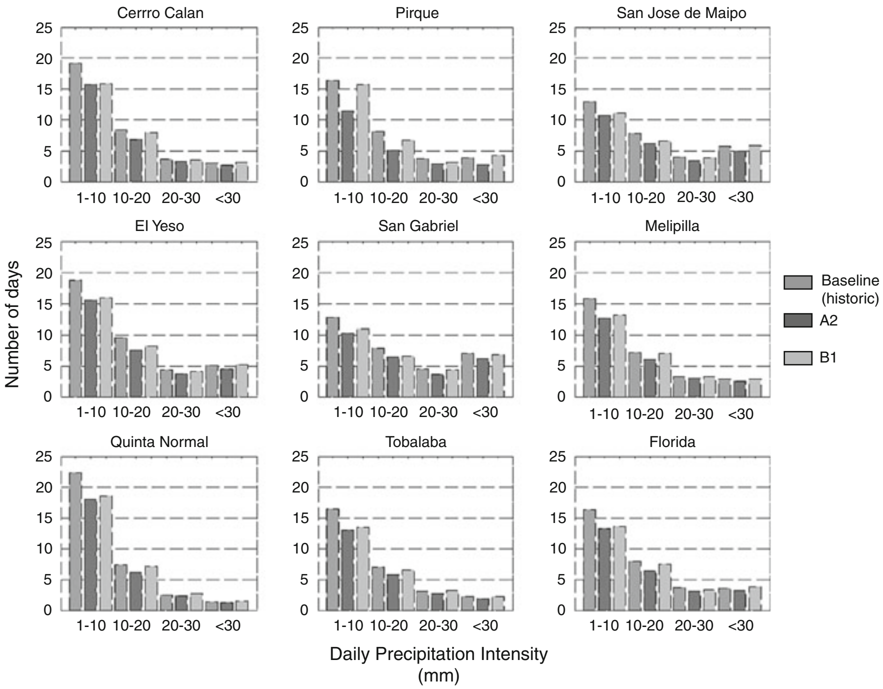

Fig. 2.7 Historic and future (2045–2065) precipitation for each analysed station grouped by scenario and daily intensity (*Source*: Authors' own presentation)
Note: Each group of three columns represents a specific daily precipitation intensity

high-intensity storms, since the overall decline in precipitation is primarily signified by a decrease in the number of days with low to medium precipitation amounts and a major decline in the number of days with 1–10 mm of precipitation. No significant changes are projected for the number of days with high-intensity precipitation, or for the average intensity of these events. Despite various sources of uncertainty, most of the models agree that Santiago will be a drier city in the future, with lower amounts of annual precipitation due to fewer rainy days.

2.4.4 Stream Flow

For the future period under analysis, dramatic changes can be observed in the hydrologic regime of the rivers concerned. Peak stream flow dates will shift to earlier months, and decreases of up to 40 % are observed for some summer months. Peak flow in winter will increase, as higher temperatures bring earlier melting of snow and ice. During the winter, lower precipitation rates and higher temperatures will reduce the amount of snow that accumulates in the high Andes, leading to a further reduction in run-off during spring and summer. A further crucial impact indicated in the hydrological model is the presence of higher stream flow values in autumn and winter. Considering model results show lower precipitation occurrence in the future, this increase in run-off is probably solely the result of increased melting during these months and a higher isotherm 0 line. Results are presented as averages for the 2045–2065 period (Table 2.10).

2.4.5 Glaciers and Secondary Data

As glaciers account for a significant percentage of stream flow volumes in February and March, the reduction in volume could have implications for water resource availability in the region during the summer months. The specific contribution of glacier melt to overall water availability in the Metropolitan Region is unknown as yet, however, with possible estimates ranging from 30 to 67 % for rivers such as the Maipo (Peña and Nazarala 1987). The exact amount of this contribution has yet to be quantified, and most glacier dynamics in the region must be examined exhaustively if meaningful estimates of future glacier evolution and its impact on water resource availability are to emerge. It is worth mentioning the special status glaciers in the central parts of Chile possess. According to Borquez et al. (2006), glaciers in the central Andes Cordillera can be classified as “polithermal”. They are found at relatively low altitudes (5,000 m.a.s.l. and below), with the ablation zone occasionally located at very low elevation. During the summer, the lower sections of these glaciers experience positive temperatures, producing run-off especially during the hot months. In a climate change context, these glaciers could be affected more than others, since major glacial mass areas here are vulnerable to high temperatures.

Table 2.10 Average monthly values for the Maipo River at San Alfonso and Mapocho River at Los Almendros stream gages (*Source*: Authors' own presentation)

SCENARIO	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
Maipo en San Alfonso												
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
Mapocho en Los Almendros												
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

Values correspond to cubic metres per second and the 2045–2065 period

There is, nevertheless, a high uncertainty associated with glaciers in Chile's central region. Much has yet to be quantified in terms of total existing glacial mass, and estimates of melt contributions to river systems refined. For further details, the reader is encouraged to review works, for example, by Pellicciotti et al. (2007, 2008) and Petersen and Pellicciotti (2011).

Although vital in many ways, "secondary variables" such as radiation, wind and relative humidity suffer from the absence of long-term records for comparison with climate model outputs. In the Metropolitan Region, these variables have been routinely measured in the past decade for agricultural purposes. Hence no statistical downscaling was attempted in this study. Analysis of the variables was confined to comparing GCM outputs for the historical and future climate scenarios, with results showing that no significant changes are to be expected for the region under future climate conditions. Given the large scale of the GCM modelling grid, however, straddling the MR between ocean- and continental-related cells, further research is needed to refine these variable estimates.

2.5 Conclusions

This chapter summarizes the main results obtained from estimates of future climate and hydrological conditions for the Metropolitan Region of Santiago. Results were presented for the 2045–2065 time period and based on the direct downscaling to local conditions of GCM projections (daily values) measured at selected meteorological stations. Output from multiple GCMs was included in the analysis in order to estimate the uncertainty affecting these projections.

Downscaled climate projections show approximately a 1–2 °C warming for the future period 2045–2065 at most stations in the region. Additionally, days with maximum temperatures above 30 °C increase in the order of 25–45 days per year (A2 scenario), depending on the station under review; this represents approximately a 30 % relative change in the annual number of days with very high temperatures.

Higher temperatures lead to higher elevations in the zero isotherm line, which in turn increase the storm run-off from higher elevation catchments. Minimum temperatures also increase, but unlike maximum temperature results, these increase more significantly at Pirque and El Yeso stations, which are located near or within the mountain region of the area. Precipitation projections are based on two indicators: average monthly values (climatology) and distribution of the number of days with precipitation.

Precipitation amounts may decrease for almost every month. In the worst case, projected reductions in precipitation vary between 10 and 30 % (20–100 mm less precipitation each year, depending on the specific location assessed). In addition, most models project fewer days with precipitation and lower precipitation rates during those days. Due to lower precipitation rates, a general decrease in stream flow magnitude is expected for the Maipo and Mapocho rivers, the most important streams in the MRS. The overall conclusion is that the city of Santiago will be both drier and hotter in the future, with a high number of days of extreme temperatures and increased drought during winter and summer.

The work presented here attempts to organize various data sources coherently into a useful decision-making product. It presents likely changes in climate for a specific time frame in the future and two scenarios that allow for further estimates on climate change related impacts and the subsequent development of specific adaptation measures (cf. Chaps. 4–8 in this volume).

Some limitations persist, however, and should be taken into account in future investigations. On the subject of methodology, only a few stations have a sufficiently long period of record to establish downscaling relations with simulated values, so that spatial interpolation of the data was confined to 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. Regarding GCM data, the current generation of GCMs (IPCC IV) does a good job in capturing the local climatology 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 these circulation patterns more successfully; therefore, projections of related phenomena such as maximum daily precipitation and extreme seasonal events (e.g., droughts) should be updated as they become available. The projection of secondary variables such as relative humidity, radiation or wind 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, stream flow projections should improve (particularly during dry periods) when hydrologic models are able to represent this component more adequately. This research is currently ongoing.

Overall, regional extrapolation of point 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 to assess future water resource availability.

Based on the data presented in this chapter, explorative scenarios are designed and presented in Chap. 3, and applied to climate change impact studies in Chaps. 4–7. Hence this chapter forms the basis for identifying, finally, adaptation needs for the MRS. As highlighted earlier, uncertainty is high—as in all climate change projections—and should be considered carefully while working with these results.

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