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Climate Change: Evidence and Future Scenarios for the Andean Region

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Climate change is one of the most relevant topics on the current international environmental agenda. It cuts across economies, trade, and political decisions in our globalized world. In South America, the countries of the Andean region will be the ones most affected by the consequences of climate change. This chapter is intended to provide an integrated overview of climate change in the Andean region based on observational studies and climate projections currently being discussed in the international and national literature on the tropical Andean countries.

Observational Evidence of Long-Term Climatic Variability and Climate Change in the Andes

Mean annual temperature in the countries of the northern Andes (Venezuela, Colombia, Ecuador, Peru) has increased by about +0.8 °C during the 20th century. Vuille and Bradley (2000) documented the tendencies of air temperature anomalies from 1939 to 1998 for the tropical Andes from 1°N to 23°S in relation to the 1961-1990 mean, and they found a positive tendency of +0.11 °C per decade for this period. This tendency tripled over the past 25 years of the 20th century (+0.34 °C per decade), although some variability is associated with the occurrence of the El Niño Southern Oscillation (ENSO). The magnitude of this warming tendency tends to be greater for climate stations at higher elevations.

Table 7.1 summarizes the tendencies observed in Andean climate and hydrometeorology in recent studies, indicating time periods, variables, and magnitude of change. The use of different time periods and analysis techniques by different studies hampers an integrated evaluation of the results. However, leaving aside problems related to differences in time-series length, it can be observed that air temperatures tend to increase. For precipitation it is difficult to obtain information that indicates any systematic tendency; nonetheless, both considerable interannual variability associated with ENSO and interdecadal variability can be observed. These tendencies are consistent with those detected by the IPCC Working Group I AR4 Report (Trenberth et al. 2007).

In the Peruvian Andes total annual and seasonal precipitation show regionally contrasting tendencies, and local factors condition differential behaviors with or without dependence on interannual variations (SENAMHI 2009a). Thus, observed tendencies show systematic increases in precipitation on the western flank and reductions in parts of the southern and central portion of the eastern flank of the Peruvian Andes (SENAMHI 2009a,c, SENAMHI 2007a,b). Evaluations of precipitation extremes have established the central Peruvian Andes as an increasingly homogeneous area with a clear tendency of reduced extreme rainfall events, whereas an increase in the number of days with extreme precipitation has been detected in the northern Peruvian Andes. A reduction in the number of cold days has primarily been observed in the south, whereas the number of warm days has increased throughout the Peruvian Andes. In the central portion of the western flank of the Peruvian Andes (Rio Santa watershed) a high-elevation warming trend of up to 0.07 °C per year has been detected, which is more pronounced than that at mid- and lower elevations (SENAMHI 2009c, SENAMHI 2005b).

On the western flank of the subtropical Andes in Chile and on the opposite flank in Argentina, lower mid-elevations (2000 m) experienced a significant warming trend of 0.28 °C and 0.23 °C, respectively, from 1979 to 2006. The northern Patagonian Andes between 37°S and 43°S have also experienced a significant warming trend of approximately 0.056 °C per decade from 1912 to 1990 on both the western and eastern flank. Throughout the subtropical Andean region in Argentina between 22°S and 28°S mean annual temperature increased by 0.62 °C during the 20th century. In the same region, based on analyses of cumulative annual precipitation series, significantly negative tendencies of -4.67% per decade have been observed, with the greatest decrease occurring during austral winter (Table 7.1).

The scarcity of continuous climatic records in large areas of the tropical Andes does not allow for conclusive evidence on mean tendencies and particularly on extremes.

Glacier Retreat

Recent studies have shown that most glaciers from Colombia to Chile and Argentina (to 25°S) have experienced drastic reductions in volume with an increased pace since the 1970s (Mark and Seltzer 2003, Leiva 2006, Vuille et al. 2008). In the central Andes glacier retreat is an indirect consequence of rising temperatures. These cause an increase in rain (rather than snow) on the lower sections of glaciers, thereby exposing the ice, increasing the glacier's capacity for absorbing solar energy and increasing melting of the ice (Favier et al. 2004). Between 35°S and 47°S in Chile, where a significant reduction in precipitation has been accompanied by increasing temperatures during the past 50 years (Carrasco et al. 2008), increased river discharge suggests that glaciers are melting. Table 7.2 summarizes results of studies on observed tendencies of glacial retreat and its impacts detected to date in some Andean countries.

Table 7.1. Summary of climatic tendencies observed in the Andean region.

Region	Period	Variable	Tendency	Reference
Cordillera Oriental-Colombia	1961-1990	Temperature	+0.1 °C to +0.2 °C	Pabon (2003)
Cordillera Occidental-Colombia	1961-1990	Precipitation	+4 %/30 years	Pabón (2003)
Cauca y Magdalena valleys-Colombia	1961-1909	Precipitation	-4%/30 years	Pabón (2003)
Inter-Andean valley-Ecuador	1905-2005	Temperature	+0.12 °C	Villacis (2008)
Inter-Andean valley-Ecuador	1980-2005	Temperature	+0.22 °C	Villacis (2008)
Inter-Andean valley-Ecuador	1891-1986	Precipitation	-10 mm/decade	Pourrut (1995)
Subtropical west Andes-Chile	1930-2000	Precipitation	-5 to -10% /decade	Quintana (2004)
Foothills-Chile	1979-2006	Temperature	+0.28 °C	Falvey and Garreaud (2009)
Eastern Andes-Chile	1979-2006	Temperature	+0.23 °C	Falvey and Garreaud (2009)
Patagonian Andes-Argentina	1912-1990	Temperature	+0.056°C/decade	Masiokas et al. (2008)
Patagonian Andes-Argentina	1912-1990	Temperature	+0.62°C/100 years	Masiokas et al. (2008)
Patagonian Andes-Argentina	1960-1990	Temperature	+0.4°C/decade	Villalba et al. (2003)
Subtropical Andes-Argentina	1950-1990	Precipitation	-12%/decade	Castañeda and Gonzalez (2008)
Subtropical Andes-Argentina	1912-1990	Precipitation	-4.67%/decade	Masiokas et al. (2008)
Piura watershed-northwestern Andes-Peru	1963-2003	Minimum temperature	+0.2 to 0.3°C/decade	SENAMHI (2005 a)
Piura watershed-northwestern Andes-Peru	1963-2003	Maximum temperature	+0.3 to 0.45°C/decade	SENAMHI (2005a)
Piura watershed-northwestern Andes-Peru	1963-2003	Precipitation	Summer, fall: +9 to 14 mm/year Winter: -0.5 mm/year Spring: +0.2 to 0.5 mm/year	SENAMHI (2005 a)
Santa watershed-central western Andes-Peru	1965-2006	Precipitation	Annual: 20-30% increase in the last 40 years	SENAMHI (2009 c)
Santa watershed-central western Andes-Peru	1965-2006	Minimum temperature	0.17ºC/decade in the upper part of the watershed	SENAMHI (2009 c)
Santa watershed-central western Andes-Peru	1965-2006	Maximum temperature	0.67ºC/decade in the upper part of the watershed	SENAMHI (2009 c)
Mantaro valley-central eastern Andes-Peru	1965-2006	Precipitation	Annual:-3 to -28 mm/year Summer: -4.5 to -7 mm/year Winter: -0.3 to -0.8 mm/year	SENAMHI (2007 a)
Mantaro valley-central eastern Andes-Peru	1965-2006	Maximum temperature	Annual: +0.03°C to +0.07°C/year Summer: +0.02 °C to +0.04/year Winter: +0.01 to +0.04 °C/year	SENAMHI (2007 a)
Mantaro valley-central eastern Andes-Peru	1965-2006	Minimum temperature	Annual: +0.01°C to +0.11°C/year Summer: +0.02 °C to +0.01/year Winter: -0.02 to +0.03 °C/year	SENAMHI (2007 a)
Arequipa-southern Andes-Peru	1964-2006	Maximum temperature	Annual: +0.06°C to +0.42°C/year Summer: -0.07 °C to +0.42/year Winter: +0.02 to +0.44 °C/year	Marengo et al. (2009)
Arequipa-southern Andes-Peru	1964-2006	Minimum temperature	Annual: +0.12°C to +0.57°C/year Summer: -0.07 °C to +0.56/year Winter: +0.26 to +0.5 °C/year	Marengo et al. (2009)

Arequipa-southern Andes-Peru	1964-2006	Precipitation	-2 to +1.5 mm/decade	Marengo et al. (2009)
Urubamba watershed-southeastern Andes-Peru	1965-2006	Precipitation	Annual:-0.7 a 8.5 mm/year (upper part of watershed) Annual 0.2 a -1.1 mm/year (lower part of watershed)	SENAMHI (2007 b)
Urubamba watershed-southeastern Andes-Peru	1965-2006	Maximum temperature	Annual: +0.01°C to +0.04°C/year	SENAMHI (2007 b)
Urubamba watershed-southeastern Andes-Peru	1965-2006	Minimum temperature	Annual: +0.02°C to +0.05°C/year	SENAMHI (2007 b)
Mayo watershed-northeastern Andes-Peru	1965-2006	Maximum temperature	Alto Mayo: -0.25°C/decade Bajo mayo:+0.43 °C/decade	SENAMHI (2009 b)
Mayo watershed-northeastern Andes-Peru	1965-2006	Temperature mínima	Alto Mayo: +0.48°C/decade Bajo Mayo: +0.22°C/decade	SENAMHI 2009 b)
Mayo watershed-northeastern Andes-Peru	1965-2006	Precipitation	Annual: -20 to +20% relative to the annual mean Summer : -10 to +40% relative to the trimester mean Winter : -10 to -40% relative to the trimester mean	SENAMHI (2009 b)

Table 7.2. Observed tendencies of Andean glacier retreat and detected impacts. This table is an updated version of table 13.3 of the IPCC AR4 GT2 report (Magrin et al. 2007).

Glacier/Period	Tendencies/Impacts
Peru[a, b] (1965-2002)	A 22% reduction in total glacier area; 12% reduction in supply of drinking water for the coastal region (where 60% of the population). The estimated lost water volume is about 7 billion m^3.
Peru[c] (1970-2002)	Up to 80% reduction in the extension of small glaciers; loss of 188 million m^3 in water reserves during the last 50 years.
Peru[d] (1998-2004)	In the Cordillera Blanca retreat of the Yanamarey glacier was 23% greater in 2001-2004 than in 1998-1999 and was responsible for a 58% increase in the mean annual discharge of the Rio Santa.
Peru[d] (1977-2004)	Melting of the Yanamarey glacier, retreating at a speed of 20 m/year (mean 1977-2003), four times faster than the 5 m/year observed between 1948 and 1977.
Peru[e] (1953-1997)	A 13% increase in the discharge of the Laguna Yanganuco in the Cordillera Blanca.
Peru[c] (1985-1996)	During the last 10 years the ice cap of the Pastoruri glacier was reduced by almost 40%.
Peru[f] (1950-2006)	Up to 50% reduction in the extension of the Coropuna glacier, generating irrigation problems in the Pampa de Majes.
Colombia[g] (1990-2000)	An 82% reduction in glacier area, an estimated retreat of 10-15 m/year corresponding to an approximately 70-80% reduction compared to 1850.
Ecuador[h] (1956-1998)	A 30% loss in glacier surface on the Cotopaxi volcano since 1956. Glacier area above 5000 m remained stable between 1956 and 1976. Subsequently an accelerated retreat was observed, with a small recovery in 2000, but without affecting the overall decreasing trend.
Bolivia[i] (1991-2002)	A 9.4% loss of the area covered by snow on the Zongo glacier, causing serious problems for agriculture, ecosystem sustainability, and causing socioeconomic impacts in the rural population.
Bolivia[i] (1940-2003)	A 47.4% loss of the area covered by snow on the Charquini glacier.
Bolivia[o] (1963-2006)	An analysis based on aerial photogrammetry of 21 glaciers in the Cordillera Real shows that on average glaciers have lost 43% of their volume between 1963 and 2006 (essentially between 1975 and 2006). Between 1975 and 2006 they lost 48% of their surface area.
Argentina[j,k] (1912-1990)	Numerous studies throughout the Patagonian Andes show a marked loss of glacier volume in the southern portion. Masiokas et al. (2008) documented strong retreat of six glaciers in the northern Patagonian Andes (between 39 and 43°S) based on an analysis of photographs. The concomitant increase in temperatures and reduction in precipitation observed during the 20th century could explain the glacial retreat.
Chile[l] (1952-2007)	Marked retreat of Patagonian glaciers during the 20th century. It is estimated that with each temperature increase of 1°C, the Andean snowline in Chile will rise by 120 elevational meters. The southern Patagonian Andes have suffered a marked loss in glacier volume.
Chile[m] (1950-2007)	Analysis of trends in flow volume in 13 Andean watersheds in Chile between 28 and 47°S that are partially fed by glaciers (between 1-23%) for the period 1950 to 2007. An increasing trend in flow volume was recorded at the end of austral summer, which the authors attributed to melting glaciers, but this trend was not significant.
Chile[n] (1970-2002)	Significant reductions in discharge of the Aconcagua and Blanco rivers in the central Chilean Andes.

[a]Chuquisengo Vásquez 2004; [b]Mark and Seltzer 2003; [c]CONAM 2001; [d]Mark et al. 2005; [e]Pouyaud et al. 2005; [f]Silverio 2004; [g]NC-Colombia 2001; [h]Jordan et al. 2005; [i]Francou et al. 2003; [j]Masiokas et al. 2008; [k]Coudrain et al. 2005; [l]Fuenzalida et al. 2006; [m]Pellicciotti et al. 2007; [n]Casassa et al. 2009; [o]Soruco et al. 2009.

Methods for Deriving Greenhouse Gas Emissions Scenarios and Future Climate Projections in the Andean Region

Revision of emissions scenarios considered in the production of future climate projections

To obtain future climate projections, climate models are run under different greenhouse gas emission scenarios and degrees of social and economic development consistent with those emissions. These socioeconomic and environmental scenarios used by the IPCC represent a framework for structured thinking about how the future could develop. All possible future climate projections depend on the range of emissions prospects. Scenarios of greenhouse gas emissions due to human activities depend on a variety of socioeconomic factors such as population and economic growth, technology, and energy use (Nakicenovic et al. 2000). By 2100, the concentration of atmospheric carbon dioxide will increase from the current (1999) 370 parts per million by volume (ppmv) to close to 550 ppmv under scenario B2 (low emissions) and to over 830 ppmv under scenario A2 (high emissions).

Use of Global and Regional Models for the Generation of Future Climate Projections in the Andean Countries

Global climate models are mathematic representations of nature, its components and their interactions, with such a degree of complexity that only powerful "supercomputers" are able to run these models. In these models the Earth's surface is divided into grid cells of equal size and shape, and the spatial resolution of the model decreases with increasing grid cell size and *vice versa*. Global models have low spatial resolution with grid cells of between 300 km and 500 km in latitudinal and longitudinal extension. This coarse resolution does not permit the detection of changes in certain areas such as coastlines and topographically complex mountain regions, nor of small-scale phenomena such as intense rainfalls. Thus, the high and steep Andean mountains are poorly covered by climate models with low spatial resolution, and linear interpolation is generally used to fill in missing regional detail. However, this procedure may introduce errors and uncertainties.

Therefore it is necessary to use climate models with greater spatial resolution (smaller grid cells of ca. 50x50 km) or regional climate models. The process of generating climate projections using regional models is called downscaling. In this method, which is frequently applied in the generation of future climate scenarios with high spatial resolution, regional climate models are run using boundary conditions of a global model. In the Andean region, future climate projections are generated with the HadRM3P regional model of the Hadley Centre for Climate Prediction and Research of the United Kingdom Met Office. This regional model has a spatial resolution of 50x50 km and it is run with the parameters of the global model HadAM3P until the end of the 21st century for scenarios A" and B2 of the IPCC. The HadRM3P model constitutes a component of the climate modeling system PRECIS (Providing Regional Climate Change Scenarios for Impact Studies).

Climate Change Scenarios: Projections for the Andean Countries

In recent years several Andean countries have developed climate change scenarios to evaluate vulnerability and impacts, either using the global models employed in the preparation of the IPCC reports, or regional models. In 2007 several South American countries analyzed climate projections for the period 2080-2099 relative to 1980-1999 based on the Japanese high-resolution (20x20 km) global atmospheric model JMA-MRI TL959L60 using the supercomputer Earth Simulator (Vergara et al. 2007). Table 7.3 provides a summary of these recent experiences from the Andean region with climate change projections until the middle or end of the 21st century, which will serve as a reference for projections of regional models to be presented and discussed subsequently.

Future climate projections for the Andean countries were generated using the only available regional simulation model HadRM3P for the periods 201-2040, 2041-2070, and 2071-2100 based on emissions scenarios A2 and B2 (Figures 7.1, 7.2; Table 7.4). These projections are coherent with those derived by the global and regional models from the IPCC´s Forth Assessment Report (Meehl et al. 2007, Christensen et al. 2007) for South America, and with the projections derived from the Japanese MRI-JMA T219L60 high resolution global model. The qualitative agreement between those models is considered as a "subjective" indicator of the confidence of the climate change projections described in Table 7.4.

Rainfall projections suggest an increase in mean precipitation for the tropical Andes region (5°N to 20°S) under the A2 scenario, with increases of up to 20-25% on the eastern and western flank of the Andes, whereas the western Andes of northern Peru may experience an increase of up to 70%, levels characteristic of El Niño years. The greatest uncertainties exist for the eastern flank and inter-Andean valleys between 5°S and 15°S. On the Altiplano, and in the subtropical Andes south to Patagonia, on the other hand, there is a tendency for a decrease in precipitation of up to 10%. The most pronounced pattern in temperature projections with a high level of confidence is a warming in near-surface air temperatures in the tropical Andes and south to Patagonia, which is greatest on the Altiplano, in the subtropical Andes, and on the eastern flank. Future warming also is predicted for inter-Andean valleys, but due to the steep topography of these regions HadRM3P projections differ in magnitude from those of the Japanese model and the IPCC's Fourth Assessment Report.

Vulnerability studies conducted in the region suggest that due to glacier retreat as a result of increasing temperatures, bottlenecks in water availability may come about in Colombia by 2015-2025, affecting water availability in the paramos (IDEAM 2000). In Peru 60% of the population will be affected by lower water availability (Chuquisengo Vásquez 2004), and the same applies to the generation of hydroelectric power. Among the affected rivers will be the Rio Mantaro, which currently generates 40% of Peruvian electricity and supplies 70% of the energy used in industry in Lima (Montoro Asencios 2004). For the Cordillera Blanca Pouyaud et al. (2005) suggested that based on a conservative 1°C warming estimate, river flow volumes will increase due to melting glaciers, with meltwater discharge reaching a peak between 2025 and 2050, followed by a progressive decrease until their disappearance between 2175 and 2250. Similar phenomena would be observed in Ecuador (Villacís 2008). In Ecuador, 7 of the country's 11 main watersheds would be affected by a reduction of river discharge by 2010 under a scenario of 2°C warming and a 15% reduction in precipitation (Cáceres in litt.). More recent studies, however, show that a slight increase may be observed in river discharge until 2030 as a result of a ca. 20% increase in precipitation according to the mean of the 21 global climatic models of the IPCC (Buytaert et al. 2009).

Andean ecosystems such as the paramos of the northern tropical Andes could be severely affected by the consequences of glacier retreat. These ecosystems hold a unique, endemic flora and provide resources and ecosystem services for nearby populations (Buytaert et al. 2006). Although our understanding of the processes involved in glacier retreat has improved greatly in recent years, the consequences for natural Andean ecosystems are still poorly known. In Ecuador, the loss of meltwater contribution to river discharge will not only affect watersheds with low (15%) glacier cover and the regulation capacity of rivers especially during the dry season (Villacís 2008), but it will also disrupt the water production capacity of paramos and existing aquifers, given that these are partly fed by glacial meltwater (Favier et al. 2008, Villacís et al. 2009).

Sources of Uncertainty and their Quantification

We are more confident about some aspects of climate change than others. For example, we have greater certainty about near-surface air temperature increases than we have about an increased occurrence of climatic extremes. The behavior of El Niño events is not well represented in climate models, and predicting how these events will be affected by global warming is therefore difficult. The uncertainties in climate projections are introduced by two factors. First, future greenhouse gas emissions are unknown, so that global warming scenarios have to project future changes in emissions based on the observed increase of emissions over the past 50 years, assuming certain behaviors of society. Second, representation of some physical processes and of interactions between components of the climatic system in climate models may be limited. This is the case, for example, for interactions between soil humidity and climate near the surface. Other sources of uncertainty also exist, such as those stemming from regionalization, specifically the type of regional model used and also the coupling of the regional and global model.

When comparing simulations of the regional HadRM3P model with those of the global models used by the IPCC's Fourth Assessment Report and those of the high-resolution Japanese model, it can be observed that these models predict drier future conditions for the southern Andes, especially during austral summer. However, this qualitative consensus could be related to systematic errors in the general circulation patterns established in current climatology, and such errors need to be corrected before building the climatology of the future. Due to the large uncertainties of climate projections, it is important to recognize the need for a greater number of regional simulations in order to reduce the inherent uncertainty associated with the formulation of models itself.

Despite the scarcity of studies on climate variability and change in the Andes, indisputable evidence exists of the severe impacts of climatic extremes that are happening or could happen in the region. Therefore, investment into climatological research is of crucial importance to evaluate with greater certainty the impacts of a changing climate on Andean and Amazonian ecosystems, biodiversity, agriculture, socioeconomic infrastructure, generation of hydroelectric power, tourism, and other sectors. The studies and climate projections presented in this chapter respond to a need to provide scientific information on climate change and glacier retreat in the Andean region, and their effects on the dynamics of montane ecosystems. This information can be helpful in the identification if necessary adaptation measures to cope with climate change and to protect Andean ecosystems.

Table 7.3. Summary of climate change experiences and projections in the Andean region using global or regional climate models. Projections are until 2001 in relation to the period 1961 to 1990 unless noted otherwise.

Region/Period/ Reference	**Projected changes**	**Models used**	**Expected impacts**
Northern Andes -Colombia Until 2100 *(Pabón 2006, 2007, 2008)*	Temperature: +2.0 °C to +4.0 °C Precipitation: -30 to +30% of annual amounts	Statistics of global models: ECHAM4 and CCM3 with 2xCO_2 Regional: HadRM3P	A reduction in annual precipitation is expected, in some regions over 30%; in the eastern foothills of the Cordillera Oriental and in the Pacific region increases would occur under scenario A2.
Colombian Andes Period 2080-89 *(Vergara et al. 2007)*	Temperature: +2.0^{o}C to +3.0 ^{o}C Precipitation +2.5 to +3 mm/day	Global: JMA-MRI TL959L60	Future temperature increase in the Andes, greater than the mean temperature projected for the entire country. Increase in precipitation on the eastern and western flanks of the Andes.
Ecuadorian Andes Period 2071-2100 *(Centella and Bezanilla in litt.)*	Temperature: + 1.8 ^{o}C to +4.0 ^{o}C Precipitation: -20% to +20%	Global: HadCM3 and ECHAM4 Regional: HadRM3P	Ecuador is expected to experience a considerable increase in temperature that could reach magnitudes of between 2.7°C and 4.3°C, accompanied by a mean increase in precipitation between 18.5% and 63%, according to scenarios A2 and B2. Temperature increases will be most severe in the Amazonian region, while the western Andes will experience the lowest increases. Among future changes in precipitation high inter-annual variability figures prominently, with elevated maxima that appear to be associated with the occurrence of major precipitation events with similar effects as El Niño events.
Ecuadorian Andes Period 2080-89 *(Centella and Benzanilla 2008)*	Temperature: + 1.8 ^{o}C to +4.0 ^{o}C Precipitation: -20% to +20%	Global: JMA-MRI TL959L60	Under the intermediate scenario A1B predicted temperature increases range from 1.8°C to 4.0°C, whereas changes in precipitation vary between -20% and +20%. Minimum temperatures are expected to increase by between 2.0°C and 4°C, with most severe increases in Amazonia.
Northwestern Andes - Peru Until 2030 *(SENAMHI 2005 a)*	Temperature: +0.2 a +2.0 C Precipitation: +5% to 10%	Global: NCAR-CSM Regional: RAMS	The upper Rio Piura watershed is expected to experience a positive precipitation trend in all trimesters approximately 5% greater than the mean except in spring, for which no major changes are predicted. An increase in the frequency of warmer days and warmer nights in summer and fall is predicted. The highest temperatures would occur in spring.
Northeastern Andes - Peru Until 2030 *(SENAMHI 2009 b)*	Temperature: +0.7 to +1.2 C Precipitation -3% to -7 %	Global: NCAR–CSM Regional: RAMS	The Mayo watershed is expected experience the greatest temperature increases in spring, with an increased tendency for warmer days and warmer nights. Mean precipitation is expected to decrease slightly by 3% annually and by 7% in summer, and extreme precipitation events would occur with decreasing frequency.
Central western Andes - Peru Until 2030 *(SENAMHI 2009 c)*	Temperature +0.2 to + 0.9 ºC Precipitation: -3% to 5% (upper elevations) -10% to -3% (lower elevations)	Global: NCAR–CSM Regional: RAMS	The Santa watershed is expected to experience slight increases in precipitation at higher elevations and slight decreases at lower elevations, which fall within the area's natural variability. Extreme temperatures would become more frequent primarily in winter and spring.

Central and southern eastern Andes - Peru Until 2100 *(SENAMHI 2007a,b)*	Temperature Over +2.0 ºC Precipitation -5 to -35% (Mantaro) +10 to +24% (Urubamba)	Global: MCGA TL959L60 MRI/JMA	The Mantaro and Urubamba watersheds are expected to experience increases in the frequency of extreme temperatures, which would be most severe at elevations above 3500 m. Precipitation would decrease to insufficient levels in large parts of the Mantaro watershed, while it would remain within natural variability in the Urubamba watershed, but with a slight increase.
Andes del Sur occidental Until 2100 *(Marengo et al. 2009)*	Temperature +2.0 to +5.0 ºC Precipitation -2 to -3 mm/day	Global: IPCC AR4 Regional: HadRM3P	In Arequipa, the most severe increases in temperature are expected to occur at elevations above 3000-4000 m. Below 4000 m climate projections predict an increase in the frequency of warm nights, possibly heat waves, and a reduction in the frequency of cold nights and days. Above 4000 m there also is a trend for an increase in warm nights and days, with more heat waves, and a reduction in the frequency of cold days and nights, particularly of days with subzero temperatures. Precipitation scenarios indicate reductions at elevations above 4000 m (2-3 mm/day less than at present) and increases at lower elevations (1-2 mm/day more than at present). For elevations below 4000 m more extensive dry periods are predicted, combined with an increase in the frequency of extreme precipitation events.
Northwest Argentina and Bolivian Altiplano Until 2100 *(Solman et al. 2007, Nuñez et al. 2008)*	Temperature: +2.5 C to +3.5 ºC Precipitation: -40%	Regional: MM5	Increases in temperature during summer months of 3.5°C and 2.5°C are projected under scenarios A2 and B2, respectively. Increases in temperature are expected to be greater for winter months (4.5°C for scenario A2 and 3.5°C for scenario B2). The region is characterized by humid summers and dry winters. For the end of the 21st century a reduction in precipitation of 40% is projected for summer months, which would lead to an increasing aridity in the region..
Subtropical Andes (28°S to 35°S), eastern flank - Argentina 2081-2090 *(Solman et al. 2007, Nuñez et al. 2008)*	Temperature: +2.5 ºC to +4.0 ºC Precipitation: -25% to +30%	Regional: MM5	Projected temperature changes during summer months are expected to reach 4°C under scenario A2, being slightly less pronounced during winter months. For the most optimistic scenario (B2), less severe increases of 2.5-3.0°C during summer and 2.0-2.5°C during winter are predicted. The region's precipitation regime is characterized by maxima during winter. For scenario A2 a 25% decrease in rainfall is predicted for the winter months, largely due to a reduction in the number of days with rain, whereas a 30% increase is predicted for summer months.
Patagonian Andes 2081-2090 *(Solman et al. 2007, Nuñez et al. 2008)*	Temperature: +1.5 ºC to +2.5 ºC Precipitation: -50% to +10%	Regional: MM5	Projected warming for the region is greatest at middle latitudes and decrease towards higher latitudes. Greatest increases are expected for summer months (3°C for scenario A, 1.5-2.0°C for scenario B2). During winter temperature increases are expected to be on the order of 2.5°C for scenario A2 and 1.5°C for scenario B2. The region is characterized by a winter precipitation regime. For the end of the 21st century A2 scenario projections indicate a reduction in winter precipitation on the order of 50% for the northern Patagonian Andes and an increase of 10% in the southern portion (south of 40°S), whereas summer precipitation is expected to increase by 30% in the north and decrease by 40% in the south. Under scenario B2 an approximately 30% increase in precipitation is expected for both summer and winter in the northern Patagonian Andes, while reductions of about 15% and 10% are expected for the southern portion in summer and winter, respectively.
Subtropicales Andes - Chile Until 2100 *(Fuenzalida et al. 2006)*	Temperature: +2.5 °C to +4.5 °C Precipitation: Reduction	Regional: HadRM3P	A warming of the central Chilean Andes in summer and of the Altiplano in winter are predicted. Important changes in the annual cycle of river discharges are expected in central Chile: increases in flow volume and inundation risk during winter as well as a decrease in flow volume during spring and summer (due to decreased meltwater discharge) are probable.

Table 7.4. Summary of expected climatic changes by the end of the 21st century under the extreme scenario A2. Qualitative indicators of reliability are defined based on consistencies in the direction of the tendencies (positive or negative) predicted by models HadRM3P, the mean of the IPCC AR4 models and the Japanese model: High = The three models present the same direction of tendencies; Medium = Two models show the same tendency, but the third model shows no or the opposite tendency; Low = Two models show opposite directions of tendencies and the third model shows no tendency, or only one of the three models predicts a tendency.

Region	**Projected changes: Temperature**	**Confidence**	**Projected changes: Precipitation**	**Confidence**
10°N-5°S Western flank	+2.0 °C to +3.0 °C	High	+15 to +20 %	High
10°N-5°S Eastern flank	+2.5°C to +4.0 °C	High	+7% to 10%	Medium
10°N-5°S Inter-Andean region	+2.0 °C to +4.0 °C	High	-4% to -15 %	Medium
5°S-10°S Western flank	+3.0 °C to +4.0 °C	High	+60 to +70 %	High
5°S-10°S Eastern flank	+4.0 °C to +5.0 °C	Medium	+16 to +25%	Low
5°S-10°S Inter-Andean region	+3.0 °C to +4.0 °C	Medium	+10% to +16%	Low
10°S-15°S Inter-Andean region – western flank	+3.0 °C to +4.0 °C	High	+6% to +11 %	Low
10°S-15°S Eastern flank	+4.0 °C to +5.0 °C	High	+16% to +22 %	Low
15°S-20°S Inter-Andean region	+3.0 °C to +5.0 °C	High	+10% to + 25%	Medium
15°S-20°S Altiplano	+4.0 °C to +5.0 °C °C	High	+4% to +10%	Low
20°S-35°S Subtropical Andes	+3.0 °C to +5.0 °C	High	-6% to -10%	Medium
South of 35°S Patagonia	+3.0 °C to +4.0 °C	High	-4% to -5%	Medium

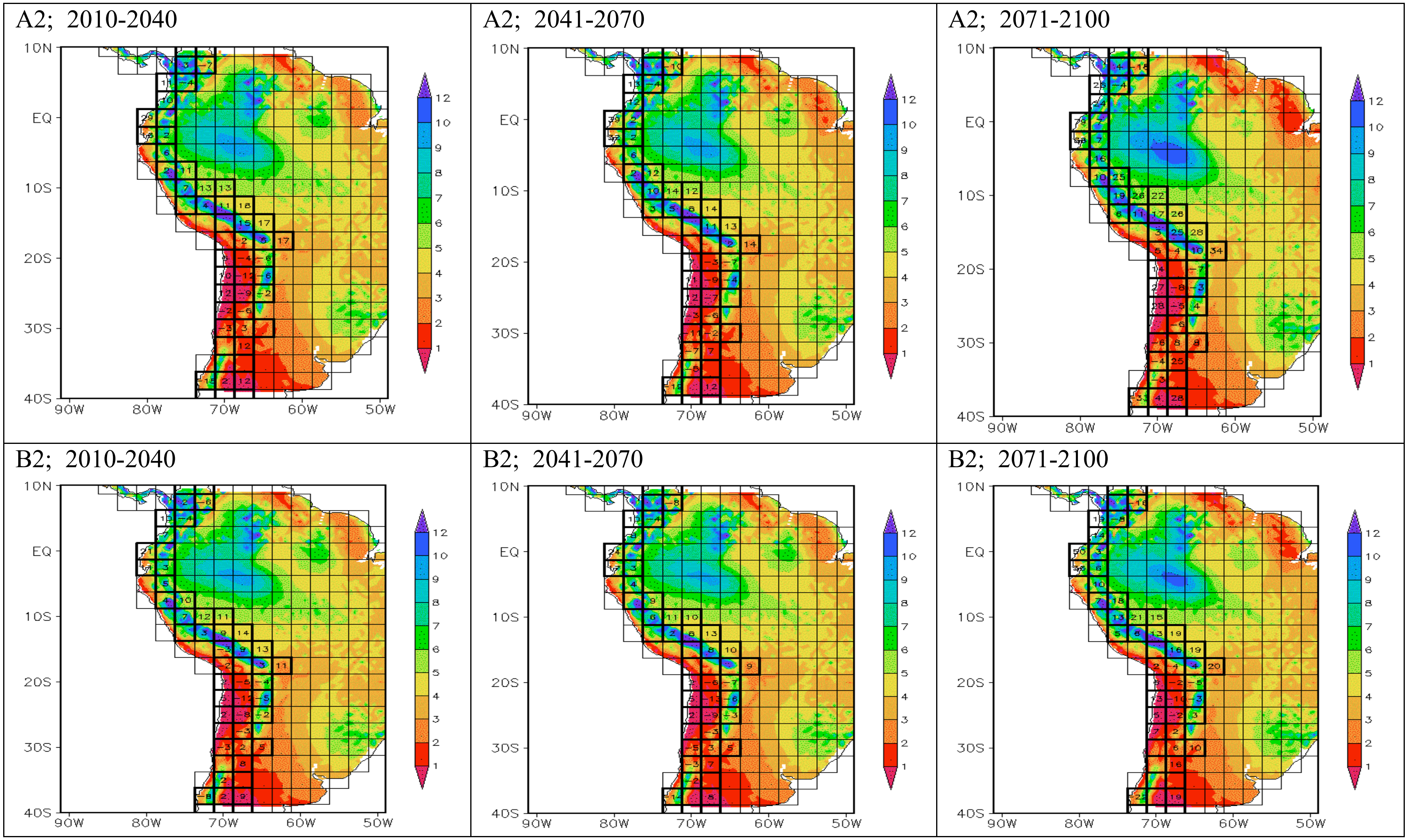

Figure 7.1. Future mean annual precipitation in mm per day (map colors) and relative changes in precipitation (numbers in grid cells; in relation to the period 1961-1990) under emissions scenarios A2 (high emission, upper row) and B2 (low emission, lower row) for the periods 2010-2040, 2041-2070, and 2071-2100 as projected by the model HadRM3P. Numbers in grid cells are only given for those cells where the projected difference is statistically significant in relation to the 30-year (1961-1990) natural variability.

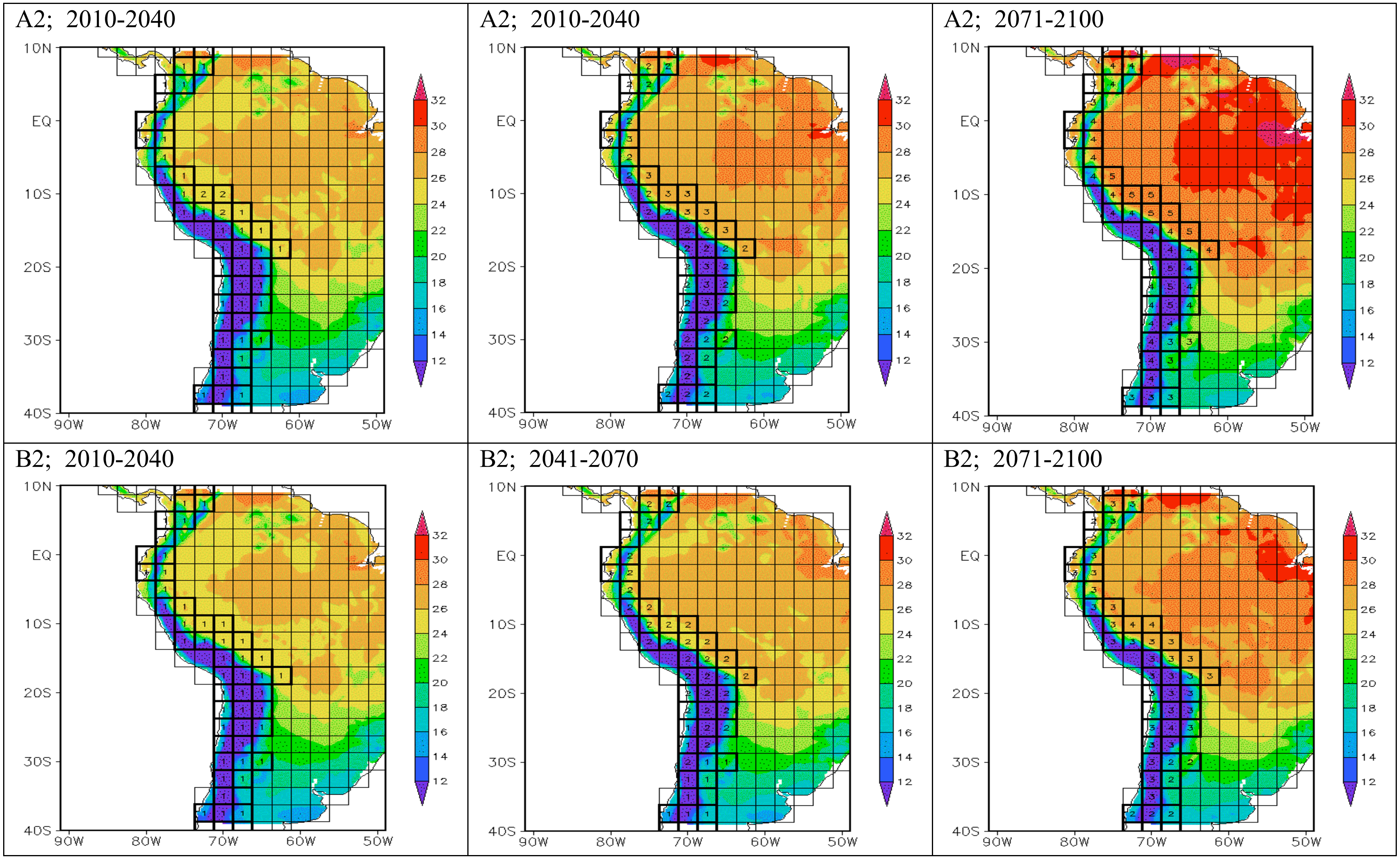

Figure 7.2. Future mean annual temperature in °C (map colors) and changes in temperature in °C (numbers in grid cells; in relation to the period 1961-1990) under emissions scenarios A2 (high emission, upper row) and B2 (low emission, lower row) for the periods 2010-2040, 2041-2070, and 2071-2100 as projected by the model HadRM3P. Numbers in grid cells are only given for those cells where the projected difference is statistically significant in relation to the 30-year (1961-1990) natural variability.

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