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Contents

Summary

The main aim of this study that has been performed in the context of the ADAPTS project, is to provide a large dataset showing the possible changes in climate that can be expected in Peru during the 21st Century. This dataset can be used with and by regional and local stakeholders in the assessment of adaptation requirements and possible adaptation strategies. The research goals are: (a) to provide maps and graphs showing the possible short, medium, and long-term changes in annual and monthly precipitation and temperature in the study region; and (b) to assess the possible impacts of climate change on the discharge of the Ocoña River.

The results of two General Circulation Models (GCMs) (HADCM3 and ECHAM5) are downscaled to a resolution suitable for regional climate impact assessment (10' x 10'). Downscaled climate data are provided for a number of future greenhouse gas emission scenarios (B1, A1B, A2), and for three time horizons, namely 2006-2035 (short-term) and 2036-2065 (medium-term), 2060-2090 (long-term). A hydrological model (STREAM) is used to simulate the monthly discharge of the Ocoña the model is driven by the downscaled climate data from both the HADCM3 and ECHAM5 models.

The downscaled precipitation data for the HADCM3 model was assessed to be not realistic, as it shows large increases in monthly precipitation up to +300%. Probably this was due to the high spatial variability in the study area in combination with the used downscaling technique. This data is not included in the hydrologic modelling exercise.

The downscaled data of the Echam5 model shows rising temperatures in the basin and precipitation will decrease. Between the three studied locations in the basin there are small differences, and the direction of change is the same. Modelled runoff shows decreasing water levels in the Ocoña River, where reduction is strongest in the period 2075.

1 Introduction

This report is written as part of the Peruvian case study of the ADAPTS project. It contributes to deliverables 1.4, 1.5 and 5.1 of the project plan. The aim of the ADAPTS project is to increase adaptive capacities of developing countries by the inclusion of climate change and adaptation considerations in water policies, local planning and investment decisions. The study area for Peru is the Ocoña river basin (figure 1).

1.1 Background

Climate change is expected to have profound impacts on the Andes in South America and the people living in the region, due to the role of glaciers in the hydrological system. In the context of the ADAPTS project (www.adapts.nl) a case study on community based adaptation in water management is implemented in the Ocoña basin in Peru. To be able to assess the impacts of climate change, more detailed information on changes in temperature and precipitation is necessary. The first activity for the ADAPTS project is to downscale information from global climate models to regional information and to assess the changes in temperature and precipitation for some areas. It is necessary to first have insights in the projected changes in the area, before adaptive measures can be developed. For this region, the presence of snow and ice is key, as these function as water buffers for the dry season.

Peru is one of the countries that will be hardest hit by climate change. This is mainly due to its high dependence on glaciers as a source of water (Bates et al., 2008). In the last 35 years, 22% of glacier's total area has retreated in Peru (Vásquez, 2004 and Mark and Seltzer, 2004). The glacier retreat is accelerating and it is very likely that the glaciers will disappear in the coming decades (Margin et al., 2007). This will lead to a decline in water resources and a change in the time of year in which water is available.

Figure 1 The Ocoña basin and the 7 provinces it covers

1.2 Regional setting

The Ocoña river basin is located in the South Western part of the Peruvian Andes. It is spread across three departments (Arequipa, Ayacucho, and Apurimac) and includes seven provinces (Figure 1). The basin covers the high Andes, with the highest point the Coropuna mountain of 6445 m.a.s.l., deep canyons and the coastal deserts. It has a total draining area of 15,998 km^2 (IRH-INRENA, 2007) and it is the second largest sized river basin of Peru considering its volumes of discharge both in the wet and in the dry season (Lasage and Hirsch, 2008).

The rainy season is from January to March and average precipitation is 500mm and 10 mm respectively for the high Andes and the coastal plain. In the middle zone yearly precipitation is around 315 mm (Lasage and Hirsch, 2008). During the warm period at the high Andes day temperatures are above freezing point (e.g. Peaks Coropuna, Solimana, Sara Sara, Firur), causing the ice and snow to melt. This melt water flows into the tributaries of the Ocoña river, which is used for irrigation in the middle zone, between 3300 m.a.s.l. and 2700 m.a.s.l. where crops (for example, alfalfa, maize and potatoes) are grown on terraces dating back to the pre-Inca era. Discharge at the mouth of the Ocoña river at Ocoña town, located at the Pacific ocean varies between 50 and 2000m^3.

Approximately 70,000 people live in the Ocoña river basin, most of them live in poverty or extreme poverty. The main economic sector in the area is agriculture. Other sectors are livestock breeding, small-scale commercial activities and mining. Most households are subsistence farmers and produce for self-consumption. There are some large landowners who produce for the local market. Livestock breeding consists of cattle, sheep and pigs. Cows are used for milk produce and to make cheese. Next to agriculture mining takes place in the region, the main exploited resources are gold, copper, tin, silver and some other non-metallics like limestone. The mining industry has a large impact on water quality due to the chemicals that are used in processing the ores.

1.3 Aims and objectives

The main aim of this study is to provide a dataset showing the possible changes in climate that can be expected in this region in Peru during the 21st Century. These projected changes in climate can be used by regional and local stakeholders in the assessment of adaptation requirements and possible adaptation strategies, for instance in the development of a Integrated River Basin Management Plan (IRBM) for the Ocoña river. Based on these datasets, stakeholders and decision-makers in the region can make informed decisions on the need for adaptation measures to adapt to climate change.

1. To provide maps and graphs showing the possible short and medium-term changes in annual and monthly precipitation and temperature in the study region;
2. To assess how two GCMs perform in this region with large differences in altitude;
3. To assess the possible impacts of climate change on the occurrence of drought events, and the incidence of high temperatures;
4. To assess the effects of these climate changes on the discharge of the Ocoña River.

1.4 Structure of the report

This report is set up as follows: Section 2 describes and discusses the methods and models used to assess the changes in climate and discharge. In Section 3, the main results are described for the locations of Coropuna, Chichas and Ocoña (high, middle and low elevation), and for the Ocoña River. The results are summarised, together with an outline of implications, in Section 4.

2 Methods

In order to assess the possible changes in regional climate in the 21st Century we used the results of two GCMs (HADCM3 and ECHAM5). The GCM results were first statistically downscaled to increase the spatial resolution, thus making the data more appropriate for a regional assessment. The downscaled data were then analysed to assess how precipitation and temperature are projected to change under a number of future scenarios, compared to the baseline period 1961-1990. These downscaled climate data were then used as input in a hydrological model, in order to simulate changes in the discharge of the Ocoña River in the 21st Century in response to the modelled changes in climate. In this section we describe the climate data and scenarios used, the methods used to downscale the data to the regional level, and the methods and data used to simulate changes in the discharge of the Ocoña River.

2.1 Climate change scenarios

The climate change scenario data used in this study are based on simulations carried out using General Circulation Models (GCMs) for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007). For our assessment we used simulations of monthly temperature and precipitation over the period 1901-2100 carried using the climate models ECHAM5[1] and HADCM3[1,2]. These models were selected since they have the highest 'skill scores' for both precipitation and temperature of all the models used for the AR4 in the region of study (Cai et al., 2009). The raw data were downloaded from the website of IPCC Data Distribution Centre (http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.html).

In order to analyse the changes in climate simulated by these models, we compared the simulated values for the baseline period 1961-1990 with the values for three dates in the future: 2020, 2050 and 2075 AD. We used these to correspond to short-term, medium term, and longer-term climate change respectively. Note that in keeping with standard methods in climatological studies, these three dates are defined as the means of 30-yr periods, so that 2020 refers to the period 2006-2035, 2050 refers to the period 2036-2065, and 2075 refers to the period 2061-2090. Also note that since the modelled baseline data for the period 1961-1990 are derived from two different climate models, the baselines differ between the HADCM3 and ECHAM5 results. For the 20th Century we used simulations forced using the scenario 20C3M, which prescribes greenhouse gases and aerosols on an annual basis according to observed values throughout the 20th Century. For the 21st Century we used simulation results forced using SRES scenarios B1, A1B, and A2 (IPCC, 2000). These scenarios are described in the following paragraphs. The data sets of temperature and precipitation data (within a period of 1901 to 2100 for the ECHAM5 model and 1900 to 2099 for the

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[1] We acknowledge the international modelling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organising the model data analysis activity, and the IPCC WG1 TSU for technical support. This work, including access to the data and technical assistance, is provided by the Model and Data Group (M&D) at the Max-Planck-Institute for Meteorology, with funding from the Federal Ministry for Education and Research and by the German Climate Computing Centre (DKRZ).

HADCM3 model) were downscaled to the regional level of the case study area by using the statistical downscaling technique of Bouwer et al. (2004).

2.1.1 SRES Scenarios B1, A1B, and A2

These scenarios were developed for and described in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000). The SRES describes 40 different emission scenarios, each making different assumptions about future emissions of greenhouse gases, land use, and other driving forces. The B1, A1B, and A2 scenarios lie towards the lower, middle, and upper section of the full spectrum of IPCC scenarios respectively (in terms of projected temperature change by the end of the 21st Century), and can therefore be used to assess climate change under a broad range of possible futures.

The B1 scenario describes a convergent world with the same global population by 2100 AD (compared to 1990 AD), peaking in the mid 21st Century and declining thereafter. The scenario assumes rapid change in economic structures towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, but without additional climate incentives. Compared to the baseline concentration of atmospheric CO_2 in 1990 AD (ca. 367 p.p.m.), the B1 scenario prescribes an increase to ca. 540 p.p.m. by 2100 AD (according to the Bern model).

The A1B scenario describes a world of very rapid economic growth, global population that peaks in the mid 21st Century and declines thereafter, and the rapid introduction of new and more efficient technologies. The major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. This scenario assumes a balance across fossil intensive and non-fossil energy sources. Compared to the baseline concentration of atmospheric CO2 in 1990 AD (ca. 367 p.p.m.), the A1B scenario prescribes an increase to ca. 703 p.p.m. in 2100 AD (according to the Bern model).

The A2 scenario describes a very heterogeneous world. The underlying theme is one of self-reliance and the preservation of local identities. Fertility patterns across regions converge very slowly, resulting in continuously increasing population. Economic development is mainly regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines and scenarios. Compared to the baseline concentration of atmospheric CO2 in 1990 AD (ca. 367 ppm), the A2 scenario prescribes an increase to ca. 836 p.p.m. by 2100 AD (according to the Bern model).

2.2 Downscaling

The raw data from the HADCM3 and ECHAM5 models were imported for the scenarios described above. HADCM3 has an equidistant grid with a spatial resolution of 3.75° in longitude and 2.5° in latitude. ECHAM5 has a spatial resolution of 1.875° in longitude and ca. 1.875° in latitude. These resolutions are rather coarse for use in regional impact assessment studies (Arnell et al., 1996; Bouwer et al., 2004; Kleinn et al., 2005; Wood et al., 2002, 2004). Hence, the data were downscaled to a higher spatial resolution. Bouwer et al. (2004) identify two main approaches to downscale climate data for use in regional impact assessments: statistical methods that transform the data in such a way as to match the main statistical properties of modelled and observed climate data sets (e.g. Bouwer et al., 2004; Wilby and Wigley, 1997; Wilby et al., 1998; Wood et al., 2002); and dynamical approaches that use finer resolution regional circulation models (RCMs) nested within coarser GCMs (e.g. Cocke and LaRow, 2000; Kim et al., 2000; Murphy, 2000; Wood et al., 2002; Yarnal et al., 2000). The results of these two approaches have been found to have similar levels of skill, with different methods performing better or worse dependent on the region of study (Wilby et al., 2000; Wood et al., 2004), but dynamical methods are computationally far more demanding (Bouwer et al., 2004). Hence, in this study we chose to use a statistical downscaling technique.

Statistical downscaling involves the use of correction factors (for temperature additive and for precipitation multiplicative), which are applied to the low resolution model data so as to preserve the statistical properties of a higher resolution observed (baseline) dataset. In this study the spatially explicit correction method based on monthly averages as described by Bouwer et al. (2004) was used. For the observed baseline datasets of precipitation and temperature, the Climate Research Unit (CRU) CL 2.0 dataset (New et al., 2002) was used. This dataset shows climatology for the period 1961-1990 for the whole world with a spatial resolution of 10’ x 10’, and is available at http://www.cru.uea.ac.uk/cru/data/hrg.htm. No correction was made to preserve the variance of the downscaled data, since observed temperature and precipitation time-series data were not available at the 10’ x 10’ resolution.

The downscaling involves two steps. The first step is a spatial downscaling procedure (Bouwer et al., 2004), whereby the values from the low resolution GCM are simply resampled onto a grid of 10’ x 10’; this resolution was selected as it is the same resolution as the CRU climate data. In the study region of this project, a resolution of 10’ x 10’ corresponds to ca. 18.47 km x 18.72 km. The spatially downscaled GCM data are then statistically downscaled using the following formulae:

$$p'_{\mathrm{GCM}(m,i)} = p_{\mathrm{GCM}(m,i)} \times \left(\frac{\overline{p}_{\mathrm{CRU}(m,i)}}{\overline{p}_{\mathrm{GCM}(m,i)}} \right) \quad (2.1)$$

where $p'_{\mathrm{GCM}(m,i)}$ is the statistically downscaled GCM precipitation for a particular month, *m*, and cell, *i*, $p_{\mathrm{GCM}(m,i)}$ is the spatially downscaled raw GCM precipitation data for a particular month, *m*, and cell, *i*, $\overline{p}_{\mathrm{CRU}(m,i)}$ is the observed (CRU) average monthly precipitation for a particular month, *m*, and cell, *i*, and $\overline{p}_{\mathrm{GCM}(m,i)}$ is the spatially downscaled raw GCM mean monthly precipitation for a particular month, *m*, and cell, *i*.

$$t'_{\mathrm{GCM}(m,i)} = t_{\mathrm{GCM}(m,i)} + (\bar{t}_{\mathrm{CRU}(m,ii)} - \bar{t}_{\mathrm{GCM}(m,i)}) \quad (2.2)$$

where $t'_{\mathrm{GCM}(m,i)}$ is the statistically downscaled GCM temperature for a particular month, *m*, and cell, *i*, $t_{\mathrm{GCM}(m,i)}$ is the spatially downscaled raw GCM temperature for a particular month, *m*, and cell, *i*, $\bar{t}_{\mathrm{CRU}(m,i)}$ is the observed (CRU) average monthly temperature for a particular month, *m*, and cell, *i*, and $\bar{t}_{\mathrm{GCM}(m,i)}$ is the spatially downscaled raw GCM mean monthly temperature for a particular month, *m*, and cell, *i*.

2.3 Validation of downscaled climate data

In order to validate the downscaled climate data, they were compared with observed climate data from weather stations. Comparisons were made for weather stations located in the region. The weather station data is supplied by the Instituto Nacional de Recursos Naturales from the Ministry of Agriculture.

In Figures 2a and 2b the monthly observed precipitation and temperature values are compared to the downscaled GCM data (ECHAM5). Table 1, shows mean annual observed and simulated precipitation. Also shown are the results of the t-test to establish whether there is a statistical correlation between the annual means of the two datasets, and the F-test to establish whether there is a statistical difference between the variability of annual observed and modelled precipitation. For Ocoña there is no statistical difference between the mean or variability of the observed and simulated annual precipitation datasets, for Chichas there was (2-tailed test, $\alpha = 0.05$).

Table 1 Comparison of observed and downscaled ECHAM5 precipitation data for the period 1961-1990.

Station	Mean annual observed precipitation (mm)		Mean annual modelled precipitation (mm)	t-test (p)	F-test (p)
Ocoña	2.7	Echam	3.4	0.958	0.015
Chichas	280	Echam	338	0.732	0.760
Significant if:	t-test p > 0.95 f-test p < 0.05				

Figure 2a and 2b show the observed climatic information for Ocoña, together with the simulated data. For both precipitation and temperature the values do not differ significantly.

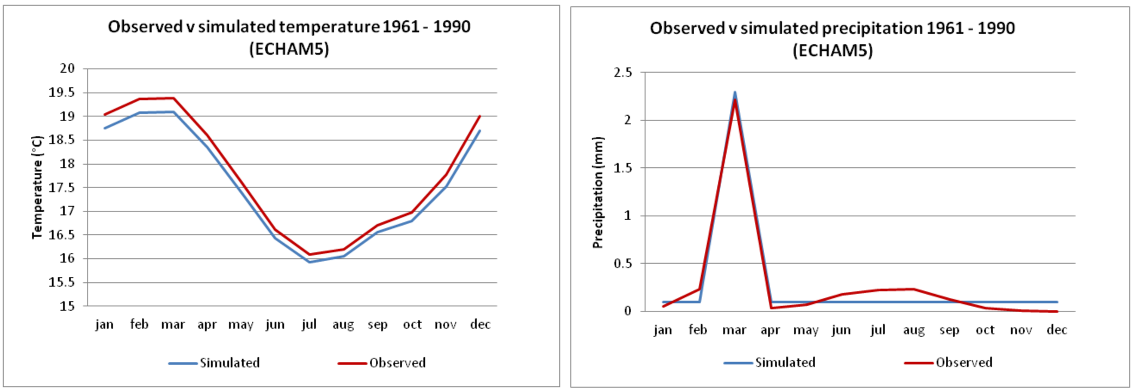

Figure 2a Graph showing the agreement between mean monthly simulated and observed precipitation and temperature at Ocoña for the period 1961-1990 (ECHAM5)

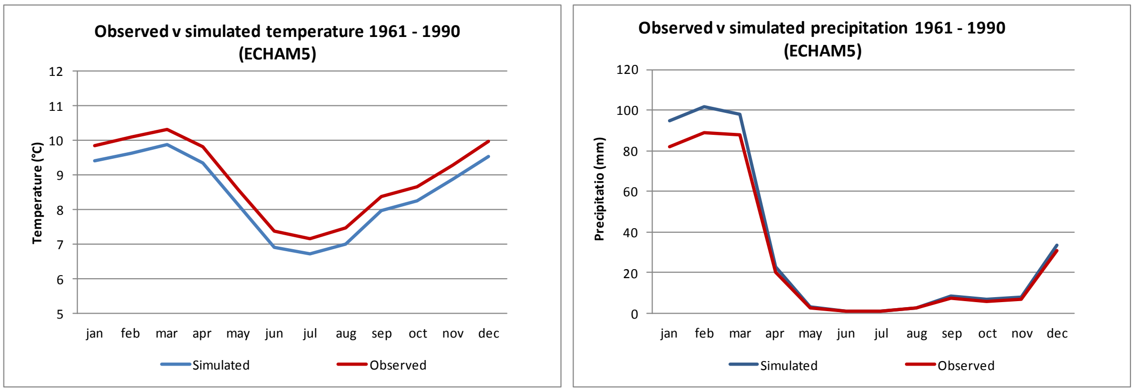

Figure 2b Graph showing the agreement between mean monthly simulated and observed temperature and precipitation at Chichas for the period 1961-1990 (ECHAM5)

2.4 Hydrologic modelling

The ADAPTS case study area is located in the basin of the Ocoña River. So we focused on this river when we developed a hydrologic model to simulate the effects of future climate change on the discharge. For this purpose we used the STREAM hydrologic model to simulate changes in monthly discharge under the climate scenarios described under paragraph 3.2.

STREAM is a grid-based spatially distributed water balance model that describes the hydrological cycle of a drainage basin as a series of storage compartments and flows (Aerts et al., 1999). It is based on the RHINEFLOW model of Kwadijk (1993), and uses a raster GIS database to calculate the water balance of each grid cell per month. The water balance is calculated using the Thornthwaite (1948) equations for potential evapotranspiration and the Thornthwaite and Mather (1957) equations for actual evapotranspiration; these equations use temperature and precipitation as the major input parameters. For each month, the model generates runoff, groundwater storage (shallow and deep), snow cover, and snow melt. The direction of water flow between cells is based on the steepest descent for the eight surrounding grid cells on a digital elevation model (DEM). The main flows and storage compartments used to calculate water availability per cell are shown in Figure 3. In this study the model was set up at a resolution of 10' x 10', since this is the resolution of the climate input data.

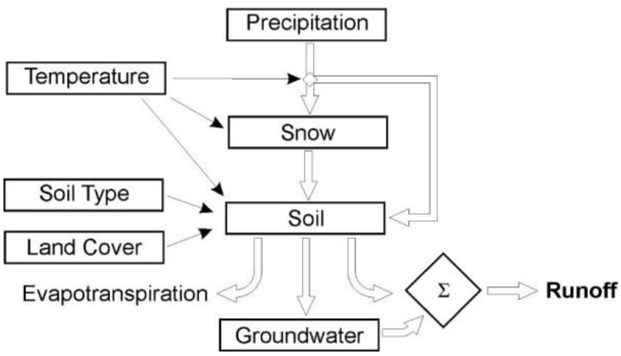

Figure 3 Flowchart showing the main storage compartments and flows of the STREAM model (Aerts et al., 1999).

STREAM (or its predecessor RHINEFLOW) has been successfully applied to numerous basins of varying sizes in different parts of the world for studies of the 20th and 21st Centuries, e.g. the Rhine in Europe (Van Deursen and Kwadijk, 1994a); the Ganges-Brahmaputra and Krishna in India (Bouwer et al., 2006; Van Deursen and Kwadijk, 1994b); the Yangtze in China (Van Deursen and Kwadijk, 1994b); and the Perfume River in Vietnam (Aerts and Bouwer, 2002a). Moreover, Aerts et al. (2006) and Ward et al. (2007) applied the model to numerous large basins around the to simulate changes in discharge over periods of thousands of years. It is also the standard hydrological model used in the ADAPTS project.

2.4.1 Model input data

To set up the STREAM model a GIS database of input maps was created, using the IDRISI Kilimanjaro software and ArcGIS (Belinfante, 2009; Singh, 2009). The various input data files are described in this section; all input maps have a spatial resolution of 10' x 10'.

Climate data

Maps showing monthly precipitation (mm) and temperature (°C) were prepared for the entire study area as described in Sections 3.1 to 3.3.

Land use data

A land use map is used to generate a map of crop factors. The crop factor is a dimensionless factor by which the reference *PE* is multiplied in order to account for the difference in *PE* over different land use types. The land use map on which the crop factors are based originates from the USGS Geological Survey. This map has a resolution of 1 km x 1 km (resolution GLC2000), and was re-projected onto a 10'by 10' (18.47 km x 18.72 km) grid for this study. The land use classes were then reclassed into so-called crop factors (CropF). A crop factor map is used in STREAM to calculate potential evapotranspiration (*PE*). The land use classes were reclassed to crop factors based on values in Kwadijk (1993) and Aerts and Bouwer (2002b), as shown in table 2.

Table 2 Land use classes and their associated crop factors, reclassed according to values in Kwadijk (1993) and Aerts and Bouwer (2002b).

Land use class	Crop factor (CropF)
Urban and built-up land	0.8
Dryland cropland and pasture	1.0
Cropland/grassland mosaic	0.9
Cropland/woodland mosaic	1.0
Grassland	0.8
Shrubland	0.8
Savannah	0.6
Forest	1.1
Water bodies	1.5
Wetlands	1.1
Barren or sparsely vegetated	0.5

Soil water holding capacity

A map showing the maximum water holding capacity (WHC) of the soil (mm) is used in STREAM in the calculation of evapotranspiration, runoff, groundwater seepage, and baseflow. We used world soil information map of ISRIC in this study (www.isric.org/NR/exeres/BC5BB444-DB94-4FE3-B102-2872B0B1A9F1.htm). The map is available at a spatial resolution of 50 km x 50 km (scale 1:5 million), and resampled to the resolution of our STREAM model.

DEM

A DEM (digital elevation model) is used in STREAM to route the flow of water through the basin; the direction of water flow between grid cells is based on the steepest descent for the eight surrounding grid cells. For this study we used elevation data from CGIAR (Consortium for Spatial Information) and converted this into a DEM in ArcGIS. The information from the DEM is used to create a flow direction map (BPGLDD) for STREAM. The flow direction map provides the direction of flow per cell.

Calibration and validation

The STREAM model is calibrated by varying model parameters with the aim of reproducing annual and monthly discharge characteristics similar to those in the observed record. The parameters used for calibration are: CropF; WHC; HEAT (used in the Thornthwaite (1948) equation for calculating potential evapotranspiration); TOGW multiplier (determines the proportion of surplus water per grid cell that runs off directly or that seeps to the groundwater); and the C factor (determines the proportion of groundwater that contributes to baseflow).

For the Ocoña river several datasets with measured runoff data are available. The available sets of tributaries of the Ocoña are: Rio Pararca, Rio Pacapausa, Rio Maran, Rio Cotahuasi, Rio Arma-Chichas, Rio Chorunga and downstream the Ocoña at Ocoña city. For calibration purposes the data from the Arma-Chichas and Ocoña were used (Belinfante, 2009). The performance for the model is summarised in table 3 and shown in figure 4. They show that the model performs well overall, with an overestimation of runoff in March.

Table 3 Results of statistical analysis comparing measured discharge series (2003-2007) and modelled discharge series for the base line scenario (1961-1990) at Ocoña. % refers to the annual mean simulated discharge as a percentage of the observed discharge. Also shown are the probabilities associated with the t-test and F-test of annual discharge, and the correlation coefficient (r) and N&S correlation coefficient between the mean monthly simulated and observed discharges.

	%	t-test (p)	F-test (p)	r	r^2	N&S
	111	0.98	0.41	0.95	0.90	0.999
Significant if:					*N&S efficiency 0 ≤ E ≤ 1* *Correlation coeff. r > 0.708*	

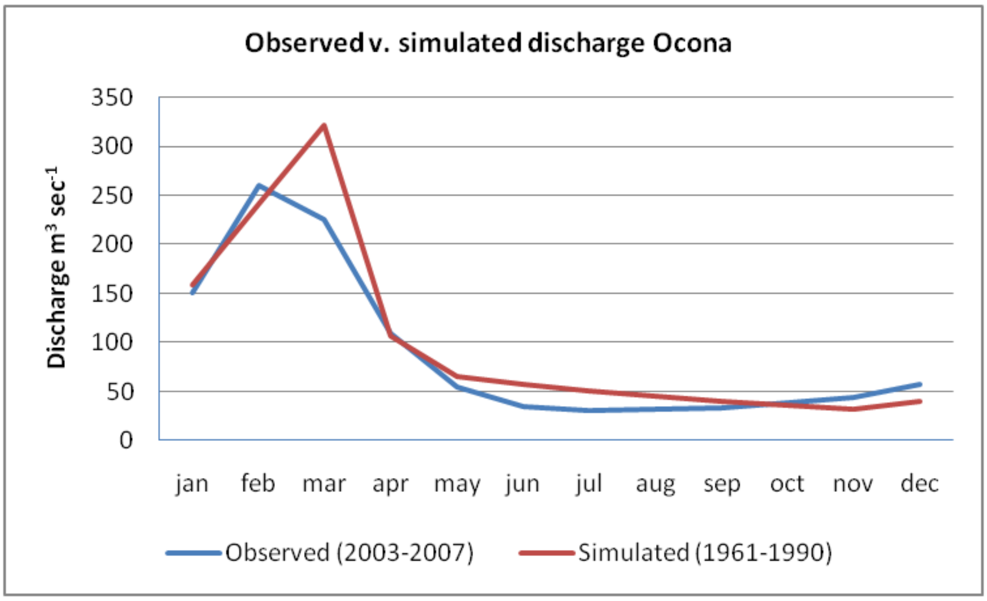

Figure 4 Discharges observed (2003-2007) and simulated for 20c3m scenario (1961-1990) for the Ocoña river at Ocoña.

3 Results

The main objectives of this study are to provide a dataset, consisting of maps and graphs showing the possible short, medium, and long-term changes in annual and monthly precipitation and temperature in the study region; and to assess the effects of these climate changes on the discharge of the Ocoña River, with special attention on the timing of water availability in a warming climate. These projected changes in climate can be used by regional and local stakeholders in the assessment of adaptation requirements and possible adaptation strategies, for instance in the development of a Integrated River Basin Management Plan (IRBM) for the Ocoña river. Based on these datasets, stakeholders and decision-makers in the region can make informed decisions on the need for adaptation measures to adapt to climate change.

The results of the study are given for three locations in the basin; at the summit of the Coropuna glacier, at Chichas which is located in the research area of ADAPTS and is the proxy for other agricultural areas of the basin and at the river mouth at Ocoña city. For all of the graphical results relating to the SRES emission scenarios, we have used the same colour coding as adopted in the Fourth Assessment Report (AR4) of the IPCC (IPCC, 2007), i.e. B1 in green, A1B in red, and A2 in yellow. This allows for direct and easy comparison with other results to be found in the AR4 (and related studies).

3.1 Summary assessment of regional climate change results

The projected changes in mean monthly temperature, precipitation and runoff, which are the result of the modelling exercise using the ECHAM5 climate data, are presented in graphs per region in this chapter. For each location the following graphs are shown:

1. mean monthly projected precipitation for 2020 for the three scenarios B1, A1b and A2 (2006-2035) and the baseline period (1961-1990);
2. mean monthly projected precipitation for 2050 for the three scenarios B1, A1b and A2 (2036-2065) and the baseline period (1961-1990);
3. mean monthly projected precipitation for 2075 for the three scenarios B1, A1b and A2 (2061-2080) and the baseline period (1961-1990).

The graphs show the mean monthly temperature and mean monthly runoff for the same periods for the different locations in the basin. It should be noted that the black line indicating the trends in long term 20th Century mean annual precipitation and temperature are based on the downscaled climate model results, and not observed values. Hence, the values shown here cannot be compared with the observed data on a year to year basis, as climate models do not simulate actual weather in an observed year, but rather the average climate over a longer time-period. We start upstream with Coropuna, followed by Chichas and ending with Ocoña.

For Coropuna the temperature for the period 2020 is projected to be 1.0 to 1.2 degrees higher than the temperature of 1990 (see figure 5). The difference between the scenarios is small. For 2050 the projected temperature will be between 1.9 to 2.6 degrees higher than for 1990. For 2075 the projected temperature will be 3.4 to 5.1 degrees above the average temperature of 1990, there is also a wider gap between the B1 and A1b and A2 scenario. Such a rise in temperature would lead to a change in the type of precipitation that occurs at the Coropuna mountain. More precipitation will be in the form of rain and a smaller portion will be in the form of snow. Also the thawing season will become longer, leading to more melt of the icecap. The mean annual temperature for 1990 is above 0 degrees while the top of the mountain is covered in snow and ice. Because the model gives average outputs for a cell of 18.47 km x 18.72 km, the part covered in snow is too small to be visible in the average.

Precipitation outcomes for Coropuna for the time slices 2020, 2050 and 2075, show a reduction in projected total precipitation of minus 31 to 94mm, 91 to 124mm, and 93 to 144mm for the respective time slices. The projected rainy season begins at the same period as 1990, for the 3 future periods. However, the projected precipitation drops in the months February and March. For the latter month the total precipitation in 2075 will be half of that in 1990. As the Coropuna is the start of the Ocoña river, we do not have results on runoff for this region.

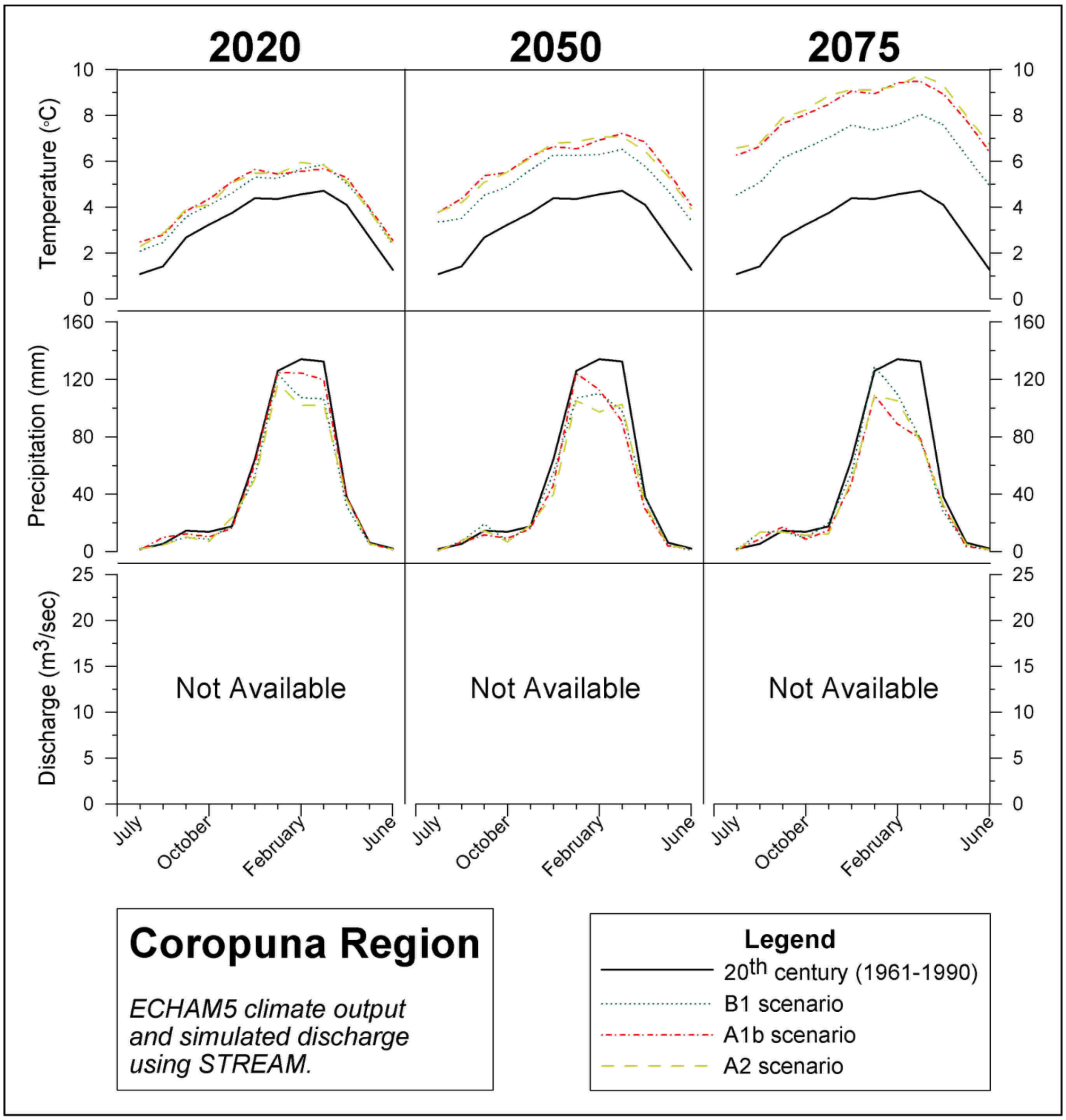

Figure 5 Change in temperature, precipitation and discharge for the Coropuna region for 2020, 2050 and 2075.

Figure 6 presents graphs showing the projected changes in mean temperature, precipitation and modelled runoff for 3 periods for the Chichas region. Projected temperatures will rise around 1 degree in 2020 up to 5.1 degrees in 2075. For 2020 a small decrease in precipitation is projected, 3 to 5 mm. For 2050 and 2075 decreases in precipitation between 63 and 99mm compared to 1990 are projected. Compared to the average yearly precipitation of 373mm during the reference period, this is a reduction of almost 27%. This projected rise in temperature and reduction in precipitation leads to a reduction in modelled discharge from 7% to 31% in 2020 up to 54% to 73% in 2075. The reduction in modelled discharge is most profound during the rainy season, from January to March, For 2050 and 2075, base flow (July-December) reduces up to 70 % (2.5m^3/sec).

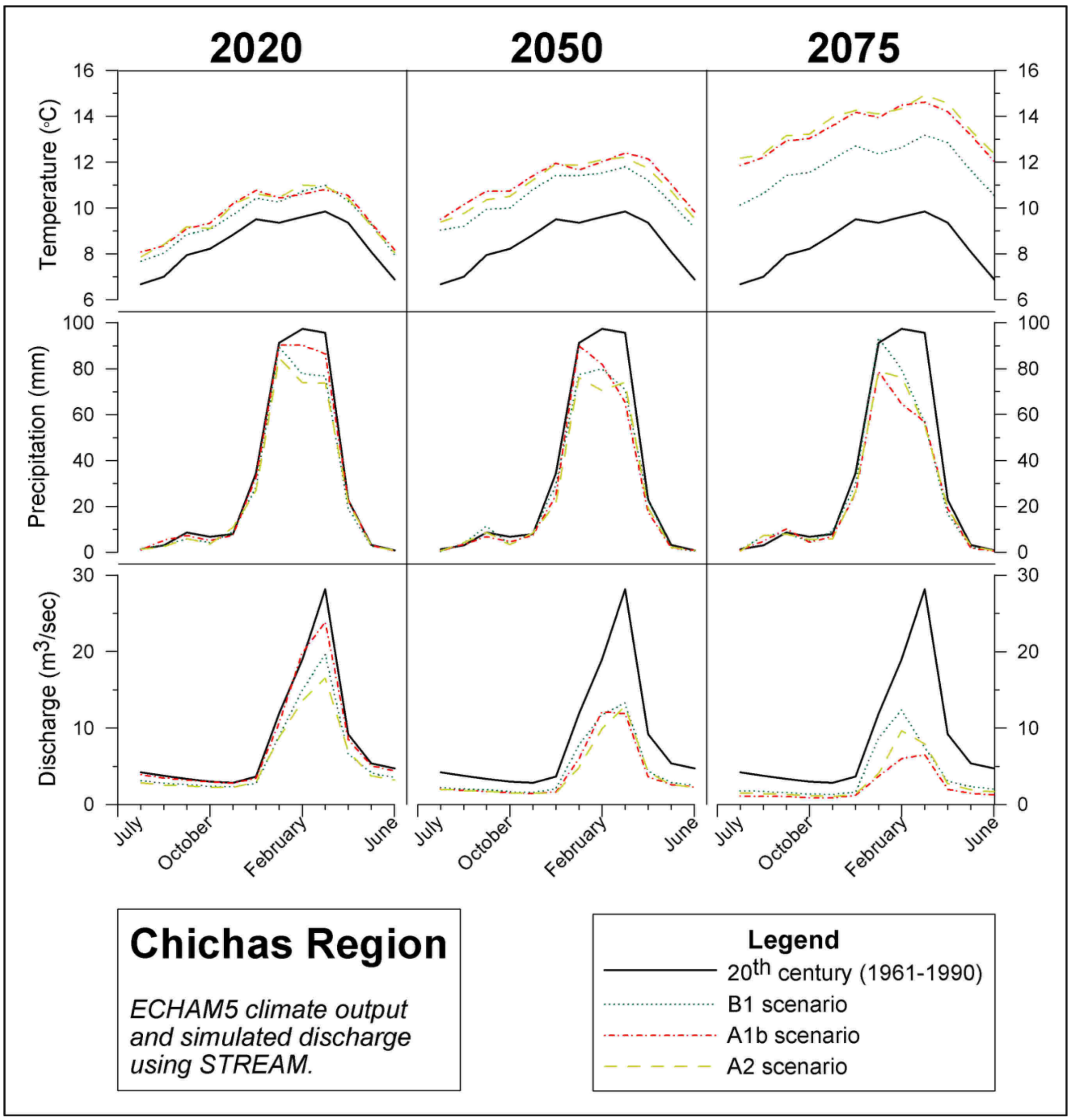

Figure 6 Change in temperature, precipitation and discharge for the Chichas region for 2020, 2050 and 2075.

The results of the ECHAM climate model shows a steady rise in projected average temperature for Ocoña from to 1.8 C in 2020, to 1.9 to 2.5 in 2050, to 3.1 to 4.8 degrees in 2075. For 2075 the B1 scenario shows the most modest change for all factors, while A1b and A2 show similar changes. Average yearly precipitation at Ocoña is low, around 3.4mm, so absolute changes in precipitation are also small. The largest projected change is under the A2 scenario in 2075, under this scenario average yearly precipitation is 2.8mm. Discharge is projected to decrease, in 2020 the reduction will be from 56 to 206m^3/s. For 2075 projected average yearly flow will reduce between 256 to 445m^3 /sec. This decrease mostly takes place during the high flow period, from January to March. The modelled flow during this period reduces between 130 to 240m^3/s.

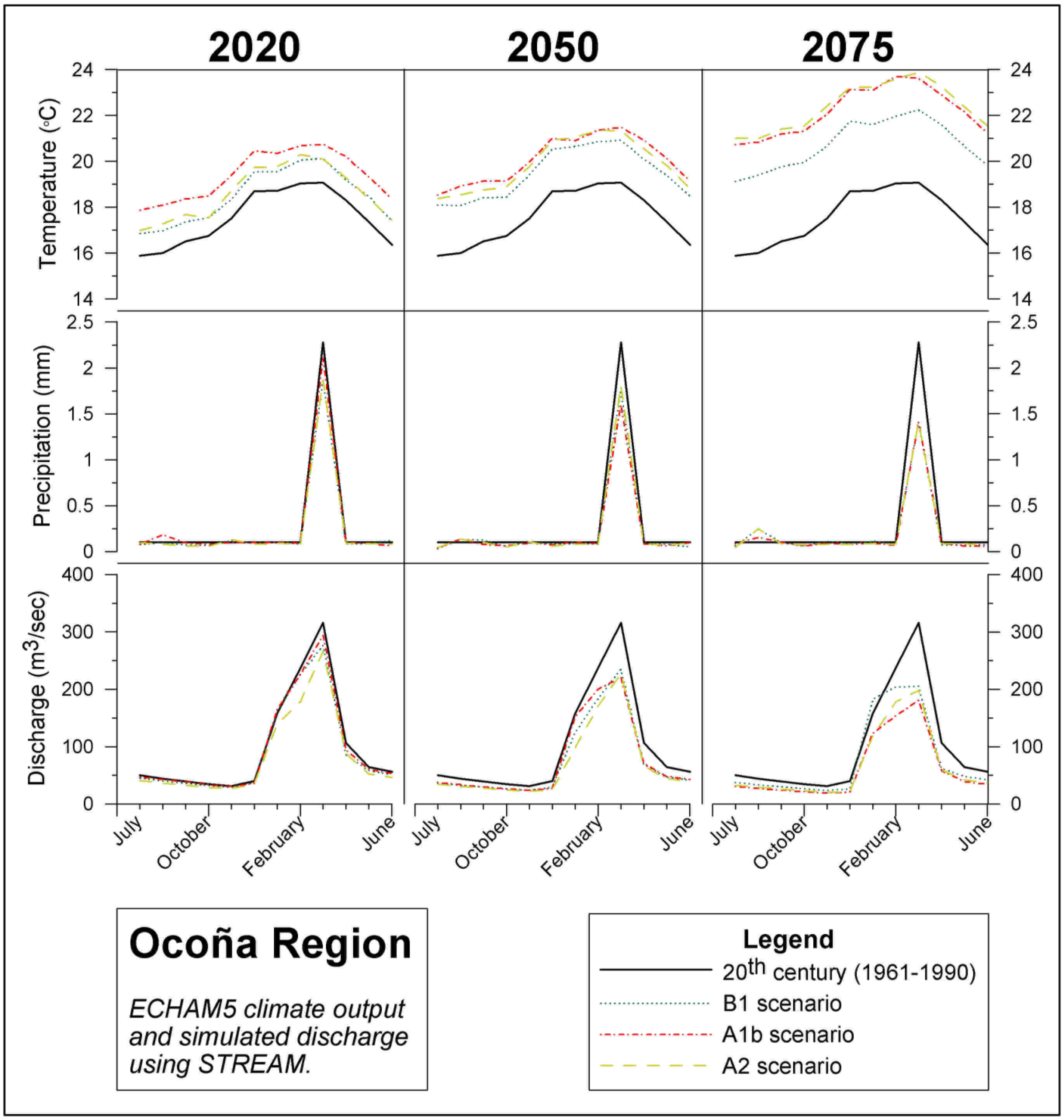

Figure 7 Change in temperature, precipitation and discharge for the Ocoña region for 2020, 2050 and 2075.

Table 4 shows the results of a study on the impacts of climate change on different climatic zones of Peru, according to 7 GCMs (Senamhi, 2009). Changes in yearly precipitation are comparable to the changes we have found in our study for the period 2050, and a bit higher than our results for 2020. For temperature our study finds larger changes for 2020 than the study of the Ministry of Environment. For the mountainous areas our study projects and increase of 1 to 1.2 degrees for the period 2020, compared to 0.4 to 0.8 degrees for the Ministry of Environment.

Table 4 Results of climate change study 2030 by the Ministry of Environment Peru (Senamhi, 2009)

	Min. temp.	Max. Temp.	Precipitation
Southern mountains	+ 0.4 to 0.8	+ 0.4 to 0.8	-20%
Southern coast	+ 0.0 to 0.4	+ 0.0 to 0.4	-20%

4 Conclusions, Implications and Recommendations

This study produced downscaled climate data available for the Ocoña River for the ECHAM5 model. The results of the downscaling of Hadley data were assessed to be incorrect, probably due to the used downscaling method. The Hadley data have not been used further and are not presented in this report. The STREAM model developed for this study performed well for most of the basin on average runoff and runoff variability.

The projected change in temperature for the different time slices (2020, 2050 and 2075) is comparable for Chichas and Coropuna, and projected temperature increase is slightly smaller for Ocoña. The projected temperature increases is nearly the same for all the months. The same applies to the projected change in precipitation in the basin. The reduction in projected precipitation however, mostly takes place during the months January to March, which is the rainy season.

These results are in line with the findings of Haylock et al. (2006), who analysed changes in precipitation for the period 1960 to 2000, and saw a decrease in precipitation in Southern Peru. The assessment of projected changes for different GCMs by the Ministry of Environment shows lower increases in temperature for 2030 compared to this study, namely plus 0.5 compared to plus 1 degree Celcius, and larger decreases in projected precipitation than our study, minus 20% compared to an average of 13% for the three scenarios for our study. As we are looking at results originating from models, it is expected there are differences between the different models and studies, leading to a range instead of one number.These small differences between these two studies might also be the result of scale of the analysis. For our study we focus on single cells for information for the three locations in the basin. These cells have a size of circa 18.5 by 19 km (10' by 10'). The study of the Ministry of environment gives the results for larger areas, thus calculating an average for multiple cells, and also uses the results of 7 GCMs, where we use only one.

The projected changes in temperature and precipitation lead to more profound changes in modelled discharge. Reduction in precipitation together with increase in temperature leads to reduction in water availability. Also, the increase in the projected temperature affects the form of the precipitation. At present, much of the precipitation is snow in the high areas of the region. In the future, a greater proportion of this is likely to fall as rain. Moreover, instead of being stored in snow and ice on the mountains, this rain will flow to the river directly. This leads to a decrease in (base flow) water levels in the Ocoña river. This projected reduction in water availability will affect farmers who use this water for irrigation of their lands. In the future, it is likely that less water will be available for irrigation and it would be advisable to develop measures to meet these changing circumstances.

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