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Rainfall and Runoff changes in South America during the twenty-first century: A comparison of HadGEM1and the CMIP3 MultiModel Ensemble

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Rachel N. McInnes, Inika H. Taylor,
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Contents

1 Introduction

Observations of climate in South America have shown that precipitation has increased in southern Brazil, Paraguay, Uraguay, north-eastern Argentina and north-west Peru and Ecuador. Rainfall has decreased in southern Chile, south-west Argentina and southern Peru [Magrin et al., 2007]. Consistent with a warming climate, there is an increasing tendency for rain to fall in intense events followed by several dry days. This trend has been observed over north-eastern Brazil. However, a lack of long-term measurements of daily precipitation in many tropical areas of Brazil means there is no conclusive evidence for trends in precipitation in many areas [Christensen et al., 2007].

Many people in South America live in areas with limited availability of fresh water, and the numbers are likely to increase. Reductions in precipitation and runoff could also severely reduce hydroelectric power generation. Water availability in many river basins of South America is currently very good, but varies considerably with the El Niño and La Niña (ENSO) cycles. For example, in the Magdalena river basin the mean flow can be reduced by 55% [Magrin et al., 2007]. In Brazil, a combination of drought and high demand caused a virtual breakdown in hydroelectric generation in 2001 [Kane, 2002].

Minuzzi et al. [2007] analysed daily precipitation data from 203 pluviometric stations located in the southeast region of Brazil, and studied data for the rainy season recorded between 1950 and 2000. In the areas North and Vale do Jequitinhonha, which are in Minas Gerais state, the rainy period generally begins between October 23rd and November 2nd, and lasts between 136 and 155 days. The duration and the dates at the beginning of the rainy period were found to be strongly correlated, as well as the precipitation total and the duration of the rainy period in practically the whole southeast region of Brazil. From the middle of the 1970s, the rainy period has started earlier and lasted longer in the southeast region of Brazil. Larger amounts of precipitation have only occurred in the southeast of Minas Gerais state and in the State of São Paulo.

An assessment of the global climate models by the Intergovernmental Panel on Climate Change (IPCC; Christensen et al. [2007]) showed that these models were poor at reproducing regional precipitation patterns. The IPCC WGI divided South America into two large regions (north and south) for their assessment, but acknowledged that these divisions hid large regional differences in precipitation. In this report, we examine precipitation and runoff changes in the major river basins in the continent from all models which were used in the IPCC Fourth Assessment Report (AR4), with a focus on the performance of the Hadley Centre's global climate model HadGEM1. Assessing precipitation and runoff changes in river basins will be of great use for adaptation studies. These results could assist planning of hydroelectric power generation and resilience to flooding events in the future.

2 Data Sources

In this section, the observations and climate model data used in this study are described. Observational data of precipitation in Brazil and surrounding countries, and model data are all available on regular grids. However, all of these data sources use different grids. To facilitate analysis, the river basin maps, observed precipitation data and all global climate model data were interpolated to the same resolution as the HadGEM1 climate model (the resolution is 1.875° longitude by 1.25° latitude; Johns et al. [2006]). The river basin mapping is described in section 2.1, the observations are described in Section 2.2, and details of the global climate models used are given in Section 2.3.

2.1 River Basins in South America

This study focused on precipitation and runoff in the main river basins in South America. The classification and definition of a river basin is not necessarily consistent between datasets. This study has been based on the 18 main river basins in South America as defined by the river routing model TRIP[1] (Total Runoff Integrated Pathways, Oki and Sud [1998]). A map showing the 18 river basins studied in this paper is shown in Figure 1. The TRIP dataset does not identify any other river basins. Even if it did, it is unlikely that smaller basins could be resolved adequately by global climate models.

2.2 Precipitation Observations

Gridded observations of monthly mean precipitation averaged over the period 1961–1990 were obtained from the IPCC Data Centre. These gridded data were created by New et al. [1999] at a resolution of 0.5° by 0.5° from a global network of rain gauges. The data for South America were extracted and regridded to the same resolution as the HadGEM1 model.

[1] http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html

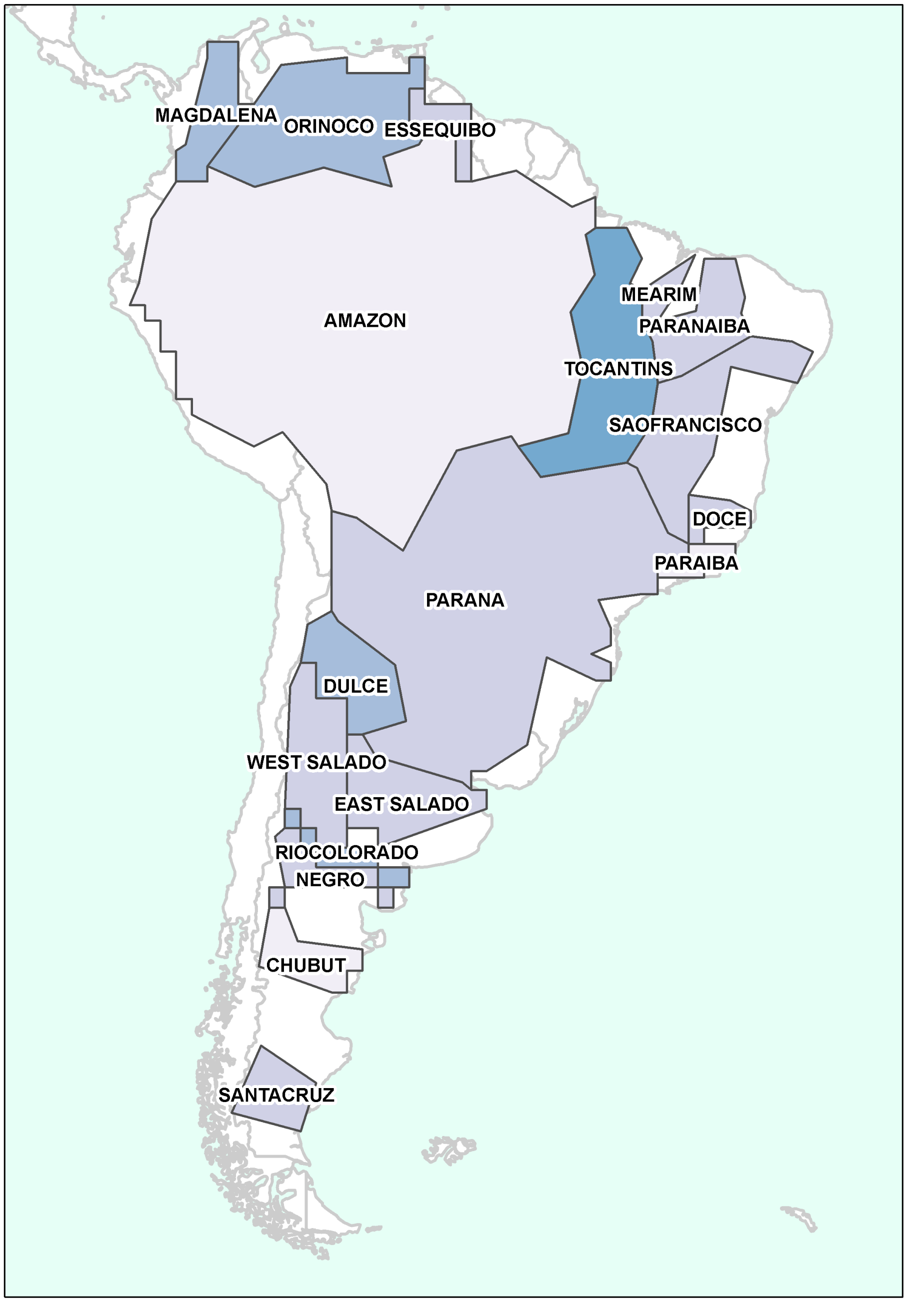

Figure 1: Map showing the positions of river basins in South America used in this study, as defined by the TRIP model [Oki and Sud, 1998]. This map was created using river basin data on with a 1° by 1° resolution.

2.3 Global Climate Model Data

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) was based on climate projections provided by many modelling centres around the world. The climate model data are referred to as the AR4 MMD (multi-model dataset). Modelled precipitation and runoff data for the period 1961–1990 from the AR4 MMD were obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI[2]). This set of simulations (referred to as '20C3M' in the PCMDI archive) used measured levels of greenhouse gases and emissions of aerosols to recreate the climate of the 20th century. Projections of future precipitation and runoff for the period 2000–2100 under the SRES A1B scenario from the AR4 MMD were also obtained. This scenario assumes a mixture of fossil fuel and renewable energy sources will be used. Results from 24 different global climate models were analysed. The names of the models used in this study are listed in the Appendix, in Section A.1. Of the 24 AR4 MMD models, all were used for the analysis of precipitation. No runoff data were available for one model, and so data from only 23 models could be analysed.

3 Analysis Methodology

Both runoff and precipitation from the AR4 MMD will be analysed. Runoff is generally a better measure of water availability than precipitation. A significant fraction of any rain which reaches the surface will evaporate, and smaller amounts can be absorbed by soils and vegetation [Clark and Gedney, 2008]. Any remaining water can flow, under gravity, both above and below ground; this flow of water is referred to as runoff, and is the maximum amount of water that could be exploited. There are rain gauges in many parts of South America, which means modelled precipitation amounts and seasonal changes can be assessed (although coverage in some areas, such as the Amazon, is sparse). However, there are very few measurements of runoff, and not enough to assess the ability of climate models to simulate runoff. A model which reproduces observed precipitation amounts and patterns may be more likely to simulate runoff correctly [Nohara et al., 2006]. However, the models use a range of methods for simulating evaporation and flow of water which in turn will affect the simulation of runoff. Hence, even if two different models reproduced observed precipitation

[2]http://www-pcmdi.llnl.gov

characteristics equally well, they could still simulate different runoff amounts.

Simulated precipitation from the AR4 MMD for the baseline period, 1961–1990, was compared with the dataset created by New et al. [1999] for South America. The performance of each model, in reproducing observed magnitudes and patterns of precipitation, will be impacted by its resolution and the particular representations of climate processes that have been used. The projections of precipitation and runoff from the AR4 MMD for the twenty-first century were analysed using overlapping 30 year periods, which were referred to by their middle decade, starting with the 2020s (2010–2039), then the 2030s (2020–2049), and ending with the 2080s (2070–2099). These time periods are illustrated in Figure 2. Thirty years is the standard time period recommended by the World Meteorological Organisation for analysis of climate change. Changes in precipitation and runoff were expressed as percentages relative to the baseline period, 1961–1990. Using percentage changes in precipitation and runoff from the models minimises the impact of biases. In climate models, many atmospheric and oceanic processes have to be approximated, as the models cannot resolve all processes. These approximations, together with our incomplete understanding of the climate system, are a major source of uncertainty in climate projections. As a consequence of these approximations, climate models contain biases in their simulations of climate variables. For example, temperatures in some areas of the Earth may be cooler than observed values, while in other regions they may be too warm. For this reason, projections of future climate are usually assessed using changes in climate variables from a defined baseline (e.g. 1961–1990), as this approach minimises the impact of any biases. The precipitation and runoff data analysed have been converted to units of megalitres per hour (Ml hr^{-1}).

4 Precipitation Analysis

Precipitation amounts and seasonality from the AR4 MMD were compared with observations. First, monthly mean precipitation amounts from the models and observations for the period 1961–1990 were totalled in each river basin and compared. Then, the multi-model means were calculated and compared with each other and the observations. The minimum and maximum model for each time period for each river basin was calculated to give an overall minimum and maximum.

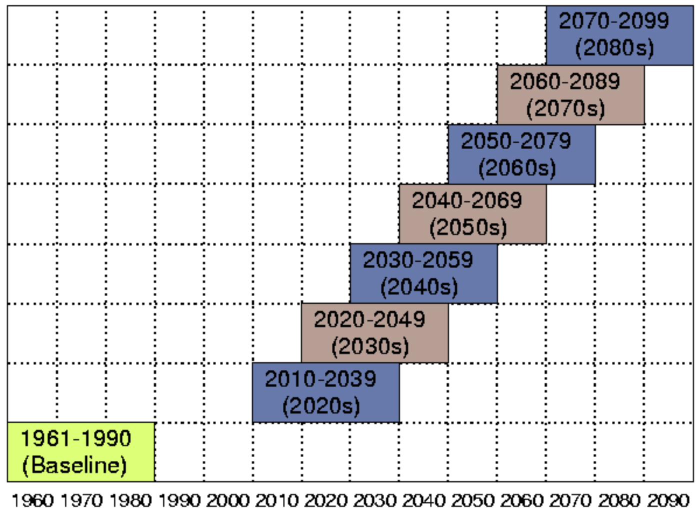

Figure 2: The baseline and seven future time periods over which the model projections were analysed. Each time period spans 30 years. For example, when the period 2040s are discussed in this paper, this means the period 2030–2059.

4.1 Comparison of Modelled and Observed Precipitation

The simulations of precipitation in each river basin from all models were compared with observed precipitation amounts and are shown in Figures 3, 4 and 5. The precipitation data are shown in units of megalitres per hour (Ml hr^{-1}). Simulations by individual models are shown by grey lines, apart from the HadGEM1 model which is shown in blue. The multi-model mean values are shown in red, and observed precipitation amounts are represented by black triangles. In most river basins, the majority of the models capture the seasonal cycles of precipitation in each river basin reasonably well, although there is a large spread in the modelled precipitation amounts, particularly during the wetter periods. In the Parana basin, the models tend to underestimate the precipitation during the drier months (May to September). For all basins, a few models either do not capture the seasonal cycle correctly, or the cycle is too weak.

The HadGEM1 model overestimates precipitation in the Amazon, Parana and Magdalene river basins, but does capture the seasonality of the precipitation reasonably well. All of the models overestimate precipitation in the Santa Cruz basin by almost an order of magnitude. In most of the other basins, the HadGEM1 model reproduces the seasonality and magnitude of precipitation quite well. It overestimates precipitation during the wetter periods in some of the basins (São Francisco, Paranaiba, Doce, Mearim and Paraiba). However, it reproduces the observations more closely than the multi-model mean in the Essequibo, Chubut, Negro, and Rio Colorado basins. Overall, it is concluded that the simulation of the magnitudes and seasonality of precipitation in each of the river basins by the HadGEM1 model is reasonable. The model tends to overestimate precipitation in some basins, but captures the seasonality well.

4.2 Assessments of Future Precipitation Changes

In the previous section, it was found that the HadGEM1 model captured the magnitude and seasonal cycle of precipitation reasonably well in most river basins. Here, the focus is on the projected changes in precipitation by the models for each of the future time periods (Section 3). Precipitation changes over South America from the AR4 MMD were analysed by Christensen et al. [2007]. These authors also showed that there are systematic errors in simulated current mean climate and its variability over South America, which makes an assessment of future changes in precipitation difficult. To illustrate this, a similar analysis to that of Christensen et al. [2007] was made. The percentage change in precipitation in December, January, February (DJF) and June, July, August (JJA) between the 2080s (2070–2099) and 1961–1990 are shown in Figure 6. A positive value indicates that future precipitation is greater than precipitation in the baseline period. Climate models are known to contain biases, which vary between different models and regions. It is implicitly assumed that the bias in a climate model does not change during a climate simulation (or that any change in the bias is negligibly small), so by using the change in precipitation and runoff from the model, the impact of any bias is minimised.

Following the method adopted by Christensen et al. [2007], if at least two thirds of the models (67%) in the AR4 MMD agree on the sign of the change in precipitation or runoff, then the change from the multi-model mean is considered to be robust; i.e., there is a strong signal from the models. The number of models which project an increase in precipitation is shown in the lower row of Figure 6. The areas of white space in the lower row are where less than 67% of the models project either an increase or decrease in precipitation, and thus areas where there is no signal from the models. There are large areas with no reliable signal in both DJF and JJA.

Rainfall is projected to increase over much of northern South America during December, Jan-

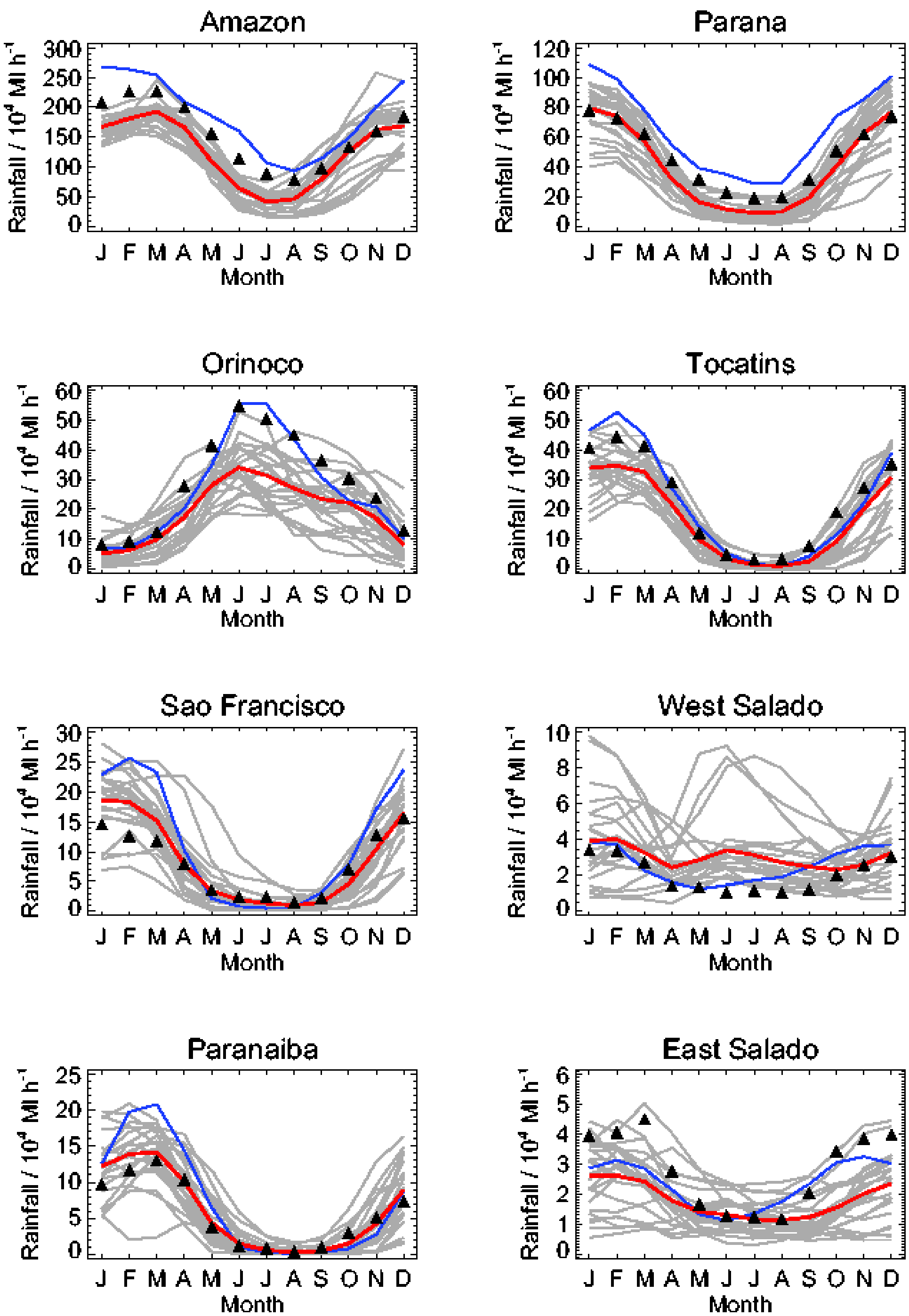

Figure 3: Comparison of modelled and observed monthly mean precipitation data for the period 1961–1990 over 8 river basins. The precipitation amounts are shown in each basin in units of Ml hr^{-1}. Each of the 24 models is shown by a grey line and the multi-model mean by the red line. The HadGEM1 line is shown in blue. Observations (from the data created by New et al. [1999]) are indicated by the black triangles.

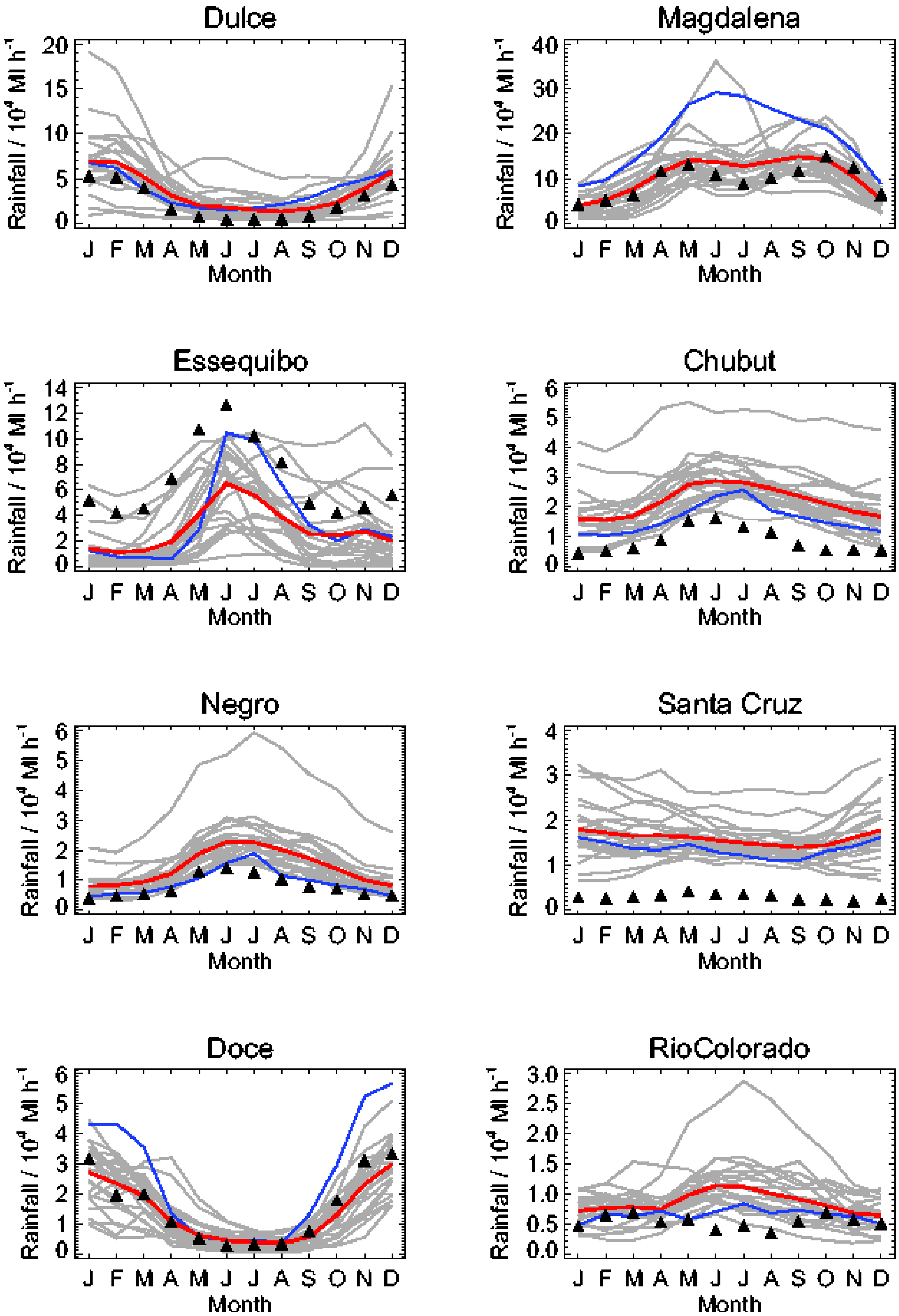

Figure 4: Comparison of modelled and observed monthly mean precipitation data for the period 1961–1990 over 8 river basins. The precipitation amounts are shown in each basin in units of Ml hr^{-1}. Each of the 24 models is shown by a grey line and the multi-model mean by the red line. The HadGEM1 line is shown in blue. Observations (from the data created by New et al. [1999]) are indicated by the black triangles.

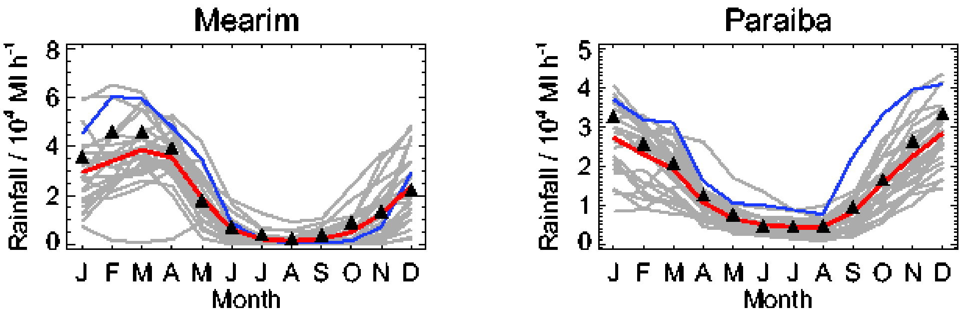

Figure 5: Comparison of modelled and observed monthly mean precipitation data for the period 1961–1990 over 2 river basins. The precipitation amounts are shown in each basin in units of Ml hr^{-1}. Each of the 24 models is shown by a grey line and the multi-model mean by the red line. The HadGEM1 line is shown in blue. Observations (from the data created by New et al. [1999]) are indicated by the black triangles.

uary, February (DJF; top-left panel of Figure 6), but decrease slightly over parts of the north eastern, eastern and south western edges. During June, July and August (JJA; top-right panel of Figure 6) large decreases in precipitation are projected over much of Brazil, up to 50%, and the decreases in JJA are larger than the increases in DJF. However, the lower two panels in Figure 6 show that model agreement over South America is poor in some areas (regions shown in white), and areas where agreement between the models is good change between seasons (areas shown in green and brown).

4.3 Changes in Rainfall in River Basins

Christensen et al. [2007] used fixed 3 month periods to define the seasons. However, the observed precipitation amounts in the river basins (Figures 3, 4 and 5) show that the wet and dry seasons do not necessarily last for 3 months. For example, in the Doce basin, the dry season appears to last from (approximately) May to September. The wet and dry seasons in each river basin were, therefore, identified using the following approach. First, the range of the modelled precipitation was calculated for each river basin, which was defined as the difference between the maximum and minimum monthly precipitation amounts (using 30-year averages for each month for the baseline period, 1961–1990). Wet and dry months were defined as those whose precipitation amounts (relative to the minimum value) lie above or below some percentage of the precipitation range. Dry

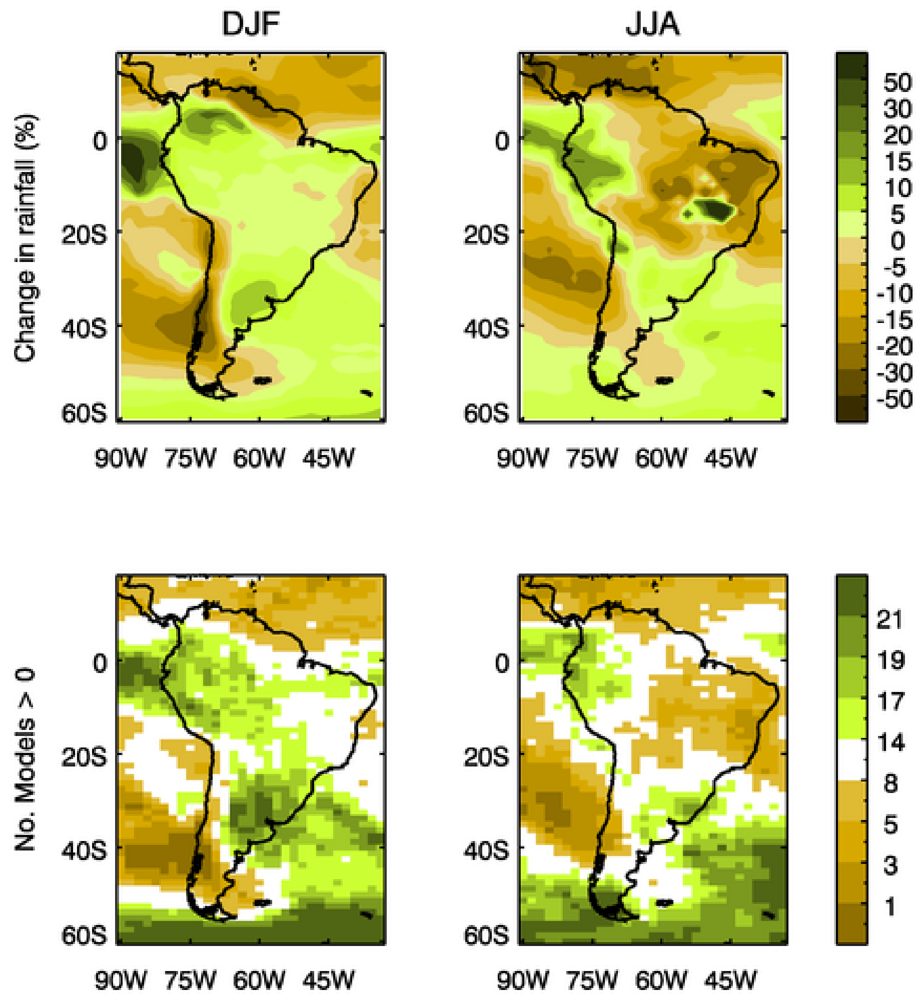

Figure 6: Projected precipitation changes over central and South America from the AR4 Multi Model Dataset under the A1B scenario, using 24 models (see Appendix Section A.1). Results for the wet season - December, January, February (DJF) - and the dry season - June, July, August (JJA) - are shown in the left- and right-hand columns respectively. Percentage changes in precipitation, averaged over all models, are shown in the top row. The bottom row shows the number of models that project an increase in precipitation. The coloured areas in the bottom row are where at least 16 out of 24 models (67%) agree on the sign of the change in precipitation, and so indicate those regions where a reliable signal from the models exists. The green colours indicate regions where precipitation is projected to increase, and the brown areas where precipitation could decrease. The white areas show where there is no reliable signal from the models. For example, the dark brown indicates that 1 model projects an increase in precipitation, therefore the remaining 23 models project a decrease in precipitation.

months were defined as those whose precipitation was 20% or less of the precipitation range, and wet months when the precipitation was 75% or more of the range. Figure 7 illustrates how these cuts were applied. These percentages were chosen to capture the appropriate months in each of the wet and dry seasons. Different percentage limits were used for some of the other river basins, owing to the very different seasonal cycles of precipitation. These thresholds are arbitrary, but better reflect the seasonal cycle of precipitation in each basin than using fixed months to define a season. For a few models, the modelled seasonal cycle was out of phase with the observations, and so using fixed months for each season might include some data which are not representative of that season. An examination of the future precipitation data for each model showed that the timing of the wet and dry seasons did not change significantly, but the magnitudes of precipitation did change in a few of the months for some of the river basins. For the East Salado basin, there is no seasonal cycle in precipitation, so only annual mean changes were calculated.

Maps showing the percentage changes in precipitation in each river basin for the dry and wet seasons from the AR4 MMD are shown in Figures 8 to 11 for all future time periods. For each time period, the minimum, multi-model mean and maximum changes are shown, and the change projected by the HadGEM1 model is also given for comparison. The actual changes are tabulated in Section A.2 in Table 2. Note that precipitation in the East Salado basin does not have a distinct wet and dry season, and so the annual mean changes are shown.

4.3.1 Dry Season Precipitation

The percentage changes in precipitation in the dry season are shown in Figures 8 and 9. Overall, the multi-model mean suggests that precipitation could decrease in most river basins during the twenty-first century. Rainfall could increase in the northernmost basins (Orinoco and Magdalena), and a few in the south of the continent (Dulce, West Salado and Santa Cruz). The largest decreases are projected to occur in the easternmost basins (Tocatins, Mearim, Paranaiba, Doce, Essequibo and São Francisco). However, there is a wide range of projected changes in precipitation from the AR4 MMD. The largest decreases in precipitation (minimum) lie between -20% and -50%, whereas a few models project an increase in precipitation in the dry season, some of which are very large (50% or more). Overall, the majority of models suggest that precipitation in the dry season could decrease in most basins, but the range of projected changes includes both increases and decreases

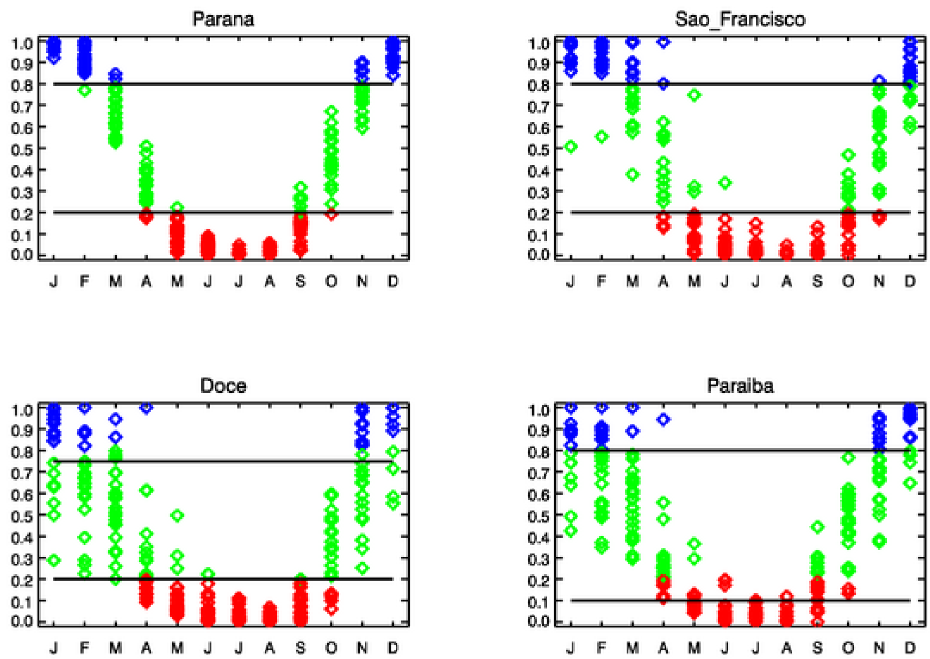

Figure 7: Example of selection of wet and dry months, shown for four river basins. The diamond symbols show monthly mean precipitation amounts from one model averaged over a 30 year period which have been scaled so that the minimum value is shown at zero and the maximum value at 1. The black lines show the thresholds used to define the wet and dry seasons. All precipitation data classed as belonging in the dry season are shown in red, in the wet season in blue and all other data in green. The seasonality was selected using this method for all river basins. Different thresholds were used for some basins.

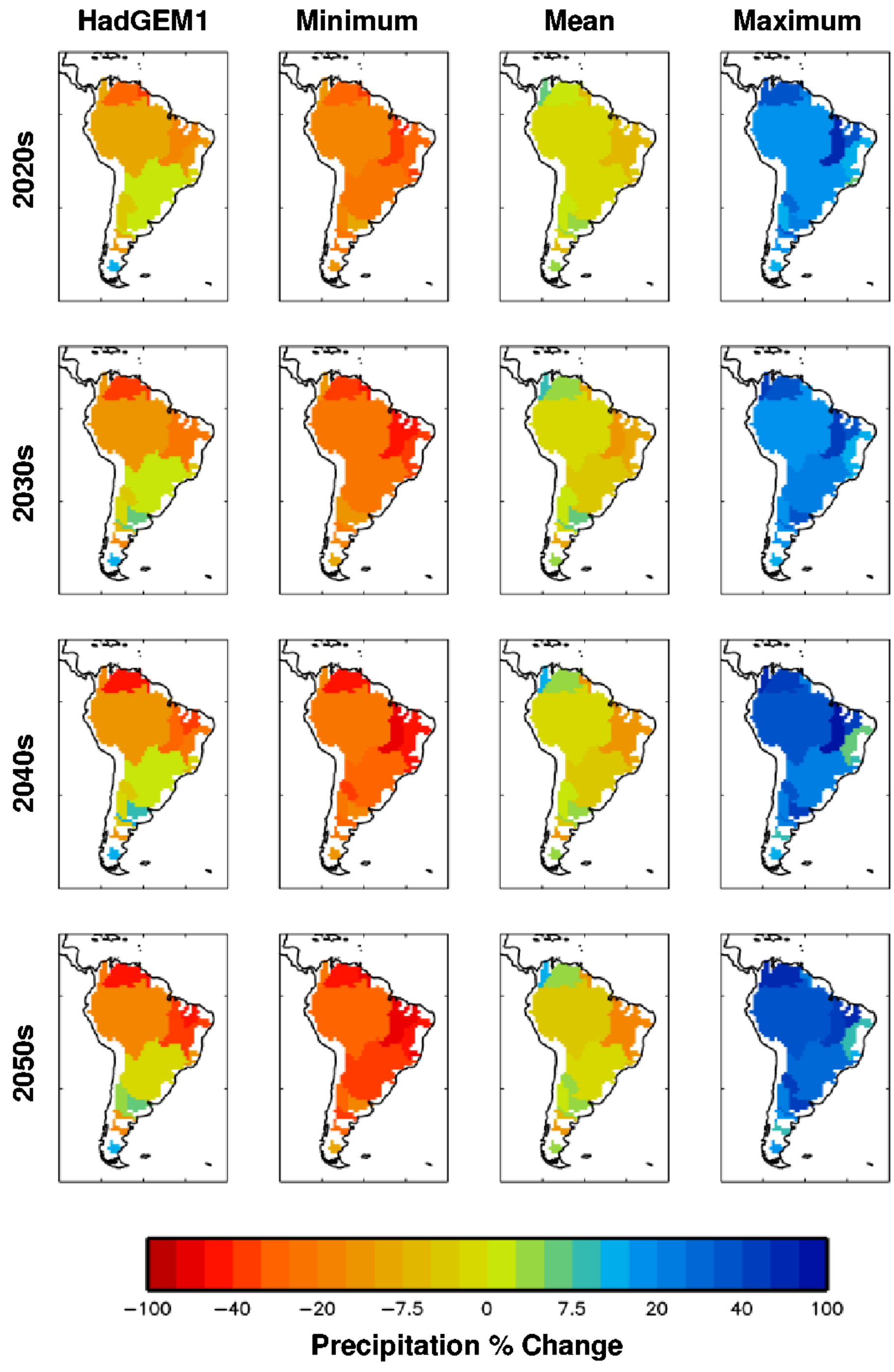

Figure 8: Maps showing the percentage change in precipitation from baseline period in the **dry season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2020s, 2030s, 2040s, and 2050s (given by each row).**

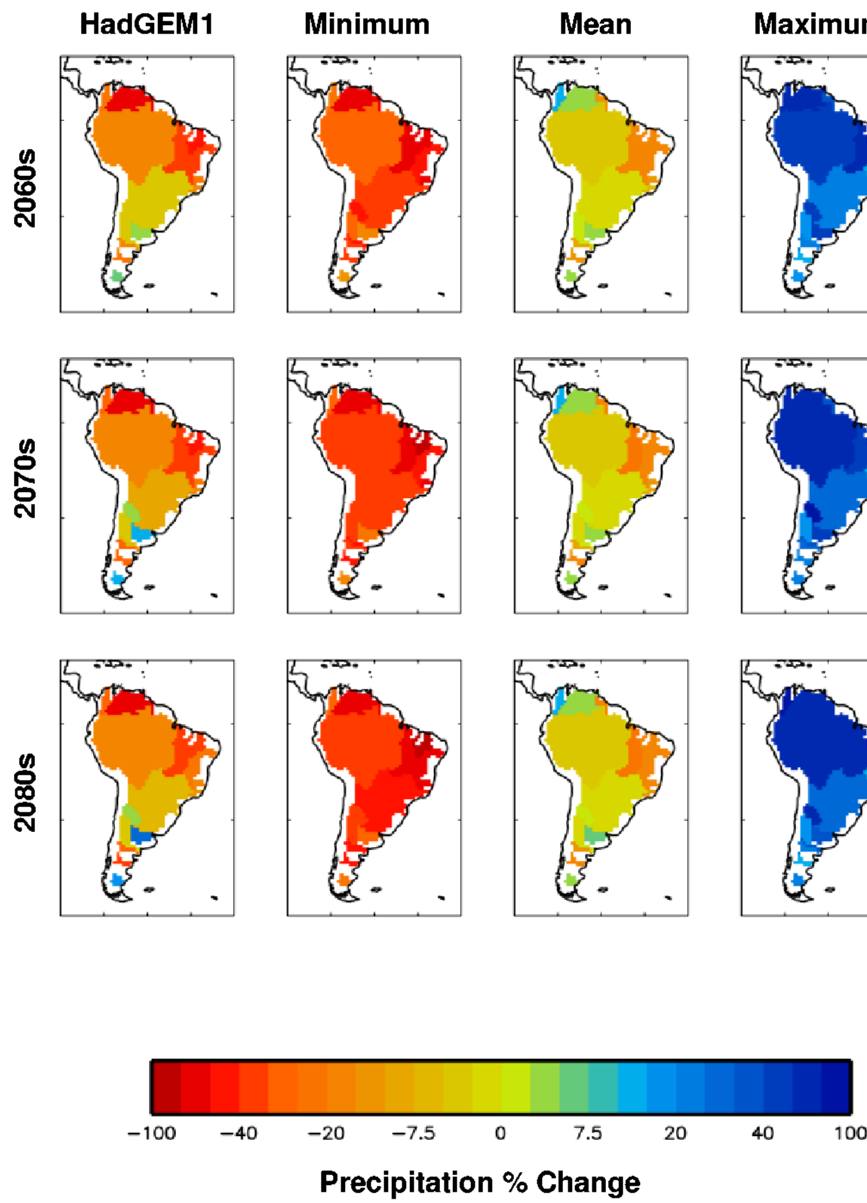

Figure 9: Maps showing the percentage change in precipitation from baseline period in the **dry season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2060s, 2070s, and 2080s (given by each row).**

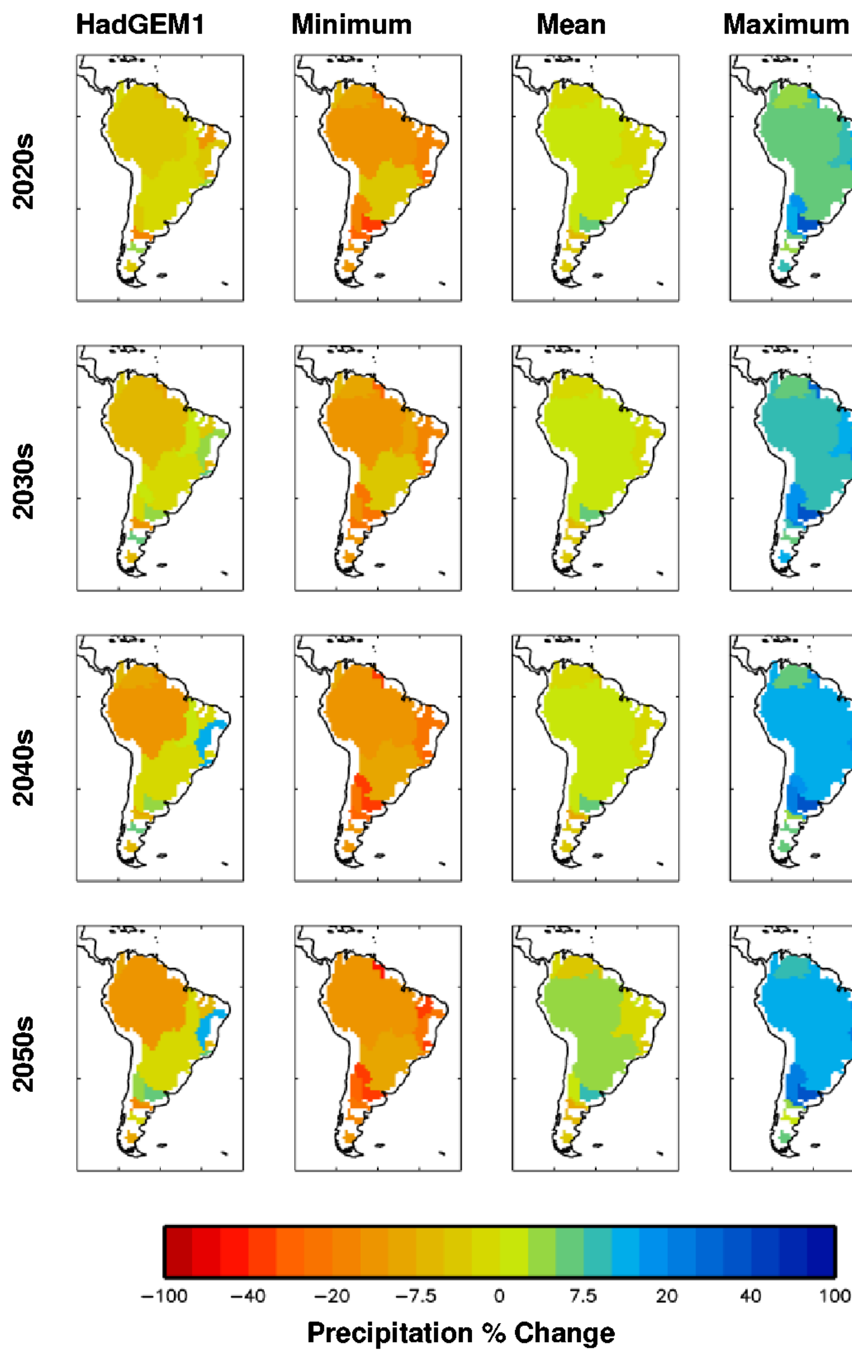

Figure 10: Maps showing the percentage change in precipitation from baseline period in the **wet season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2020s, 2030s, 2040s, and 2050s (given by each row).**

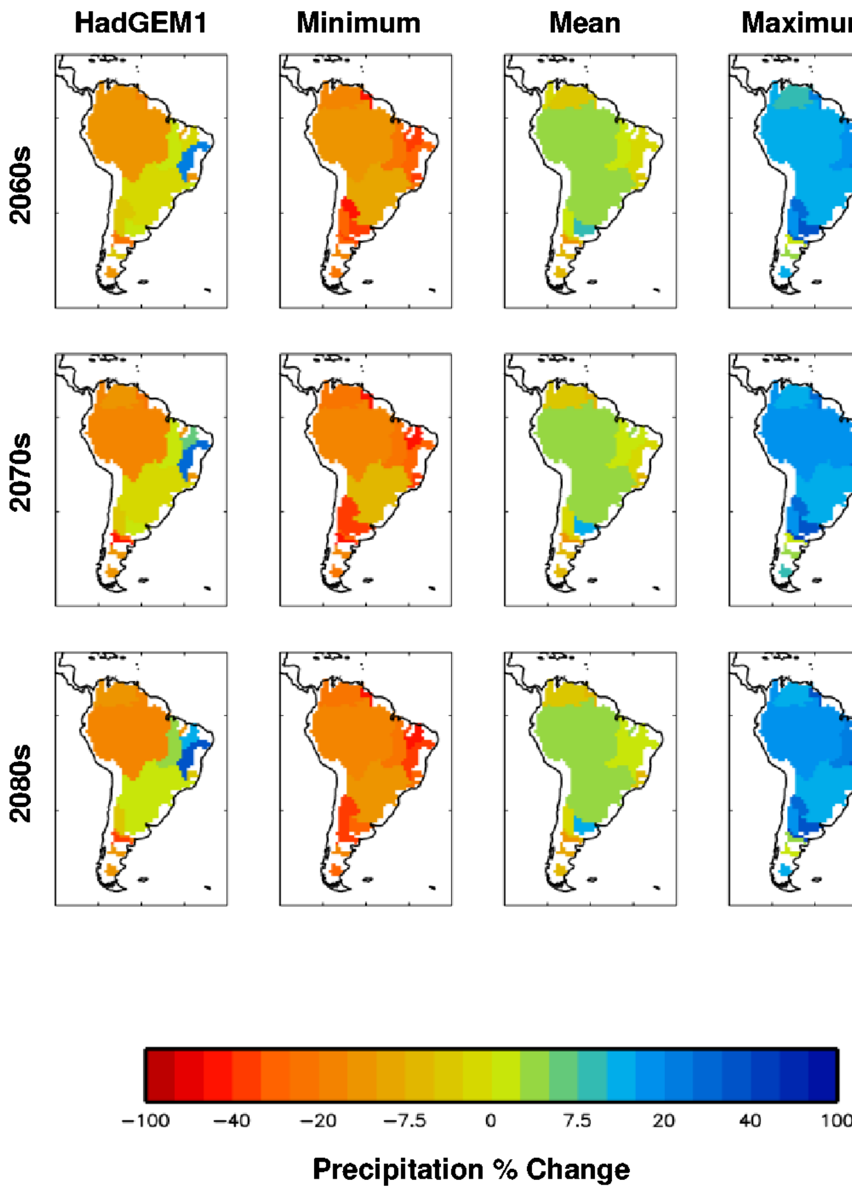

Figure 11: Maps showing the percentage change in precipitation from baseline period in the **wet season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2060s, 2070s, and 2080s (given by each row).**

in precipitation in all basins.

The precipitation changes from the HadGEM1 model generally lie between the minimum and the mean of the AR4 MMD. There is a north-south split in the precipitation changes from this model. In the northern half of South America, significant decreases in precipitation are projected over all basins, which are close to the minimum of the AR4 MMD. However, in the southern half of the continent, small increases in precipitation are projected in most of the river basins, which are close to the multi-model mean changes from the AR4 MMD.

4.3.2 Wet Season Precipitation

The percentage changes in precipitation in the wet season are shown in Figures 10 and 11. Again, the models in the AR4 MMD project both increases and decreases in precipitation in all basins, but the multi-model mean suggests an decrease in the majority (11 out of 18) of the basins. The largest increase from the multi-model mean is in the East Salado basin, where precipitation is projected to increase by about 15%. Larger increases in precipitation are also projected over the Amazon and Parana basins. The range of projections from the AR4 MMD includes a significant drying (the minimum changes lie between 0 and -20%), or a large increase in precipitation (between 10% and 40%).

For the 2020s and 2030s, the projected changes in precipitation from the HadGEM1 model are similar to the multi-model mean, but beyond these two time periods a large drying is projected across the Amazon basin and the other basins to the north, and resembles the minimum change from the AR4 MMD, except for the easternmost basins (Tocatins and São Francisco) which are closer to the maximum.

4.4 Summary of Precipitation Changes

During the dry season the AR4 MMD projects a small decrease in precipitation in most river basins, except for the northern basins Magdalena and Orinoco, and the West Salado and Dulce basins, where an increase in precipitation is projected. The HadGEM1 model, however, projects a drying over most of the river basins in the northern half of South America, but a small increase in precipitation over the Parana basin and the other basins which lie further south. For the northern half of South America, the precipitation changes from the HadGEM1 model have the largest or near largest amount of drying, and closely resemble the minimum changes from the AR4 MMD. In the southern half of South America, the projections from HadGEM1 lie close to the multi-model mean.

During the wet sason, HadGEM1 projects a drying over the Amazon and the basins to the north, and in these regions more closely resembles the minimum from the AR4 MMD. For the southern river basins, HadGEM1 also projects a small decrease or increase in precipitation, and again resembles the minimum changes from the AR4 MMD. However, for the eastern basins, HadGEM1 projects an increase in precipitation which is greater than the multi-model mean value and lies closer to the maximum value from the AR4 MMD. The HadGEM1 model thus projects a drying in the future across most of the river basins in South America in both the wet and dry seasons, whereas the multi-model mean from the AR4 MMD suggests that precipitation could decrease in the dry season but increase in the wet season. The changes in many of the basins are small ($< 10\%$). The largest changes occur in the dry season in the Tocatins, São Francisco, Essequibo, Chubut, Doce, and Mearim basins, and in the wet season in the West Salado and Negro basins.

5 Runoff Analysis

Runoff is water that flows into and out of a region, both above and below the ground. The majority of runoff flows underground. As mentioned in Section 1, changes in runoff are more likely to give a better indication of the possible changes in water availability than precipitation. Runoff in climate models is calculated from the precipitation rate and changes in soil moisture [Clark and Gedney, 2008]. Evaporation of water from the soil is important because it has a strong influence on the soil moisture content and hence the runoff. However, climate models use different representations of soil moisture and calculations of evaporation, which combined with the differences in patterns and amounts of future precipitation, mean that there is usually a larger spread in projections of runoff than precipitation. Only 23 models from the AR4 MMD are considered for runoff changes, because runoff data were not available from one model.

5.1 Previous Assessments of Modelled Runoff

There have been two previous analyses of runoff using the AR4 models, both of which calculated river flows using modelled runoff. These analyses only considered annual mean runoff, which was used as an input for models of river flow, and the river flows were then compared with observations. Milly et al. [2005] converted modelled annual mean runoff to stream flows and selected the 12 models that had closest agreement with measured discharges, using 165 river basins in all parts of the globe. They then calculated changes in annual runoff between 2041–2060 and the twentieth century. Runoff in an area similar to the Parana basin was projected to increase by about 10%, whereas a small reduction (5%) or no change was projected for three other basins. Nohara et al. [2006] used modelled runoff to drive a river flow model, TRIP [Oki and Sud, 1998] and examined changes in the flow of 24 major rivers between 2081–2100 and 1981–2000. Their results suggest that annual mean flow of the Parana River will increase by 5%, mostly between November and March (the wet season).

5.2 Evaluation of Present-Day Runoff

The analysis described in Section 4.2 was repeated using modelled total runoff (the total of both the surface and subsurface components) in each river basin. However, owing to the lack of availability of runoff measurements, no comparison between models and observations has been possible. Instead, we looked at the overall pattern of the modelled runoff from the AR4 MMD, and compared the multi-model mean and HadGEM1. The monthly mean runoff amounts, again averaged over the period 1961–1990, are shown in Figures 12, 13 and 14. It can be seen, by comparing Figure 3 with Figure 12, for example, that the seasonal cycle of runoff is very similar to that of precipitation in all the river basins. However, there is a greater spread between the modelled runoff amounts than the precipitation amounts, particularly during the wetter months. The runoff data from a few of the models appeared erroneous in some basins. The runoff amounts are approximately half of the precipitation amounts, which illustrate the important role of evaporation in determining water availability.

Several of the smaller river basins exhibit a limited seasonal pattern in runoff even where one was present with modelled rainfall (e.g. the Dulce basin). For some river basins, the range in modelled runoff amounts is larger than the range in rainfall amounts. HadGEM1 performs differently across the river basins, being higher than the multi model mean for the largest river basins (Amazon and Parana), though the seasonality is close to the multi-model mean. For the smaller southern river basins, HadGEM1 simulates less runoff than the multi-model mean.

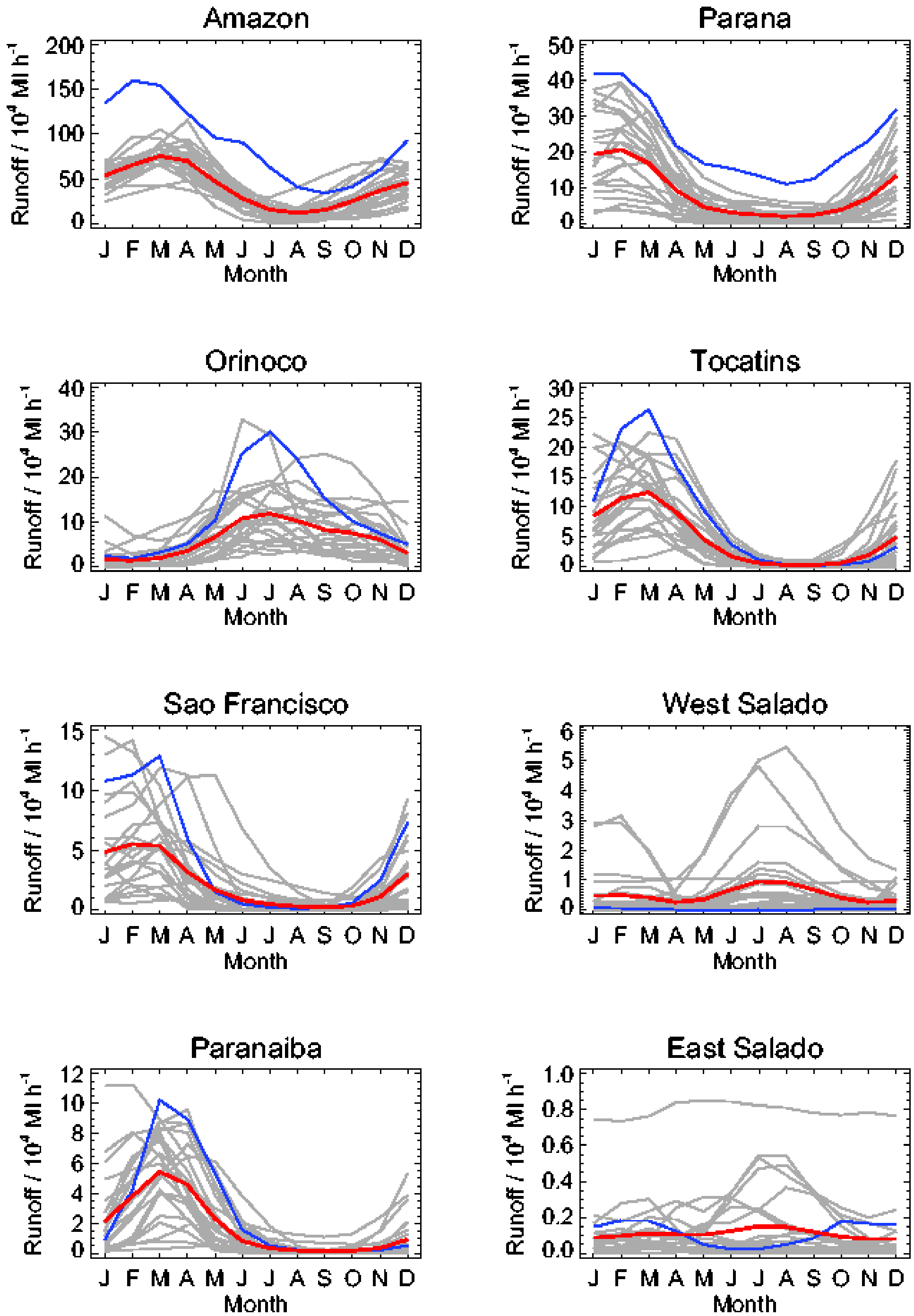

Figure 12: Comparison of modelled monthly mean runoff data for the period 1961–1990 over 8 river basins. The runoff amounts are shown in each basin in units of Ml hr^{-1}. Each of the 22 models is shown by a grey line, the multi-model mean by a red line, and the HadGEM1 line in blue.

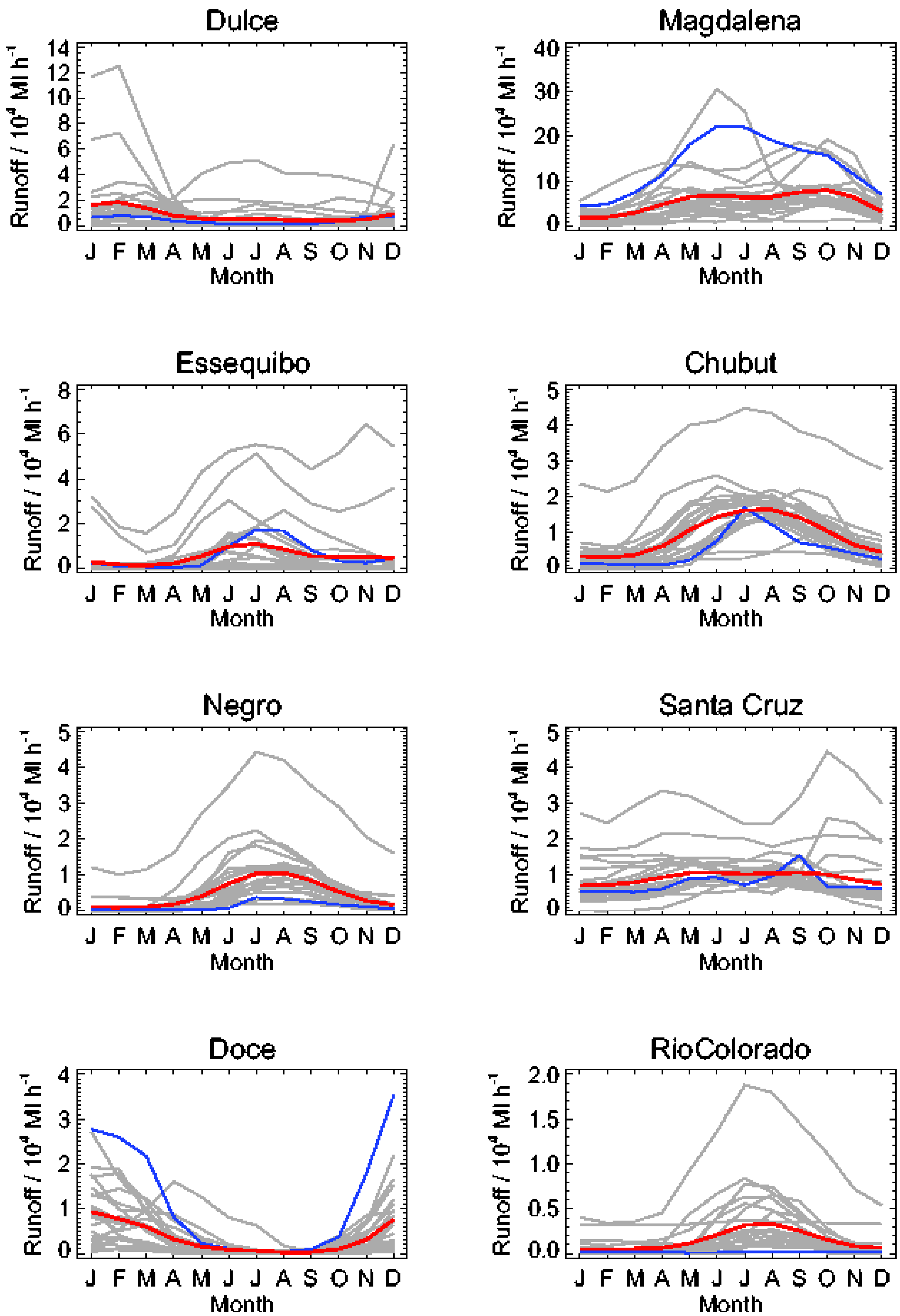

Figure 13: Comparison of modelled monthly mean runoff data for the period 1961–1990 over 8 river basins. The runoff amounts are shown in each basin in units of Ml hr^{-1}. Each of the 22 models is shown by a grey line, the multi-model mean by a red line, and the HadGEM1 line in blue.

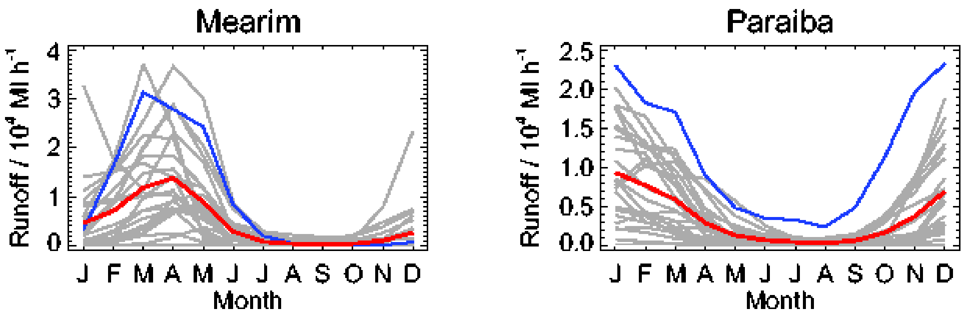

Figure 14: Comparison of modelled monthly mean runoff data for the period 1961–1990 over two river basins. The runoff amounts are shown in each basin in units of Ml hr^{-1}. The multi-model mean is shown by the red line, and the HadGEM1 simulation by a blue line. Each of the other 22 models is shown by a grey line.

5.3 Assessments of Future Runoff Changes

Percentage changes in runoff (from the 1961–1990 mean) are shown in Figures 15 to 18 for each river basin for the dry and wet seasons. Maximum, mean and minimum changes in runoff from the AR4 MMD are listed in Section A.3, Table 3 in the Appendix, plus the percentage change predicted using HadGEM1.

5.3.1 Dry Season Runoff

The projected changes in runoff in the dry season during the twenty-first century are shown in Figures 15 and 16. The multi-model mean and HadGEM1 projections are broadly similar in magnitude in most of the river basins. Both project a small decrease in runoff in the larger basins (Amazon and Parana), and an increase in runoff in the East Salado and eastern basins (Mearim, Paranaiba and Doce). HadGEM1 projects an increase in runoff in the São Francisco basin, whereas the multi-model mean projects a decrease. The largest differences between HadGEM1 and the multi-model mean occur in the northernmost basins (Magdalena, Orinoco and Essequibo). HadGEM1 projects a large decrease in runoff (about -40%) whereas the multi-model mean projects an increase, of about 5% in the 2020s to 15% in the 2080s. Overall, there is greater spatial variability in the projections from the HadGEM1 model than the multi-model mean. However, this is expected, as the averaging process will tend to smooth out such differences.

The dry season changes are generally greater than those for the wet season. There appears to be a north-south pattern of future runoff changes with increases in runoff projected by the multi-model mean for the northern river basins in the dry season (with the exception of the Sao Francisco, Doce and Paraiba basins) and decreases projected for the southern river basins by the 2080s. Generally, the HadGEM1 model projections are close to the mean in the 2020s, with some exceptions that are both higher and lower than the mean, mainly with the smaller river basins. The projections from HadGEM1 for the end of the century see a larger spatial variability, with the central river basins close to the mean changes, the eastern basins closer to the maximum and the northern and southern river basins nearer the minimum values.

5.3.2 Wet Season Runoff

For the wet season (Figures 17 and 18), the ranges of projected changes in runoff from the models are still large, but are smaller than for the dry season. The multi-model mean results suggest that runoff in many basins will only change slightly in the future (between -5% and 5%). The exceptions are the southernmost basins. Runoff in the East Salado and Rio Colorado basins is projected to increase significantly, but decrease in the Negro, Chubut and Santa Cruz basins. The projections from the HadGEM1 model have a different spatial pattern to the multi-model mean. First, HadGEM1 projects a trend of reducing runoff in the Amazon and other northern basins, but larger increases in runoff in the São Francisco, Doce and Paraiba basins than the multi-model mean. The projected changes in the southernmost basins in HadGEM1 and the multi-model mean are similar, except for the West Salado and Dulce basins, where HadGEM1 projects a larger increase in runoff.

Projections for wet season runoff changes from the 2020s to the 2080s are slightly more complex than those for the dry season. Once again, there is a rough north-south split, with the multi model mean runoff projected to increase in the north and decrease in the south. However, for the smaller river basins in the very north, (Orinoco, Essequibo and the Magdalena) runoff is projected to decrease by the end of the century. Runoff may also decrease in the eastern river basins, Doce and Paraiba, but in the southern basin, Rio Colorado, runoff is projected to increase. The East Salado river basin did not exhibit any clear seasonal behaviour in the present day or future and so has been treated as an annual mean. The multi-model mean projects a small increase in runoff by the end of the century for this basin with a similar range between maximums and minimums as the other river basins. The maximum modelled changes in runoff for the wet season are not as high as for the dry season, with the exception of the maximum for the Rio Colorado basin, for which extraneously high increases in runoff are given. Similarly, the minimum model projections are not as low as for the dry season, indicating a narrower range of projections. For the Chubut, Negro and Santa Cruz river basins, 90% or more of the models agreed on the sign of change for the mean.

The projections for HadGEM1 are again spatially variable for each time period; however, they are less variable than for the dry season, particularly in the 2020s. By the end of the century the spatial variability has increased with much the same pattern as for the dry season, so that a drying is projected for the northern and southern river basins by the end of the century, and runoff is projected to increase in the eastern and central river basins.

5.4 Summary of Runoff Changes

Modelled changes in runoff in the 21st century from the AR4 MMD, and the HadGEM1 model (which is part of the AR4 MMD) have been analysed. There is a large spread in the projected changes, and both increases and decreases in runoff are simulated by the models in all river basins and time periods. The runoff changes in the wet season are less reliable in all basins, because less than 67% of models agreed on the sign of the change in most cases. There is a broad north-south spatial pattern in the projected mean changes from the baseline for both the dry and wet seasons. The pattern indicates an increase in runoff the north and a decrease in the south. The dry season changes are generally greater than those projected for the wet season, including the maximum and minimum model projections.

Some very large percentage changes in runoff were projected by a few models in some of the river basins (Essequibo, Rio Colorado and West Salado). An analysis of the original runoff data for these particular models showed that the runoff values were very small throughout the simulation period (2000–2100) apart from a few large excursions. It is possible the data have been scaled in some way, or the smaller values have been lost. The global models do not resolve the smaller river basins very well, and so the changes calculated here originate from just a few model grid boxes. However, the changes in rainfall and runoff from the models in question are not outliers in most other river basins.

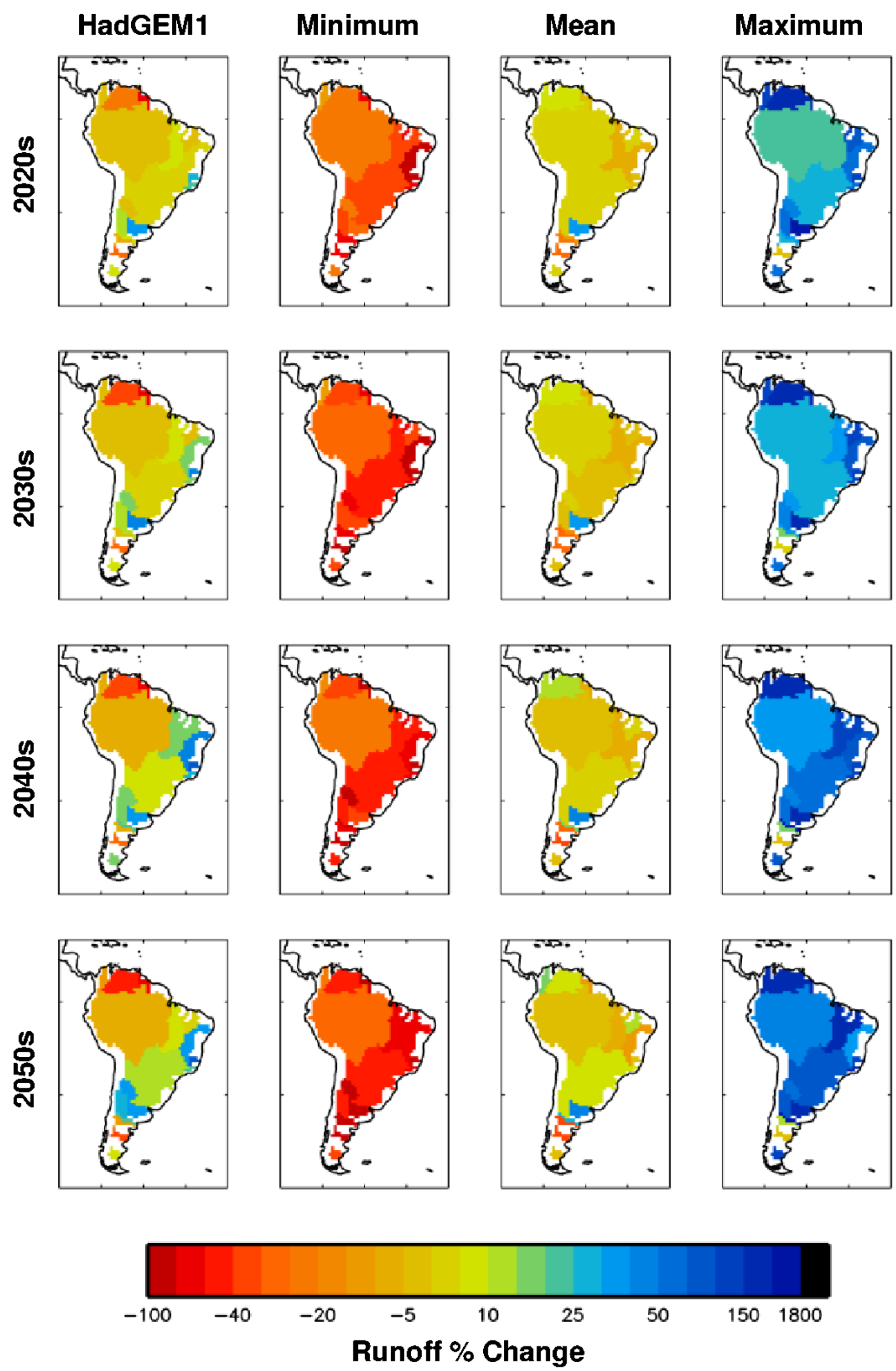

Figure 15: Maps showing the percentage change in runoff from baseline period in the **dry season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2020s, 2030s, 2040s, and 2050s (given by each row).**

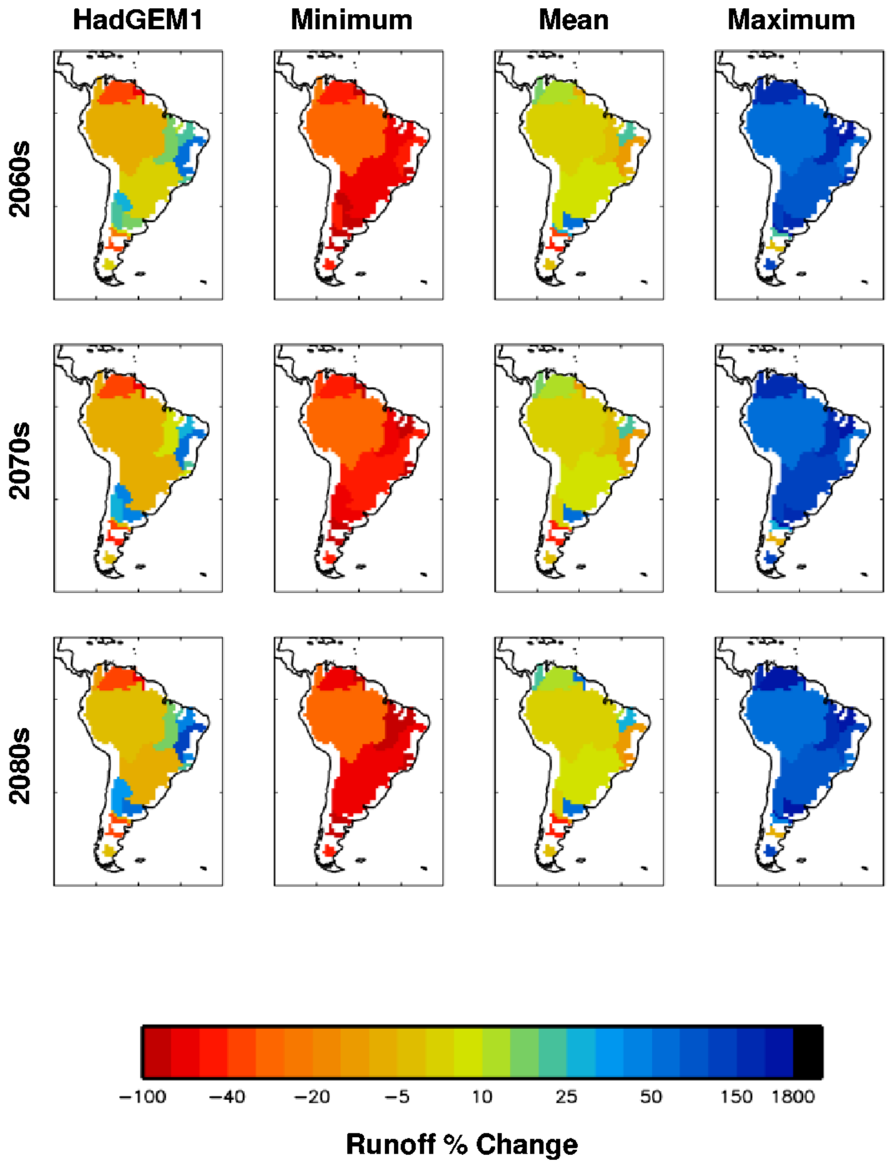

Figure 16: Maps showing the percentage change in runoff from baseline period in the **dry season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2060s, 2070s, and 2080s (given by each row).**

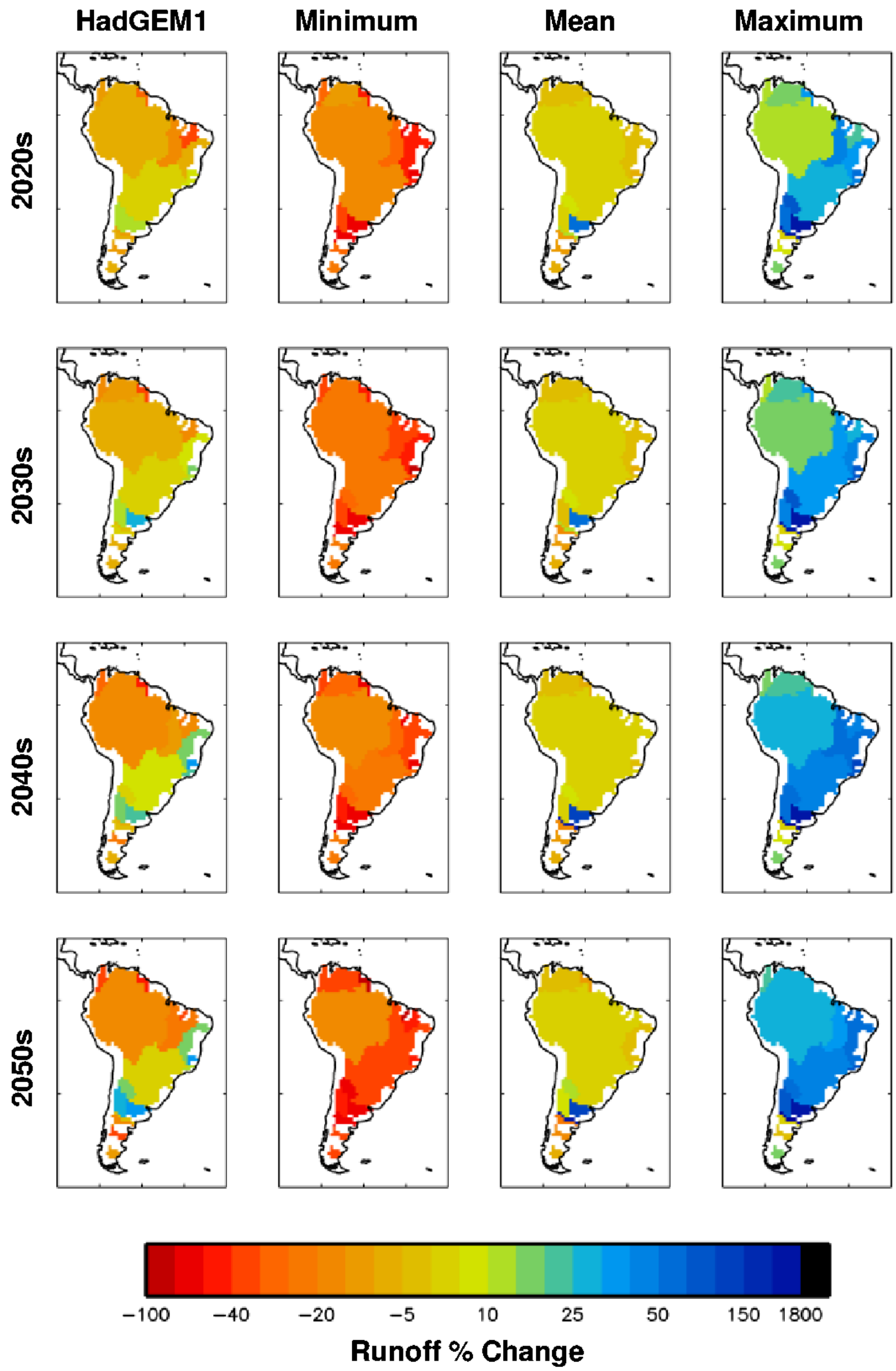

Figure 17: Maps showing the percentage change in runoff from baseline period in the **wet season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2020s, 2030s, 2040s, and 2050s (given by each row).**

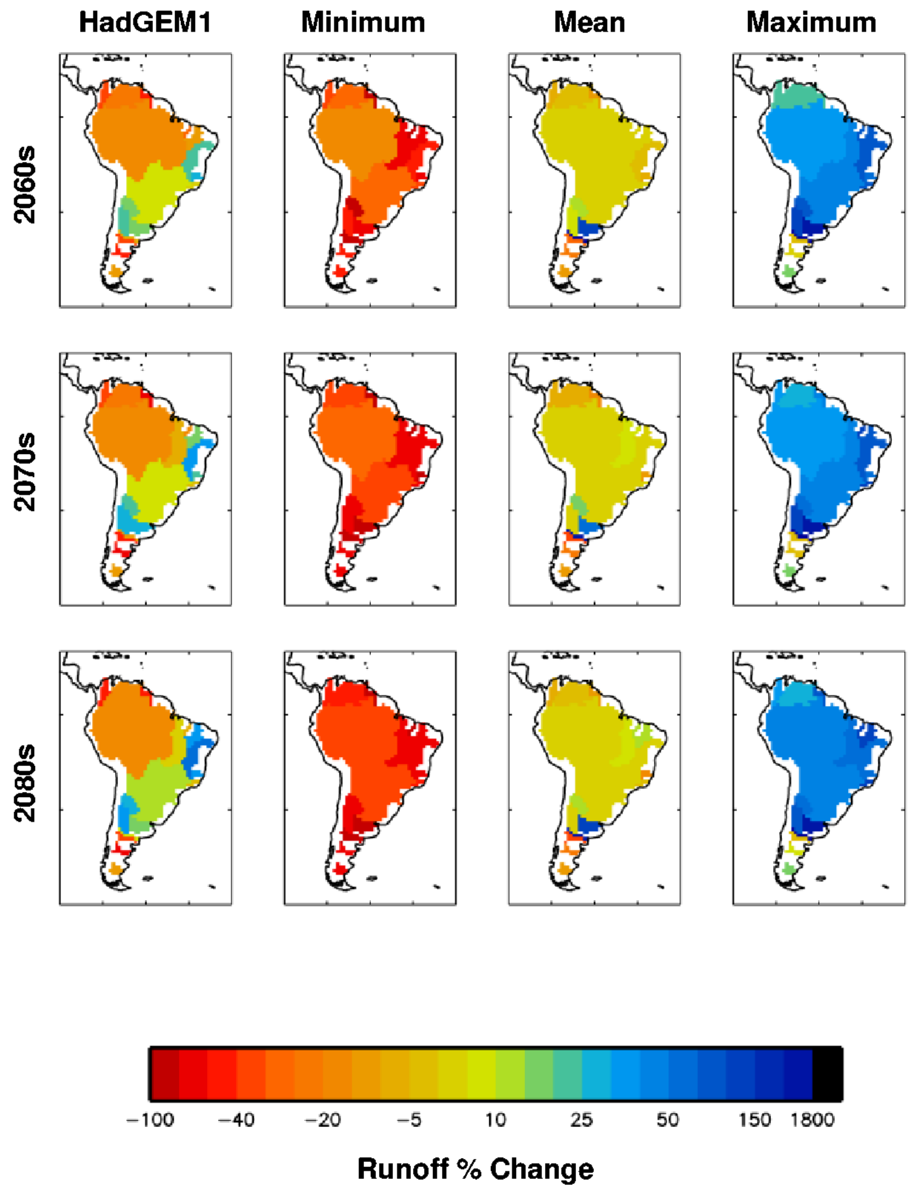

Figure 18: Maps showing the percentage change in runoff from baseline period in the **wet season for the 18 river basins studied. The baseline was defined to be 1961–1990. The 4 columns show HadGEM1 (left column), Minimum (second column), Mean (third column) and Maximum (right column) percentage changes of the AR4 models for the 2060s, 2070s, and 2080s (given by each row).**

There is a broad north-south spatial pattern in the projected mean changes from the baseline for both the dry and wet seasons of an increase in the north and a decrease in the south. The dry season changes are generally greater than those projected for the wet season, including the maximum and minimum model projections. The HadGEM1 projections are spatially variable with the larger central river basins projecting changes that are relatively close to the multi model mean. By the end of the century, this spatial variability increases for both the wet and dry seasons

6 Summary

The simulations of precipitation and runoff in the major river basins in South America from the multi-model ensemble used for the IPCC Fourth Assessment Report (AR4 MMD) have been calculated and assessed. The precipitation simulations for the period 1961–1990 were compared with observed precipitation data. The changes in precipitation and runoff projected for the twenty-first century were then assessed. Additionally, the projections from the Hadley Centre global climate model HadGEM1 have been compared with the maximum, mean and minimum changes from the AR4 MMD (note that HadGEM1 is part of the AR4 MMD).

The AR4 MMD models generally capture the seasonality and magnitude of precipitation in most river basins, although there were a few exceptions. There is greater disagreement between the models during the wet months than in the dry months. The HadGEM1 model performed as well as or better than the multi-model mean in many basins, although it overestimates precipitation in some basins (Amazon, Parana, Doce and Magdalena).

An analysis of the projected changes in precipitation and runoff from the AR4 MMD showed that there was a wide spread in the projections, with both increases and decreases in precipitation and runoff in all river basins at all times. Using the if 67% of the models agree on the sign of the change, then the change from the AR4 MMD was considered to be robust. The changes in the dry and wet seasons are robust in 10 and 9 basins respectively. The changes in precipitation in many of the basins are small ($< 10\%$). The largest changes ($> 10\%$) occur in the dry season in the Tocatins, São Francisco, Essequibo, Chubut, Doce, and Mearim basins, and in the wet season in the West Salado and Negro basins.

7 Caveats

The impact of a changing climate on water resources in South America has been studied using only one emissions scenario (the one regarded as "medium emissions" in UKCP09). The projections for the next few decades would be the same for other scenarios, however, later in the century, any changes in rainfall and runoff would also depend on the emissions scenario chosen. Nevertheless, the uncertainty in regional climate for a given emissions scenario is probably the main source of uncertainty in the projected rainfall and runoff changes.

A systematic assessment of all possible impacts on rainfall and runoff (for example, forest clearence, over-exploitation of water resources) has not been made. Only the information that was already available has been analysed. Therefore, other changes in water resources in South America outside of the ranges calculated here may be possible. For example, the climate models used for the Fourth Assessment Report did not include any changes in vegetation type and cover in response to climate (and the feedback of those changes on local climate), and only a few models included the physiological impact of rising CO_2 levels on evapotranspiration (which in turn impacts on modelled runoff).

A Appendix

A.1 PCMDI Models in IPCC AR4 Used in this Study

Program for Climate Model Diagnosis and Intercomparison (PCMDI) models from the IPCC Fourth Assessment Report (AR4) used in this study are shown in Table 1.

Table 1: Models in the AR4 Multi Model Dataset used in this study.

Model Names			
bccr_bcm2_0	cccma_cgcm3_1	cccma_cgcm3_1_t63	cnrm_cm3
csiro_mk3_0	csiro_mk3_5	gfdl_cm2_0	gfdl_cm2_1
giss_aom	giss_model_e_h	giss_model_e_r	iap_fgoals1_0_g
ingv_echam4	inmcm3_0	ipsl_cm4	miroc3_2_hires
miroc3_2_medres	miub_echo_g	mpi_echam5	mri_cgcm2_3_2a
ncar_ccsm3_0	ncar_pcm1	ukmo_hadcm3	ukmo_hadgem1

A.2 Table of Precipitation Results

Table 2: Percentage changes in precipitation in each river basin for the wet season and the dry season. The table shows the maximum, mean and minimum changes from the AR4 MMD for each season, plus the change from HadGEM1. If 67% or more of the models agreed on the sign of the change, the mean change is shown in bold, and if 90% or more of the models agreed on the sign, the mean change is shown in bold and with a ∗ symbol. Note that the river basin East Salado did not have a clear wet and dry season and so annual mean changes are listed.

Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
Amazon	Wet	Max	5.9	7.7	10.2	11.2	13.7	16.3	19.1
		Mean	**1.2**	**1.5**	**2.0**	**2.7**	**3.4**	**3.8**	**4.2**
		HadGEM1	-4.3	-6.4	-11.1	-11.6	-14.4	-16.0	-17.7
		Min	-10.5	-11.4	-12.2	-11.6	-14.4	-16.0	-17.7
	Dry	Max	19.7	19.9	30.6	32.8	46.5	52.2	54.9
		Mean	-0.9	-2.2	-2.5	-3.9	-3.1	-3.6	-3.0
		HadGEM1	-9.6	-11.1	-13.7	-18.5	-18.3	-18.0	-16.6
		Min	-15.6	-21.4	-22.9	-27.9	-25.5	-32.0	-38.7

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
Parana	Wet	Max	6.0	8.0	11.2	12.8	13.0	12.5	13.7
		Mean	**1.8**	**2.2**	**2.3**	**2.9**	**3.5**	**3.8**	**3.9**
		HadGEM1	-2.3	-2.5	-2.0	-1.6	-0.8	-0.2	0.5
		Min	-4.2	-3.3	-8.4	-9.8	-9.5	-7.4	-11.7
	Dry	Max	15.9	21.1	21.0	25.7	24.2	29.5	28.0
		Mean	-1.9	-2.7	-3.3	-2.1	-2.4	-1.5	-2.4
		HadGEM1	1.8	0.1	2.2	-1.6	-4.2	-8.8	-5.8
		Min	-20.9	-21.2	-29.4	-36.6	-32.5	-36.6	-41.7
Orinoco	Wet	Max	4.1	6.3	7.4	8.9	9.9	12.6	13.3
		Mean	-1.7	-1.7	-2.1	-2.6	-3.3	-4.2	-4.3
		HadGEM1	-4.0	-6.2	-9.6	-11.7	-12.9	-14.6	-12.0
		Min	-9.8	-8.7	-11.1	-14.3	-18.8	-21.0	-24.9
	Dry	Max	30.7	34.5	46.7	54.8	65.1	58.3	63.0
		Mean	2.4	3.1	4.3	4.6	4.6	4.2	3.8
		HadGEM1	-27.4	-35.3	-45.9	-48.4	-51.7	-54.1	-57.2
		Min	-27.4	-35.3	-45.9	-48.4	-51.7	-54.1	-57.2
Tocatins	Wet	Max	9.8	12.1	13.8	14.5	17.0	19.3	22.7
		Mean	-0.2	0.3	0.3	-0.2	0.2	0.8	1.5
		HadGEM1	-0.6	1.0	0.6	-1.2	0.7	0.6	3.1
		Min	-12.0	-9.6	-11.1	-13.4	-24.3	-22.9	-24.4
	Dry	Max	56.7	42.3	79.3	48.4	53.4	47.1	51.0
		Mean	**-7.3**	**-11.2**	**-14.1**	**-19.0**	**-18.9**	**-21.4**	**-24.1**
		HadGEM1	-17.0	-23.6	-27.6	-37.4	-39.2	-38.2	-37.9
		Min	-36.2	-47.8	-54.2	-55.2	-57.8	-65.1	-71.1
São Francisco	Wet	Max	14.4	17.5	18.4	21.5	21.5	29.0	38.4
		Mean	-1.5	-1.7	-0.8	-2.1	-1.2	-0.9	0.4
		HadGEM1	-4.2	2.5	10.9	14.0	20.2	29.0	38.4
		Min	-19.6	-19.8	-21.3	-20.5	-25.2	-26.5	-31.6
	Dry	Max	10.2	11.2	6.6	8.1	10.4	14.1	13.9
		Mean	**-6.3**	**-10.0**	**-13.7***	**-16.3***	**-16.3**	**-16.9***	**-18.4**
		HadGEM1	-12.8	-21.7	-24.9	-40.0	-38.8	-30.8	-21.0
		Min	-27.7	-34.7	-45.3	-47.4	-45.2	-42.5	-51.6
East Salado	*Annual*	Max	14.3	16.0	20.0	23.1	17.7	18.3	18.9
		Mean	0.9	1.1	0.9	1.1	-0.0	-0.7	-1.2
		HadGEM1	-3.1	-1.4	-0.5	2.6	-3.5	-4.6	-3.8
		Min	-17.0	-14.9	-24.2	-25.7	-30.0	-32.2	-32.6
Paranaiba	Wet	Max	7.1	8.6	10.7	17.0	21.4	24.7	31.0
		Mean	-2.1	-1.3	-1.0	-1.1	-0.5	0.1	1.8
		HadGEM1	-10.2	-4.8	-2.0	-5.5	-1.1	6.9	11.1
		Min	-15.5	-15.1	-20.8	-32.5	-37.7	-44.7	-41.8

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
	Dry	Max	32.0	32.5	48.7	58.2	81.8	78.4	81.4
		Mean	-5.2	**-9.7**	**-13.1**	**-16.7**	**-15.1**	**-15.5**	**-16.5**
		HadGEM1	-19.8	-22.4	-32.9	-45.2	-42.8	-40.8	-36.9
		Min	-27.4	-42.1	-44.1	-53.2	-60.4	-77.7	-79.3
West Salado	Wet	Max	32.3	31.9	36.5	36.0	36.8	39.8	37.8
		Mean	**5.0**	**6.3**	**7.2**	**7.8**	**8.9**	**10.6**	**11.7***
		HadGEM1	-1.0	3.9	3.0	6.4	0.5	0.6	0.4
		Min	-35.5	-24.8	-34.0	-37.1	-37.4	-33.4	-29.5
	Dry	Max	24.9	36.3	40.2	49.4	43.5	44.3	35.7
		Mean	**3.8**	**5.3**	3.2	4.3	3.6	**4.6**	**5.1**
		HadGEM1	0.9	6.3	9.6	6.9	4.0	13.1	26.5
		Min	-9.4	-14.2	-17.1	-19.0	-18.8	-23.0	-27.0
Dulce	Wet	Max	16.9	17.2	19.6	21.3	25.0	26.1	27.6
		Mean	1.7	1.2	1.4	**2.9**	**3.3**	**4.0**	**3.9**
		HadGEM1	-0.7	1.0	-2.2	-2.0	-3.1	-0.2	0.5
		Min	-16.2	-21.0	-35.6	-35.6	-40.8	-33.3	-36.1
	Dry	Max	27.0	22.2	32.6	48.0	48.6	78.8	64.3
		Mean	0.0	0.7	0.2	2.6	-0.2	0.4	0.0
		HadGEM1	-2.7	-3.4	-3.5	-0.5	-3.5	4.3	3.3
		Min	-21.2	-22.2	-33.0	-33.7	-41.6	-34.0	-38.3
Magdalena	Wet	Max	6.2	8.6	11.0	12.8	14.5	16.3	19.0
		Mean	**-0.4**	-1.1	-1.1	-1.8	-2.3	-3.3	-3.4
		HadGEM1	-0.8	-3.1	-6.4	-8.4	-12.4	-15.2	-14.6
		Min	-6.8	-7.5	-8.9	-13.9	-17.6	-21.3	-24.3
	Dry	Max	36.2	40.9	58.2	60.3	72.5	70.1	79.0
		Mean	**6.0**	7.7	**10.0**	**11.2**	**12.8**	**13.8**	**14.0**
		HadGEM1	-9.5	-10.7	-18.6	-20.2	-23.6	-25.3	-29.6
		Min	-11.4	-11.5	-18.6	-20.2	-23.6	-25.3	-29.6
Essequibo	Wet	Max	13.1	26.7	17.1	14.9	22.5	28.1	30.5
		Mean	**-2.5**	-2.3	-3.2	-4.2	-4.7	-6.0	-5.9
		HadGEM1	-6.0	-8.8	-13.5	-14.3	-15.8	-20.7	-18.0
		Min	-20.5	-26.4	-30.3	-42.3	-46.8	-45.1	-49.7
	Dry	Max	20.4	15.3	20.6	20.6	38.5	33.9	53.4
		Mean	-6.2	**-9.0**	**-11.1**	**-14.3**	**-14.8**	**-17.9**	**-17.9**
		HadGEM1	-35.8	-39.9	-45.2	-47.9	-50.7	-51.6	-54.0
		Min	-35.8	-42.0	-46.0	-59.2	-65.2	-69.1	-73.4
Chubut	Wet	Max	4.4	6.7	6.1	1.6	3.1	3.7	0.2
		Mean	**-3.9**	**-3.6**	**-4.1**	**-6.0**	**-6.9**	**-7.2***	**-7.7***
		HadGEM1	4.1	6.4	5.2	-0.3	-2.6	-12.7	-13.2
		Min	-14.4	-11.7	-10.6	-17.4	-18.2	-18.1	-18.3

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
	Dry	Max	17.0	15.0	9.0	9.8	10.9	21.9	11.0
		Mean	**-7.0**	**-8.2***	**-10.8***	**-12.5***	**-14.7***	**-16.6***	**-18.9***
		HadGEM1	-14.9	-16.3	-13.3	-19.7	-22.3	-28.1	-32.1
		Min	-20.2	-20.0	-23.3	-26.8	-30.2	-40.8	-41.5
Negro	Wet	Max	6.0	7.5	4.5	3.0	1.9	0.7	3.1
		Mean	**-6.3**	**-6.8***	**-8.3***	**-9.8**	**-10.6***	**-11.4***	**-12.7***
		HadGEM1	-18.5	-13.4	-5.4	-17.1	-24.1	-40.5	-39.5
		Min	-26.6	-23.3	-26.5	-23.3	-28.8	-40.5	-39.5
	Dry	Max	21.1	15.1	21.6	16.3	22.7	26.5	22.4
		Mean	-1.7	**-2.1**	-3.5	**-5.4**	**-8.0**	**-9.7**	**-10.4**
		HadGEM1	-9.3	-5.7	-2.8	-10.4	-19.2	-26.8	-26.3
		Min	-20.2	-20.9	-26.7	-31.6	-39.8	-39.7	-42.3
Santa Cruz	Wet	Max	9.4	10.4	6.3	6.8	11.1	9.5	12.3
		Mean	**-4.0**	**-4.0**	**-4.4**	**-4.9**	**-5.8**	**-6.4**	**-6.0**
		HadGEM1	-3.1	-6.5	-7.1	-9.4	-10.9	-10.9	-12.6
		Min	-12.6	-12.4	-12.7	-13.7	-20.1	-23.6	-25.8
	Dry	Max	10.3	14.5	13.9	16.4	18.0	21.1	21.9
		Mean	**2.8**	**3.7**	**3.9**	**3.2**	**2.9**	**3.7**	**4.9**
		HadGEM1	10.3	14.5	13.9	10.6	7.3	13.3	15.5
		Min	-10.4	-8.7	-13.0	-8.4	-13.3	-16.1	-20.9
Doce	Wet	Max	27.3	48.1	45.8	23.9	18.8	18.5	18.0
		Mean	-1.2	-0.9	-0.8	-2.9	-3.4	-5.3	**-6.1**
		HadGEM1	-9.1	-5.2	-2.4	-7.2	-14.9	-11.4	-2.9
		Min	-29.3	-27.9	-28.4	-32.4	-35.0	-36.4	-29.9
	Dry	Max	10.1	13.8	9.1	12.4	10.2	6.1	4.4
		Mean	-5.0	**-6.4**	**-9.3**	**-10.9**	**-13.5**	**-14.6**	**-17.3**
		HadGEM1	-1.1	-4.0	-1.2	-10.9	-21.5	-24.5	-15.7
		Min	-32.5	-37.1	-48.6	-55.1	-54.3	-53.0	-56.9
Rio Colorado	Wet	Max	17.8	23.8	19.4	28.1	38.6	43.4	49.8
		Mean	**-4.6**	**-3.8**	**-4.8**	**-3.7**	-3.9	-4.8	**-6.8**
		HadGEM1	-17.4	-10.4	-8.9	-13.1	-20.8	-26.5	-23.0
		Min	-25.7	-22.6	-26.6	-22.2	-32.4	-29.2	-32.7
	Dry	Max	30.4	27.9	29.7	28.6	21.8	30.2	31.7
		Mean	**4.7**	**5.0**	2.6	2.5	2.1	2.1	0.8
		HadGEM1	0.3	6.6	10.2	4.5	-3.2	-5.2	-1.5
		Min	-24.1	-19.5	-29.3	-34.8	-40.7	-44.2	-45.1
Mearim	Wet	Max	11.0	12.1	10.4	15.2	22.6	31.4	38.8
		Mean	-0.5	**0.8**	0.3	0.5	1.3	2.7	**4.6**
		HadGEM1	-0.6	1.4	-3.5	-8.5	-9.3	-12.0	-11.9
		Min	-14.1	-12.9	-16.7	-23.5	-31.7	-34.6	-31.3

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
	Dry	Max	26.1	29.9	54.4	70.2	89.2	89.2	90.8
		Mean	-4.5	**-9.0**	**-13.2**	**-16.3**	**-16.4**	**-15.7**	**-17.1**
		HadGEM1	-22.5	-25.5	-33.4	-45.5	-37.6	-34.2	-33.8
		Min	-45.8	-58.8	-55.5	-65.3	-72.4	-86.6	-87.3
Paraiba	Wet	Max	8.0	9.7	10.9	18.5	18.9	23.6	15.0
		Mean	-2.2	-2.5	-1.9	**-2.5**	-2.2	-3.1	-4.0
		HadGEM1	3.2	6.9	10.9	7.4	1.8	-0.9	2.1
		Min	-16.9	-15.9	-17.0	-17.9	-20.6	-31.0	-21.0
	Dry	Max	5.0	10.6	22.2	26.8	27.7	24.4	18.2
		Mean	-5.4	**-6.2**	**-6.9**	**-6.1**	-6.3	**-8.3**	**-10.2**
		HadGEM1	-0.6	-0.5	-5.8	-13.5	-15.8	-19.0	-11.5
		Min	-29.9	-35.9	-40.5	-34.0	-30.9	-36.0	-42.0

A.3 Table of Runoff Results

Table 3: Percentage changes in precipitation in each river basin for the dry season and the wet season. The table shows the maximum, mean and minimum changes from the AR4 MMD for each season, plus the change from HadGEM1. If 67% or more of the models agreed on the sign of the change, the mean change is shown in bold, and if 90% or more of the models agreed on the sign, the mean change is shown in bold and with a $*$ symbol. Note that the river basin East Salado did not have an observed wet and dry season and so annual mean changes are given.

Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
Amazon	Wet	Max	13.4	18.9	27.1	29.6	33.2	38.4	47.5
		Mean	0.7	0.8	1.2	1.8	3.0	**3.7**	4.7
		HadGEM1	-7.8	-9.1	-15.1	-16.1	-18.0	-17.8	-18.5
		Min	-15.4	-22.7	-15.2	-17.3	-18.0	-26.9	-30.5
	Dry	Max	22.6	27.0	37.7	44.9	55.2	61.9	65.0
		Mean	1.0	0.2	-0.2	-1.1	0.3	0.2	1.7
		HadGEM1	-5.0	-3.7	-5.1	-5.7	-5.2	-6.8	-4.6
		Min	-21.8	-27.0	-24.7	-29.4	-27.0	-28.6	-25.4
Parana	Wet	Max	26.4	36.3	42.6	43.1	43.4	46.9	43.5
		Mean	**1.7**	1.5	2.3	2.8	4.1	4.1	4.1
		HadGEM1	2.2	2.1	6.1	4.9	5.1	5.4	10.0
		Min	-17.1	-20.6	-21.4	-35.0	-26.7	-32.2	-39.1

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
	Dry	Max	25.1	28.4	56.5	77.8	98.4	105.2	95.9
		Mean	0.8	-0.2	2.8	6.5	7.2	7.2	6.2
		HadGEM1	0.5	2.3	7.7	10.3	2.9	-7.3	-7.9
		Min	-36.1	-44.2	-48.2	-40.7	-55.9	-42.8	-53.9
Orinoco	Wet	Max	18.2	24.9	21.5	26.8	24.6	27.8	28.4
		Mean	-1.3	-1.6	-2.3	-2.6	-3.9	-5.7	-4.8
		HadGEM1	-6.4	-10.5	-18.9	-18.0	-20.2	-23.1	-19.6
		Min	-14.7	-24.6	-25.1	-30.1	-28.3	-37.4	-42.4
	Dry	Max	208.4	212.2	286.1	309.6	349.1	343.0	418.9
		Mean	8.9	8.3	10.8	9.3	11.3	10.0	12.2
		HadGEM1	-24.8	-30.2	-38.7	-41.8	-38.1	-36.4	-37.6
		Min	-24.8	-30.2	-38.7	-41.8	-44.3	-43.2	-51.8
Tocatins	Wet	Max	41.7	38.9	50.2	32.7	46.4	49.2	60.8
		Mean	2.1	2.8	3.9	2.8	4.9	6.1	7.6
		HadGEM1	-15.2	-9.4	-14.4	-21.6	-16.2	-9.5	3.9
		Min	-29.1	-36.6	-28.1	-33.9	-60.7	-61.2	-64.7
	Dry	Max	24.5	39.3	121.5	181.4	230.5	251.0	324.3
		Mean	-6.4	-8.0	**-8.4**	-7.8	**-4.7**	-1.6	0.6
		HadGEM1	9.1	8.0	16.2	7.3	15.2	9.1	19.5
		Min	-36.1	-41.3	-47.3	-64.6	-74.2	-68.6	-79.6
São Francisco	Wet	Max	33.6	49.8	61.1	63.9	80.9	88.3	72.8
		Mean	-1.9	-1.5	1.3	-1.2	-0.7	0.5	2.9
		HadGEM1	-7.2	6.1	15.7	17.6	22.7	32.8	56.5
		Min	-41.8	-42.7	-38.1	-38.2	-46.6	-53.1	-60.9
	Dry	Max	67.8	88.2	94.9	39.1	56.2	68.3	104.4
		Mean	**-5.1**	**-8.0**	**-8.3**	**-13.7**	**-11.7**	**-13.3**	**-15.0**
		HadGEM1	4.8	16.1	47.9	39.1	56.2	68.3	104.4
		Min	-84.9	-82.2	-59.4	-52.8	-45.1	-49.7	-50.4
East Salado	*Annual*	Max	51.2	43.7	51.8	75.8	113.0	114.8	96.5
		Mean	0.4	-0.1	4.0	7.4	7.0	3.4	**2.7**
		HadGEM1	10.3	11.0	16.6	26.4	24.1	27.3	31.0
		Min	-37.0	-35.6	-40.3	-45.0	-49.0	-50.5	-57.7
Paranaiba	Wet	Max	22.9	28.0	41.4	62.4	82.3	85.8	100.3
		Mean	-4.3	-1.8	0.3	0.2	2.6	4.5	11.8
		HadGEM1	-31.4	-19.7	-17.1	-23.3	-11.4	19.8	32.8
		Min	-45.8	-38.5	-35.5	-49.4	-63.8	-74.8	-71.3
	Dry	Max	78.9	111.1	141.3	342.1	509.9	490.1	622.8
		Mean	0.8	-0.6	4.5	10.0	21.0	21.5	27.4
		HadGEM1	-2.9	-2.5	17.3	4.9	21.3	25.0	45.2
		Min	-37.3	-37.4	-44.7	-63.4	-73.1	-78.6	-75.6

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
West Salado	Wet	Max	742.8	455.7	1613.0	1187.8	1389.0	429.1	1267.3
		Mean	**63.0**	**52.0**	**113.4**	**103.9**	**119.9**	**73.5**	**123.7**
		HadGEM1	11.8	29.2	21.7	32.9	16.0	26.8	18.8
		Min	-61.2	-53.7	-51.9	-55.5	-50.8	-76.7	-78.7
	Dry	Max	355.6	204.8	216.7	308.7	300.8	345.2	432.4
		Mean	**36.6**	**34.5**	**42.4**	**49.3**	**53.6**	**63.6**	**74.5**
		HadGEM1	31.5	41.8	31.6	34.6	19.3	48.3	54.6
		Min	-25.5	-31.7	-36.6	-79.3	-82.8	-68.5	-68.3
Dulce	Wet	Max	84.5	75.2	55.4	71.6	78.8	71.3	72.2
		Mean	7.5	5.8	6.6	10.8	**12.3**	**15.0**	13.8
		HadGEM1	0.2	3.6	4.3	16.8	18.3	24.7	29.2
		Min	-18.4	-29.5	-29.1	-57.6	-92.3	-74.0	-73.8
	Dry	Max	47.9	35.7	45.7	59.8	76.8	125.5	97.5
		Mean	4.7	1.6	**4.6**	**7.0**	**6.5**	8.4	6.8
		HadGEM1	-0.2	15.9	18.0	35.5	28.7	44.4	38.0
		Min	-22.8	-73.1	-91.8	-88.2	-85.1	-59.5	-64.0
Magdalena	Wet	Max	12.8	14.2	17.1	21.9	23.1	33.9	39.5
		Mean	-2.9	-4.1	-3.9	-4.4	-5.4	-6.6	-6.4
		HadGEM1	-12.2	-16.3	-27.1	-31.3	-35.9	-36.9	-41.2
		Min	-28.3	-36.2	-30.3	-31.3	-35.9	-36.9	-41.2
	Dry	Max	116.4	134.4	194.8	199.1	231.0	221.4	260.2
		Mean	7.8	9.6	14.6	15.3	17.9	18.3	20.8
		HadGEM1	-2.9	-3.1	-8.5	-11.7	-10.0	-9.3	-10.9
		Min	-13.9	-13.2	-16.4	-20.8	-21.0	-33.6	-29.9
Essequibo	Wet	Max	34.1	36.0	21.5	29.5	24.3	43.3	86.5
		Mean	-4.6	-4.1	-5.9	**-11.7**	**-13.4**	**-16.9**	**-12.9**
		HadGEM1	-28.4	-30.2	-44.6	-44.5	-47.2	-53.5	-47.5
		Min	-41.2	-42.6	-65.9	-81.9	-93.9	-90.7	-82.6
	Dry	Max	164.0	159.5	178.3	157.1	166.7	186.6	1767.3
		Mean	-2.9	**-5.1**	**-7.8**	**-10.6**	**-9.8**	**-13.0**	**56.7**
		HadGEM1	-60.4	-60.8	-69.2	-70.3	-70.0	-71.6	-68.8
		Min	-69.2	-71.9	-77.9	-83.5	-93.8	-96.2	-92.4
Chubut	Wet	Max	7.9	6.0	6.5	-0.2	0.1	-1.4	5.8
		Mean	**-10.1***	**-10.1**	**-12.2***	**-16.4***	**-20.6***	**-22.9***	**-24.2***
		HadGEM1	-12.9	-5.1	-20.1	-31.7	-49.4	-58.5	-67.8
		Min	-27.8	-24.0	-23.2	-31.7	-49.4	-58.5	-67.8
	Dry	Max	-4.3	0.4	-3.8	-3.3	-4.7	-6.1	-7.8
		Mean	**-26.4***	**-28.9***	**-32.7***	**-35.9***	**-41.7***	**-45.6***	**-48.6***
		HadGEM1	-29.3	-26.7	-27.4	-34.9	-36.5	-41.5	-39.5
		Min	-71.2	-78.5	-82.5	-86.5	-89.4	-86.6	-90.0

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
Negro	Wet	Max	0.7	1.2	1.0	1.6	-1.1	-4.8	-2.3
		Mean	**-14.2***	**-16.4***	**-19.8***	**-24.6***	**-29.4***	**-31.9***	**-33.8***
		HadGEM1	-6.7	1.2	-2.5	-17.3	-36.9	-40.5	-40.0
		Min	-50.5	-52.4	-61.6	-74.5	-85.3	-88.1	-92.5
	Dry	Max	27.0	17.7	17.5	10.2	23.5	29.0	45.3
		Mean	**-20.2***	**-25.4***	**-29.7***	**-35.8***	**-39.1***	**-41.7***	**-41.7***
		HadGEM1	-6.3	-4.5	-7.5	-14.7	-25.0	-38.2	-35.4
		Min	-60.3	-63.3	-67.7	-76.8	-82.9	-83.7	-85.6
Santa Cruz	Wet	Max	15.4	15.7	16.6	16.2	17.7	15.7	15.7
		Mean	**-9.1**	**-8.6**	**-9.0**	**-9.9***	**-12.3***	**-14.0**	**-14.2**
		HadGEM1	-9.8	-6.8	-9.0	-12.4	-13.4	-10.7	-10.8
		Min	-23.7	-22.8	-23.9	-31.2	-44.5	-53.8	-61.4
	Dry	Max	70.3	72.3	88.5	109.2	121.8	119.8	116.7
		Mean	**0.2**	-0.1	**-0.6**	**-1.7**	**-1.9**	**-2.3**	-1.0
		HadGEM1	9.2	9.2	15.2	5.8	2.8	-2.6	-1.5
		Min	-23.0	-31.3	-41.8	-39.8	-42.1	-44.4	-49.4
Doce	Wet	Max	57.2	86.3	105.8	66.6	58.7	54.8	65.4
		Mean	-5.2	-5.9	**-3.0**	-4.4	-8.4	**-12.7**	**-15.4**
		HadGEM1	9.3	19.3	34.9	32.6	29.7	20.2	31.6
		Min	-64.6	-82.3	-57.7	-50.0	-57.6	-75.5	-70.6
	Dry	Max	107.7	119.3	136.2	104.5	106.9	102.3	68.4
		Mean	**-3.8**	**-1.8**	**0.8**	**-4.5**	-5.9	**-10.6**	**-17.2**
		HadGEM1	27.3	45.0	84.6	75.6	55.3	24.6	45.5
		Min	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0
Rio Colorado	Wet	Max	641.8	641.8	15094.9	17612.5	50816.3	36511.2	33444.7
		Mean	**12.4**	**13.5**	**640.9**	**747.3**	**2185.3**	**1563.0**	**1427.0**
		HadGEM1	-14.5	-5.0	-7.6	-4.9	-8.1	-11.2	5.2
		Min	-62.7	-59.4	-61.7	-73.4	-75.6	-86.2	-86.5
	Dry	Max	37.8	36.6	873.5	1134.5	1113.8	616.6	380.6
		Mean	**-13.0**	**-16.7**	**18.8**	**29.8**	**26.8**	**3.1**	**-11.3**
		HadGEM1	5.3	14.8	20.2	23.3	8.3	-1.1	-9.1
		Min	-65.0	-71.0	-76.4	-80.0	-82.8	-82.0	-82.0
Mearim	Wet	Max	39.3	51.2	56.3	61.9	82.3	106.1	124.3
		Mean	-4.8	0.3	-0.0	0.0	1.2	5.5	10.3
		HadGEM1	-16.3	-10.0	-20.2	-33.7	-27.7	-15.4	-9.3
		Min	-63.1	-47.5	-58.2	-78.0	-97.4	-100.0	-100.0
	Dry	Max	106.9	63.1	60.8	135.7	207.1	249.8	355.8
		Mean	-2.2	-4.5	-0.8	-2.6	1.9	9.0	12.1
		HadGEM1	3.7	5.0	17.1	2.2	12.4	5.9	21.8
		Min	-50.1	-53.2	-55.8	-79.3	-97.1	-94.1	-92.0

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Basin	Season		Future Time Periods						
			2020s	2030s	2040s	2050s	2060s	2070s	2080s
Paraiba	Wet	Max	49.5	85.0	92.5	97.7	96.5	121.7	103.6
		Mean	0.5	-0.1	3.3	**1.0**	2.2	**0.1**	**-3.1**
		HadGEM1	8.0	10.6	20.1	14.2	4.8	-4.9	-2.8
		Min	-42.2	-32.2	-28.7	-38.9	-40.0	-57.6	-42.2
	Dry	Max	69.3	143.5	145.4	325.1	250.1	232.4	51.4
		Mean	-4.8	**3.6**	3.3	6.8	**-0.0**	**-1.9**	**-13.9**
		HadGEM1	22.3	17.8	29.2	22.8	20.3	9.5	22.8
		Min	-53.2	-68.0	-53.8	-61.0	-71.8	-91.4	-91.6

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