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Regional aspects of future precipitation and meteorological drought characteristics over Southern South America projected by a CMIP5 multi-model ensemble

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ABSTRACT: This article addresses the regional impacts of climate change on precipitation and meteorological drought over Southern South America (SSA) through a CMIP5 multi-model ensemble based on 15 General Circulation Models (GCMs) forced under two different greenhouse gas concentration pathways (RCP4.5 and RCP8.5). An assessment of the biases in the representation of the precipitation annual cycle was performed over the 1979–2008 period over five regions within SSA, based on a comparison between the GCMs precipitation outputs with the Global Precipitation Climatology Centre (GPCC) dataset. The multi-model ensemble well reproduces the shape of the annual cycle of precipitation over most of SSA, although the monthly totals were overestimated (underestimated) over the North-West and South (North-East and Central-East) regions. Changes in precipitation and meteorological drought characteristics were identified by the difference for early (2011–2040) and late (2071–2100) 21st century values with respect to the 1979–2008 baseline, using the standardized precipitation index as a short- and long-term drought indicator. Future climate conditions are expected to modify the regional characteristics of meteorological droughts over SSA, but the range of uncertainty in the expected changes is high. A significant increase in the number of drought events in all the regions for most of the 21st century sub-periods is projected for the multi-model ensemble. The mean duration of drought events will be shorter, with no significant changes in the severity of droughts and the occurrence of multi-decadal changes in the number of critical dry months is likely, although the significance in the changes depends on the region, future time horizon and greenhouse gas concentration pathways. These results overlap with a projected increase in precipitation over most of the regions, which has a strong seasonality and, therefore, will have some implications upon the future meteorological drought developments and the agricultural and hydrological practices in SSA.

KEY WORDS meteorological drought; CMIP5 models; standardized precipitation index; climate change; Southern South America

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1. Introduction

Droughts are perceived as one of the costliest and least understood natural disasters, given the difficulty in defining its beginning and end, its slow development and its multiple regional aspects. The impacts of drought are evident at the environmental level, through the acceleration of desertification processes, generating an increase in the fire risk, affecting natural habitats and ecosystems and limiting the availability of water for domestic and industrial use. The success of drought preparedness and mitigation depends, to a large extent, upon timely information on drought onset, progress and areal extent (Morid *et al.*, 2006).

In Southern South America (SSA), agriculture and hydrology have social and economical relevance. According to Popescu *et al.* (2012), rainfed agriculture represents the 92% of the agricultural lands in Argentina; 90% in Bolivia and Brazil; 97% in Uruguay and 60% in Paraguay. The La Plata Basin, the fifth most important basin in the world and one of the biggest water reservoirs of the planet, covers a great portion of the above mentioned countries. The hydropower generation in the La Plata Basin represents the 76% of the total generated hydropower of the five countries that encompasses the basin (Cuya *et al.*, 2013). Trends at different time scales during the second part of the 20th century showed an increase in precipitation totals (Castañeda and Barros, 2001; Liebmann *et al.*, 2004; Penalba and Vargas, 2004; Boulanger *et al.*, 2005; Barros *et al.*, 2008). Over most of SSA, this temporal variability was accompanied by an increase in extreme precipitation events (Penalba and Robledo, 2010), a decrease in dry

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days (Rivera *et al.*, 2013) and an increase in the soil water content (Forte Lay *et al.*, 2008). These trends, together with adequate soils and the technological development, favoured the expansion of the agricultural frontier over Argentina. Also, in all the countries of SSA, an increase in the hydropower generation was evident, a condition that was apparently favoured by the precipitation trends since 1970s (Atlas de Energías Renovables del Mercosur, 2013). However, droughts were a recurrent phenomenon over the region, with enormous economical implications. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) stated that increases in intensity and/or duration of drought is likely in many regions of the world since 1970 (IPCC, 2013). Dai (2011) indicated that during the last three decades, the occurrence of large-scale droughts was observed in all the continents. Particularly, SSA experienced large-scale droughts during the years 1962, 1965/1966, 1971/1972, 1988/1989, 1995/1996, and 2008/2009 (Rivera and Penalba, 2014).

Future projections indicated that trends in precipitation over SSA for the end of the 21st century will continue with the pattern observed during the second half of the 20th century (Marengo *et al.*, 2009; Barros *et al.*, 2013; Blázquez and Núñez, 2013). However, Junquas *et al.* (2012) showed that the first half of the 21st century will be characterized by a diminishing in precipitation values related to summer (December to February), which is in line to the recent observed trends in the period 1990–2010 (Krepper and Zucarelli, 2012; Rivera and Penalba, 2014). Moreover, Blázquez *et al.* (2012) analysed the future changes in the annual cycle of mean precipitation over 12 sub-regions of SSA, finding significant positive changes during autumn season in most of the regions. Besides the evaluations of changes in precipitation at different time scales, the changes in drought characteristics – frequency, duration, severity – is not properly documented over the region. A baseline assessment of the future changes in drought characteristics over SSA was performed by Penalba and Rivera (2013), which identified that an increase in the frequency of short- and long-term droughts is projected for the 21st century by a Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble over most of SSA, together with a decrease in its mean duration. These results were in line with the findings of Sheffield and Wood (2008), which performed a global assessment of the projected changes in droughts based on the Special Report on Emissions Scenarios (SRES) A2, A1B and B1. Nevertheless, the expected spatial pattern of changes obtained by Penalba and Rivera (2013) was highly heterogeneous, which prevents regional conclusions and warns about the need of a regional assessment taking into account the various precipitation features over SSA. This kind of analysis is relevant in order to identify whether these changes would present difficulties for water resource and drought contingency planning, agriculture and environmental management at a regional level (Vidal and Wade, 2009).

The aim of this article is to address the regional aspects of future drought characteristics over SSA through a CMIP5 multi-model ensemble for two greenhouse gas concentration pathways (RCP4.5 and RCP8.5). This study will give insight into further possible changes of drought at a regional basis, taking into account the different climatic features over SSA, especially regarding its precipitation patterns. Similar researches were carried out by Blenkinsop and Fowler (2007) over Europe; Strzepek *et al.* (2010) over United States and Kirono *et al.* (2011) over Australia. It is expected that the outcomes of this study will provide a measure of the likelihood of further drought changes under the CMIP5 framework, which was a key factor of the IPCC's AR5.

2. Data

The SSA region corresponds to the area of South America located south of 19°S. This region comprises the countries of Argentina, Chile, Paraguay, Uruguay and the southern portions of Bolivia and Brazil. The diverse patterns of weather, climate and climatic variability over SSA, arise from the long meridional span of the continent (Garreaud and Aceituno, 2007). In particular, spatial and temporal patterns of precipitation in the region are influenced by the combination of topography – with the Andes ranges standing out – the South Atlantic Convergence Zone (Kodama, 1992), a low-level jet (Virji, 1981; Vera *et al.*, 2006a) and the semi-permanent high pressure systems of the Atlantic and Pacific oceans. For more information regarding the physical mechanisms associated to the precipitation patterns over SSA, the reader may refer to Vera *et al.* (2006b), Garreaud and Aceituno (2007), Garreaud *et al.* (2009) and Insel *et al.* (2010), among others.

For the regional assessment, SSA was divided into five sub-regions: Northwest (NW), Northeast (NE), Central-West (CW), Central-East (CE) and South (S) (Figure 1). All the regions show a coherent behaviour from the climatological point of view of precipitation (Rivera *et al.*, 2013) and the regions resemble the spatial homogeneous patterns found in Bettolli *et al.* (2010) for the dry days and Rivera (2014) for the SPI at different time scales, which proves its appropriateness for the regional analysis.

Observed monthly rainfall totals over SSA were obtained from the Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis v6 gridded at $1° \times 1°$ resolution (Schneider *et al.*, 2014), totalizing 617 grid points excluding the southern oceans. This dataset spans the 1979–2008 period, which was selected as a baseline for the evaluation of future changes. The GPCC dataset was selected because of its agreement with the spatial and temporal patterns of rain gauge data over the region (Spennemann *et al.*, 2015). The spatial resolution of the dataset was selected in order to analyse a fair number of grid points per region – instead of the 2.5° resolution – avoiding the addition of uncertainty in the rainfall behaviour, which could be obtained by selecting the 0.5° resolution. The number of the grid points in each region is: 102 for NW, 166 for NE, 110 for CW, 76 for CE and 163 for S.

For the assessment of future drought conditions we used an ensemble of monthly modelled precipitation data from 15 General Circulation Models (GCMs) belonging to the

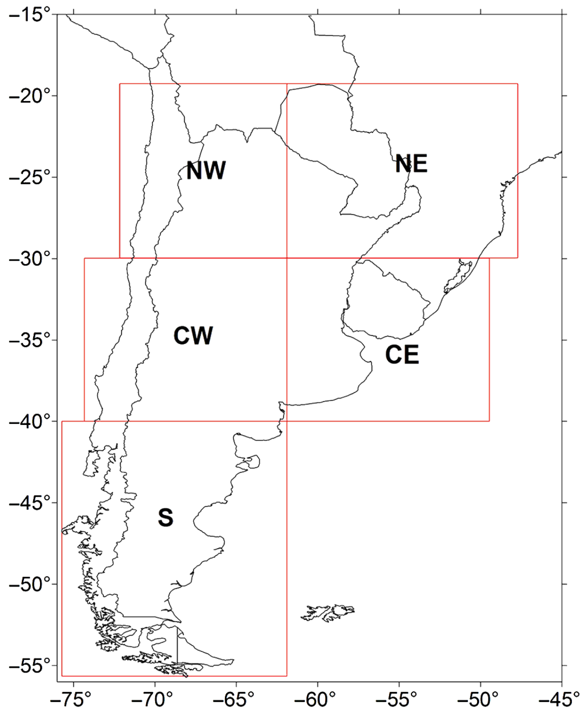

Figure 1. Regions used in this study: North-West (NW), North-East (NE), Central-West (CW), Central-East (CE), South (S).

CMIP5 experiments (Taylor *et al.*, 2012). Table 1 lists the selected models used in this study, with their respective modelling groups and countries. Criteria for the selection of models were based on the availability of data, primarily for future projections. Given that most of the models have different spatial resolutions, all the model outputs were regridded to $1° \times 1°$ resolution using bilinear interpolation (Accadia *et al.*, 2003). Even when the resolution of most of the models is lower than 1°, the selection was made to match the resolution of the GPCC dataset. This regridding procedure can be a source of uncertainty. However, the spatial extent of droughts is larger than other climate events, like extreme rainfall, and therefore, its contribution to uncertainty should be small. Moreover, the use of bilinear interpolation has a very little smoothing effect in the value of precipitation extremes (Kopparla *et al.*, 2013); and Schwalm *et al.* (2013) identified that the selection of the spatial resolution and regridding algorithm has the lowest importance in the evaluation of model skills. The 15 GCM runs considered in this study cover two of the four Representative Concentration Pathways (RCPs) available in the current scientific literature: the RCP4.5, which represents a stabilization without overshoot pathway to 4.5 W m^{-2} at stabilization after 2100; and the RPC8.5, which represents a rising radiative forcing pathway leading to 8.5 W m^{-2} by 2100 (van Vuuren *et al.*, 2011). The CO_2 concentration levels for scenarios RCP8.5 and RCP4.5 are similar to the levels of A1F1 and B1 SRES scenarios, respectively (Dike *et al.*, 2014). Three periods of 30 years were considered in order to evaluate changes in future climate: current climate (1979–2008) and projections for the early 21st century (2011–2040) and late 21st century (2071–2100). Moreover, for the assessment of decadal variations in the number of months in which the spatial extent of droughts affect more than 30% of the grid points in each of the regions we selected five additional periods: 2021–2050, 2031–2060, 2041–2070, 2051–2080, and 2061–2090.

3. Methodology

In order to identify drought characteristics, we used the standardized precipitation index (SPI) (McKee *et al.*, 1993). The SPI is a meteorological drought index as it is based solely on precipitation data (Belayneh *et al.*, 2014). It has been recommended by the Lincoln Declaration on Drought Indices (Hayes *et al.*, 2011) and according to Penalba and Rivera (2015) is the most adequate drought index for SSA. The SPI was calculated on time scales of 3 and 12 months, which enables the representation of short- and long-term droughts, respectively. Given its focus on precipitation, SPI droughts are most relevant for rainfall-dependent activities such as rainfed agriculture or municipal water supply in certain regions (Strzepek *et al.*, 2010). The time scale over which precipitation deficits accumulate functionally separates different types of drought (McKee *et al.*, 1993) and, therefore, this hazard will impact different sectors and activities depending on the time scale considered, as stated in Edwards and McKee (1997).

For the calculation of the SPI, the accumulated precipitation time series were divided in 12 monthly series of 30 years, each of them were fitted to a theoretical probability density function that represents the behaviour of precipitation over the study area. Following Penalba and Rivera (2012), we used the two-parameter gamma probability density function, which appropriately fits the accumulated precipitation in SSA for the 1961–2008 period in time scales from 1 to 12 months. This was verified for the time scales –3 and 12 months – and periods – current climate, early and late 21st century – used in the study, obtaining more than 95% of grid points with significant fits at the 95% level, according to the Anderson-Darling test (Anderson and Darling, 1952). The 12 probability density functions for each time scale and period were translated to 12 cumulative density functions. Given that the gamma distribution is undefined for $x = 0$, the relative frequency of precipitation containing zero values (q) was considered for the cumulative density function:

$$H(x) = q + (1-q)\,G(x) \tag{1}$$

where $G(x)$ is the gamma cumulative density function. Finally, an equi-probability transformation from the cumulative density functions to the standard normal distribution with the mean of 0 and the variance of 1 were performed to obtain the SPI.

The SPI was widely used for the analysis of current and future drought conditions. For example, Al-Qinna *et al.* (2011) used the SPI for the assessment of present and future climate droughts over Jordania. Heinrich and Gobiet

Table 1. List of the 15 CMIP5 global climate models considered for the study.

Model	Institute (country)	Resolution (Latitude × Longitude)
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (Australia)	1.24° × 1.88°
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration (China)	2.81° × 2.81°
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University (China)	2.81° × 2.81°
CCSM4	National Center for Atmospheric Research (USA)	0.94° × 1.25°
CNRM-CM5	Centre National de Recherches Meteorologiques (France)	1.41° × 1.41°
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization (Australia)	1.87° × 1.87°
GISS-E2-R	NASA Goddard Institute for Space Studies (USA)	2.0° × 2.5°
INMCM4	Institute for Numerical Mathematics (Russia)	1.5° × 2.0°
IPSL-CM5A-LR	Institut Pierre-Simon Laplace (France)	1.87° × 3.75°
IPSL-CM5B-LR	Institut Pierre-Simon Laplace (France)	1.87° × 3.75°
MIROC5	Atmosphere and Ocean Research Institute, University of Tokyo (Japan)	1.41° × 1.41°
MPI-ESM-LR	Max Planck Institute for Meteorology (Germany)	1.87° × 1.87°
MPI-ESM-MR	Max Planck Institute for Meteorology (Germany)	1.87° × 1.87°
MRI-CGCM3	Meteorological Research Institute (Japan)	1.13° × 1.13°
NorESM1-M	Norwegian Climate Centre, Norway	1.87° × 2.5°

(2012) evaluated the future changes in dry spells identified through the SPI over Europe. At a global scale, Orlowsky and Seneviratne (2013) identified changes of drought in selected hot spot regions, while Taylor *et al.* (2013) analysed the uncertainties in future drought projections based on SPI, among other drought indices. The SPI was calculated for the 3 and 12 months accumulated precipitation from the GPCC database and the simulated precipitation from the multi-model ensemble in the same time scales for the three time periods considered. A drought event was defined as the period of time where SPI values are below to −1.0, which means that precipitation departures from average conditions exceed one standard deviation. Five parameters were considered for drought characterization: frequency – number of droughts over the period of interest; duration – average duration of all drought events; severity – average SPI values of all drought events; maximum duration and maximum severity.

In order to identify significant changes between the meteorological drought parameters of current and future climate, we used a bootstrap resampling procedure (Efron and Tibshirani, 1993). The bootstrap is a computing-intensive statistical method that provides a confidence band around the multi-model ensemble parameters. Its advantage is that it is less restricted by parametric assumptions than more traditional approaches (Mudelsee, 2011). The confidence intervals were based on 1000 resamples for the 95% significance level; therefore, they are given by the interval between the 50th and the 950th largest values. By comparing the values of the drought parameters based on the multi-model ensemble with the percentile-based confidence interval constructed with the resampling of the present time values, we can assess whether the future drought characteristics will significantly change. This methodology was also applied to assess future changes in the number of months in which the spatial extent of droughts affect more than 30% of the grid points in each of the regions. The 30% threshold was previously used by Krepper and Zucarelli (2012) in order to define critical dry months over the La Plata Basin. The significance test was applied only to assess changes based on the multi-model ensemble mean; nevertheless, all the calculations were performed for both individual GCMs and ensemble mean.

The mean error in the representation of the monthly precipitation values for each model and the multi-model ensemble was computed as the annual average of the following expression:

$$\text{Mean error} = \{100 \text{ x Precipitation [GCMs]} / \text{Precipitation [GPCC]}\} - 100 \quad (2)$$

4. Results

4.1. Regional precipitation features and model skills

In order to analyse the skill of the model precipitation outputs, the annual cycle of precipitation for the period 1979–2008 was calculated for the GPCC database at a regional basis and compared with each of the GCMs and multi-model ensemble mean. Figure 2 shows the comparison between the observed and the modelled precipitation annual cycle for the selected five regions. The NW region is characterized by a marked precipitation annual cycle, with wet summers and dry winters (Figure 2(a)). The precipitation during the warm season is associated to the combination of the humid fluxes from the tropical continental zone and the Atlantic Ocean (Doyle and Barros, 2002; Vargas *et al.*, 2002). Most of this region possesses a semi-arid climate (Fernández and Busso, 1997; Vuille and Ammann, 1997), with annual precipitations less than 400 mm according to the GPCC data (Figure 2(a)). The GCMs tend to overestimate the monthly precipitation values during all the year, with mean errors higher than 100% in most of the models. This wet bias was identified by Insel *et al.* (2010) and Gulizia and Camilloni (2014), among others, which could be associated to a misrepresentation

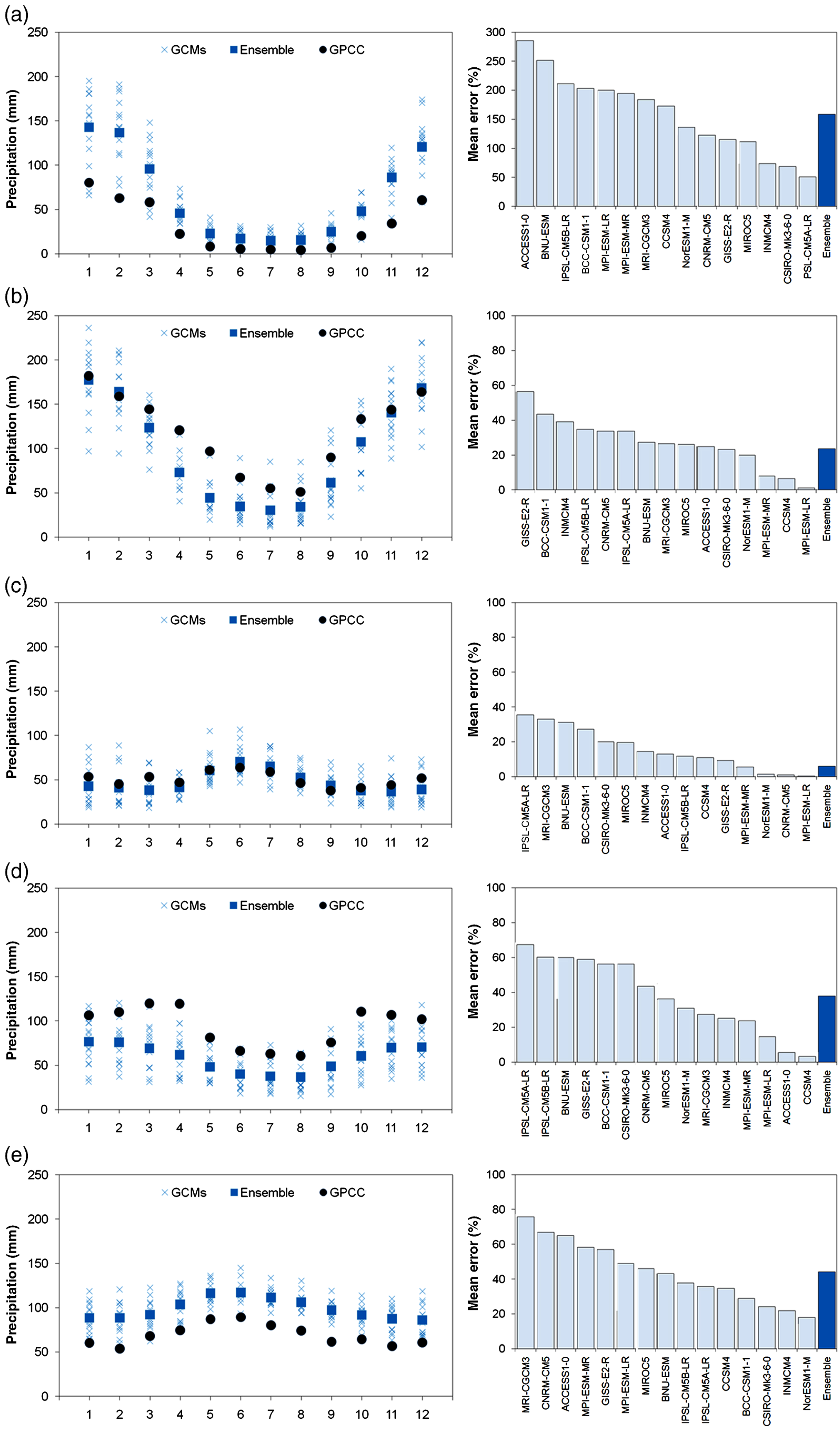

Figure 2. Observed and modelled precipitation annual cycles for the 1979–2008 period. Left panels show the monthly mean precipitation values for the GPCC (circles), the individual GCMs (crosses) and the multi-model ensemble mean (squares). Right panel shows the mean errors for each GCM and for the multi-model ensemble mean. Regions are (a) NW, (b) NE, (c) CW, (d) CE, (e) S. Notice that the scale for the mean error of the NW region is three times larger than for the other ones.

of the complex topography and the moisture transport in the region. The multi-model ensemble mean shows errors higher than 150%, with large differences in the precipitation amounts of the warm season. In the case of the NE region, the annual cycle is pronounced (Figure 2(b)) and the combination of deep convection during the warm season and the passage of cold front systems during the cold season leads to high annual precipitation values (Montecinos *et al.*, 2000). There is an underestimation of precipitation during the March–October period in most of the GCMs, which leads to a 20% error in the multi-model ensemble mean (Figure 2(b)). Also there is a shift in the month of minimum precipitation – from July in the GCMs to August in the observations – and a tendency of GCMs to represent a symmetrical annual cycle. The CW region shows higher precipitations during the cold season (Figure 2(c)), which reflects the dominance of the precipitation cycle in Central Chile and the Andes ranges (Aceituno, 1988). The precipitation cycle east of the Andes is influenced by continental air masses that contribute to the summer precipitation totals (Compagnucci *et al.*, 2002; Masiokas *et al.*, 2006). This precipitation pattern is a consequence of the interaction between the humid fluxes from the quasi-stationary South Pacific anticyclone and the Andes topography (Masiokas *et al.*, 2006), the occurrence of cut-off lows during the cold season (Garreaud and Fuenzalida, 2007) and the passage of cold fronts (Seluchi *et al.*, 2006). The multi-model ensemble mean gives a very good representation of the annual cycle, with a mean error of 6%. Observed precipitation in the CE region (Figure 2(d)) shows a semi-annual cycle as a result of two rain-producing factors: warming (represented by the annual cycle) and advection of humidity (represented by the semi-annual cycle) (Penalba and Vargas, 2004). This semi-annual cycle is not represented by the multi-model ensemble mean, although some individual GCMs – e.g. ACCESS1-0 and CCSM4 – resemble this pattern. This could be because of the good performance of CCSM4 in simulating convection and large-scale precipitation features (Yin *et al.*, 2013), and also because of the good agreement of ACCESS1-0 simulations of annual precipitation features (Pascale *et al.*, 2014). Regarding precipitation monthly values, GCMs tend to underestimate accumulated precipitation in all the months, leading to a multi-model ensemble mean error close to 40%. This result was also found by Gulizia and Camilloni (2014), who obtained a dry bias of 25–50% in both CMIP3 and CMIP5 simulations. Finally, the annual cycle of the S region shows a pattern similar to the one observed in the Central-West region, with the wet season during autumn and winter (Figure 2(e)). Both the multi-model ensemble mean and the individual GCMs tend to overestimate all the monthly precipitation values, with an error of approximately 45% for the multi-model ensemble mean. It is noteworthy that no individual GCM stood out in all the regions considered.

4.2. Future changes in regional precipitation patterns

Regarding the future changes in mean annual precipitation, the multi-model ensemble mean under both RCP4.5 and RPC8.5 scenarios projects precipitation increases during the 2011–2040 period for the NW, CW and CE regions, while for the S region the projections show no changes with respect to the 1979–2008 period and a slight decrease in annual precipitation for the NE region (Figure 3). Precipitation increases during winter and autumn are projected for the NW region, although there is a large uncertainty among the different GCMs which can be attributed to the biases in the representation of the mean values and seasonality of precipitation over the region. Regarding the NE region, the slight decrease projected for the mean annual precipitation could be associated with an expected decrease in winter precipitation values, which is supported with the results of Marengo *et al.* (2009), who analysed future changes of climate in South America with three regional models. The highest dispersion among the GCMs over the NE region is observed between May and November. For the CW region, projections indicate increases in the September–April period, i.e. the wet season, which can result in an increase in seasonality of precipitation over the region. This result is coherent with the findings of Blázquez *et al.* (2012) for the December–April period over a region located within the CW. Increases during the autumn season are expected for the CE region, while a slight decrease is projected for June and July. Finally, projections for the 2011–2040 period shows no changes in the annual cycle of precipitation of the S region, which was also shown by Blázquez *et al.* (2012). Over this region, projections for the individual GCMs indicate changes less than 40% in precipitation totals for all the months, which is noteworthy in comparison with the dispersion observed in the rest of the regions. This section gives a quantitative assessment of the expected changes in precipitation amounts and its seasonality and no significance tests were applied.

Differences for the 2071–2100 period with respect to the 1979–2008 baseline indicate a similar pattern of expected regional changes than in the case of the 2011–2040 period (not shown), which could indicate that the changes in the process that control the regional precipitation patterns will remain constant during the 21st century.

Taking into account the results of the previous section, the use of individual GCMs for the assessment of precipitation changes at a regional basis in SSA is not advisable, given the spread in the evaluation of precipitation characteristics and its future changes. This uncertainty will be present in any statistic related to precipitation and its variability, as the case of meteorological drought parameters. However, the use of a multi-model ensemble and its mean can contribute to a better estimation of future precipitation and drought characteristics.

4.3. Future changes in regional drought characteristics

4.3.1. *Short-term droughts – SPI3*

Figure 4 shows the regional characteristics of droughts at 3-month time scale, for the 1979–2008 period and for the beginning and end of the 21st century for the RCP4.5 and RCP8.5 climate change simulations. Based on the

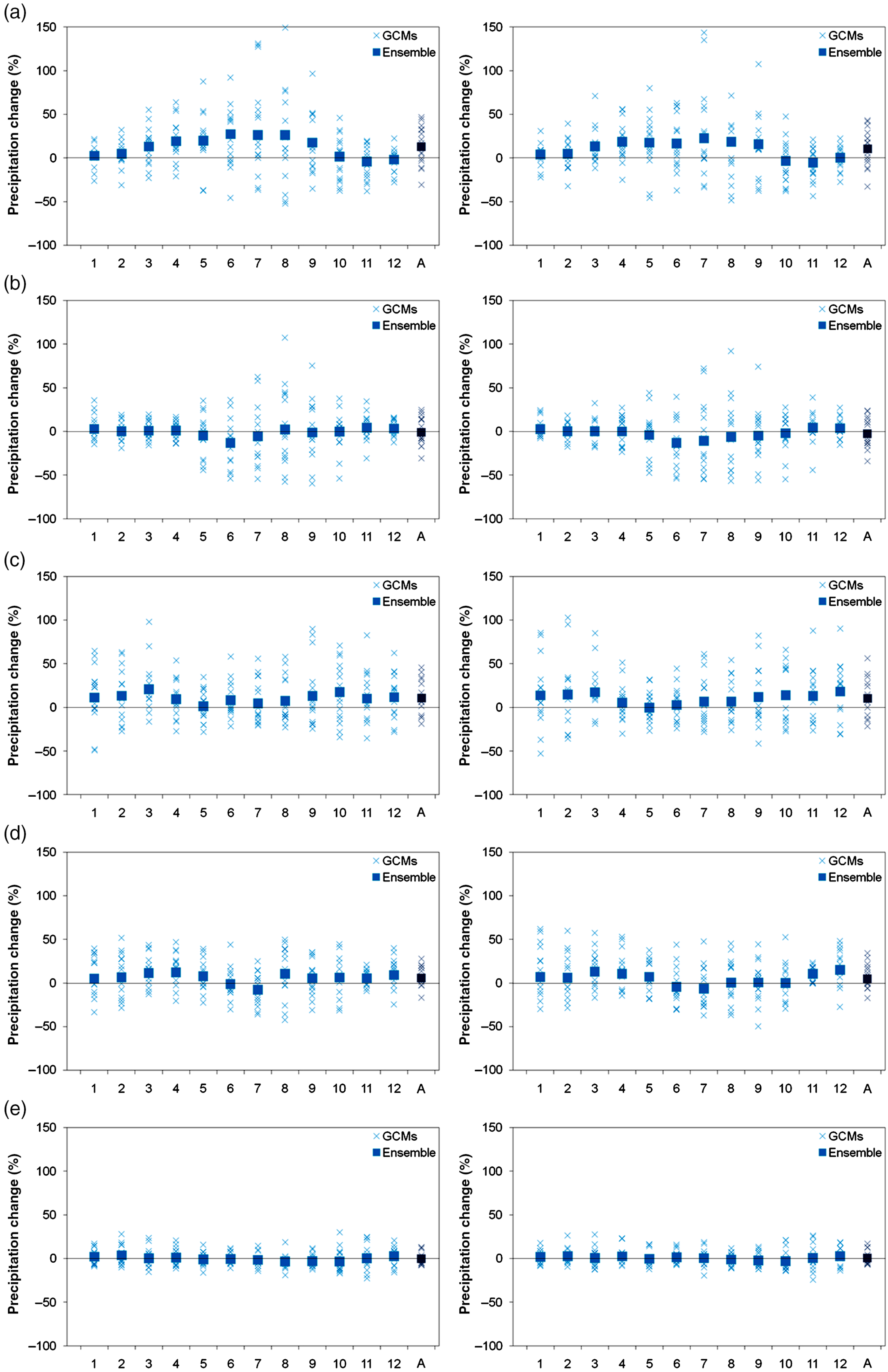

Figure 3. Projected changes (in %) in mean monthly and annual precipitation for the period 2011–2040 relative to the 1979–2008 baseline. Left (right) panel shows the projections under the RCP4.5 (RCP8.5) scenario. Regions are (a) NW, (b) NE, (c) CW, (d) CE, (e) S.

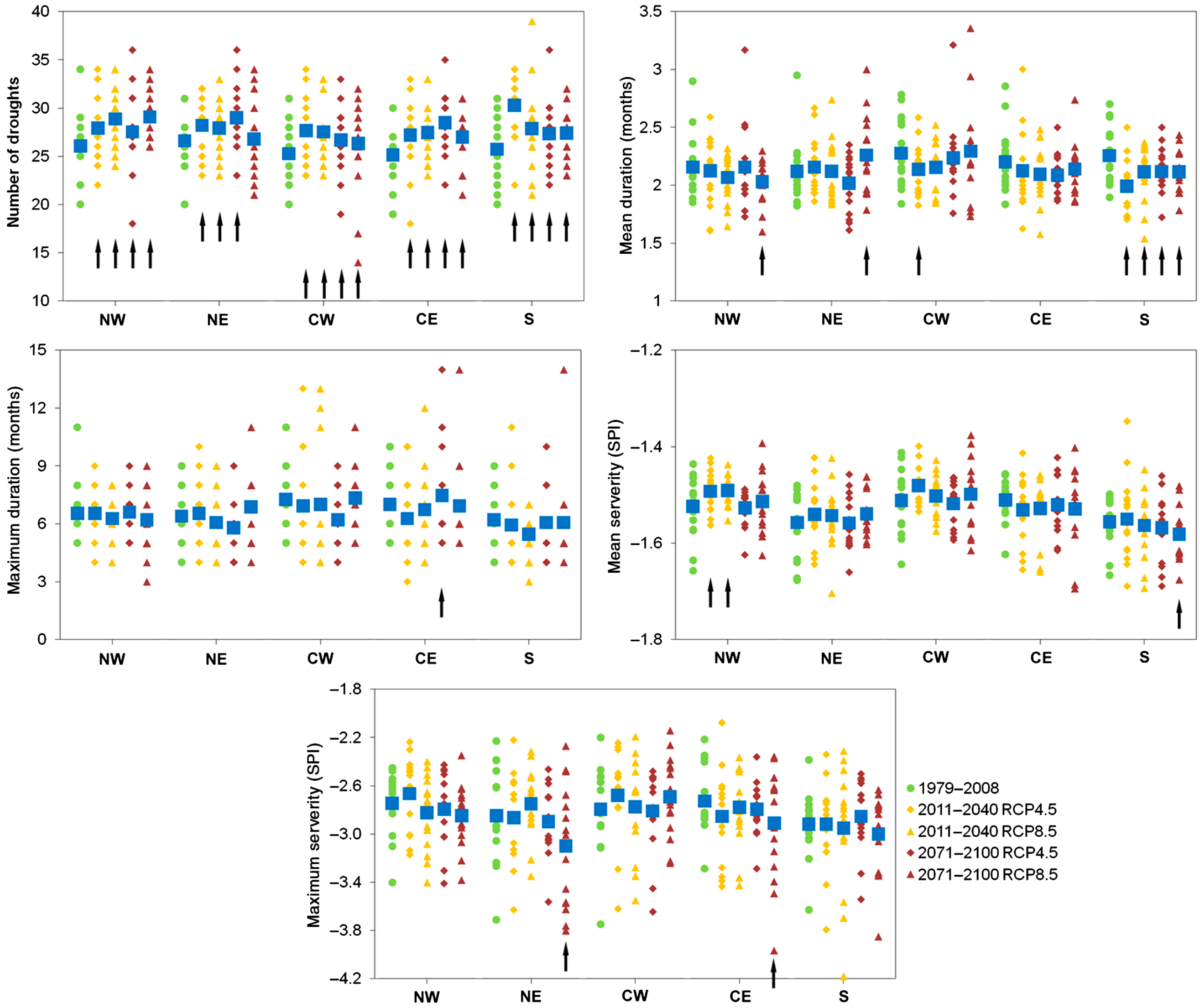

Figure 4. Regional SPI3 parameters for the 1979–2008 baseline and for the early and late 21st century, projected for the RCP4.5 and RCP8.5 scenarios. Squares indicate the multi-model ensemble mean results. Arrows indicate significant changes in the drought parameters.

multi-model ensemble mean results, it is expected a significant increase in the number of short-term droughts events during the 21st century in all the regions of SSA. The multi-model ensemble mean projects between 26 and 31 drought events for the 30-year period considered, although a large dispersion is observed in the individual GCMs. Regarding the mean duration, projections indicate a decrease for the 21st century, which is in line with the increase in the number of drought events and could be indicative of an increase in the interannual variability of precipitation over SSA. Significant changes are projected mainly for the S region, with mean values around 2 months. No significant changes were projected for the maximum duration of droughts, except for a significant increase for the late 21st century over the CE region under the RCP4.5 scenario. In all the cases, maximum duration of short-term drought events is projected to have between 5 and 8 months taking into account the multi-model ensemble mean results. A non-significant increase in the severity of short-term droughts is projected for the CE and S regions, while for the rest of SSA the multi-model projections indicate a non-significant decrease in the severity values, mainly during the 2011–2040 period. For the early 21st century the decrease in severity will be significant in the NW region. In all the cases the uncertainty depends mainly on the GCM considered and to a lesser extent on the region and period analysed.

4.3.2. *Long-term droughts – SPI12*

In the case of long-term droughts, significant changes in the multi-model ensemble mean results are expected in all the regions for the 21st century, with a generalized increase in the number of droughts and a decrease in its mean duration (Figure 5). Multi-model projections indicate the occurrence of 10–15 drought events within the 30-year periods, with higher mean values in the S regions. In the case of the NE region, significant increases in the number of long-term droughts are projected under the RCP4.5 scenario, with 2–3 additional events for the 30-year periods. This is in line with a significant decrease in the drought

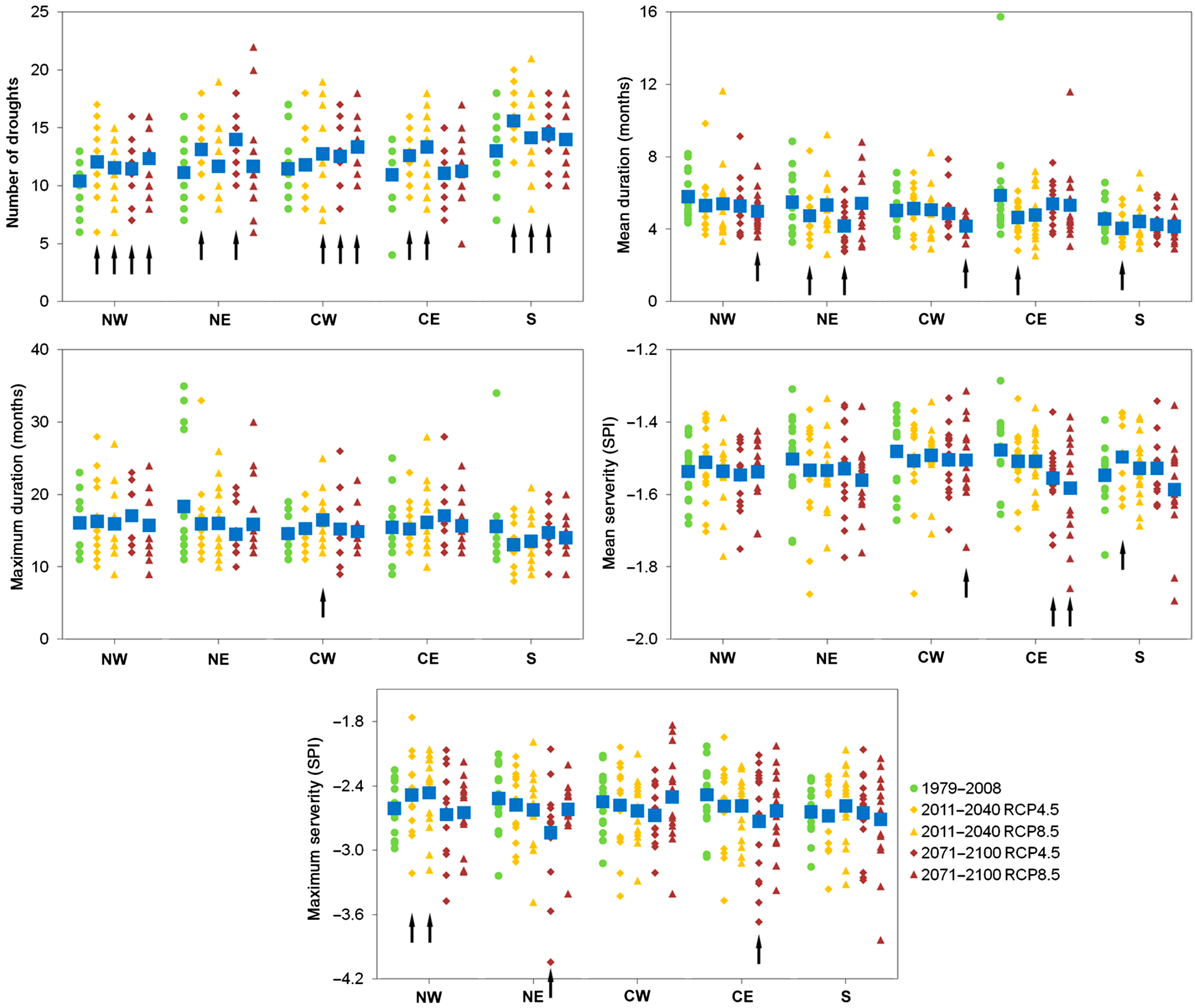

Figure 5. Regional SPI3 parameters for the 1979–2008 baseline and for the early and late 21st century, projected for the SPI12 parameters.

mean duration over the region. In the CW region, projections indicate a larger number of drought events for the late 21st century, particularly under the RCP8.5 scenario. Significant increases in the number of droughts are expected during the 2011–2040 period over the CE region, while projections indicate near normal conditions for the 2071–2100 period in comparison to the 1979–2008 baseline. Multi-model ensemble average drought durations are likely to be above 4 months in all the regions. Significant decreases in drought duration are expected during the late 21st century under the RCP8.5 scenario in the NW and CW regions, and also for the early 21st century over the CE and S regions under the RCP4.5 scenario. This last scenario projects significant decreases in the NE region for both future periods. The uncertainty in the mean drought duration tends to be smaller for the CW, S and CE region in comparison to the NW and NE regions. Regarding the maximum duration of the long-term droughts, no changes are expected for the NW region, while projections indicate decreases in the NE and S regions and increases in the CW and CE regions. The only significant increase is projected for early 21st century under the RCP8.5 scenario over the CW region. The occurrence of multi-year droughts is likely in all the regions of SSA during the 21st century. The mean drought severity is projected to increase during the 21st century over the NE, CW and CE regions (Figure 5), although for NE region the expected increases are non-significant, as the case as the decreases projected for the NW region. A significant decrease is projected under the RCP4.5 scenario for the early 21st century over the S region. In the case of the maximum severity, significant increases are expected during the 2071–2100 period under the RCP4.5 scenario for the NE and CE regions, and a significant decrease is likely during the early 21st century over the NW region.

4.3.3. *Number of critical dry months*

In order to perform a thorough assessment of the regional aspects of drought, the changes in the number of months in which each of the regions are affected by drought conditions at least in 30% of the grid points were analysed. Figure 6 shows the number of critical dry months for

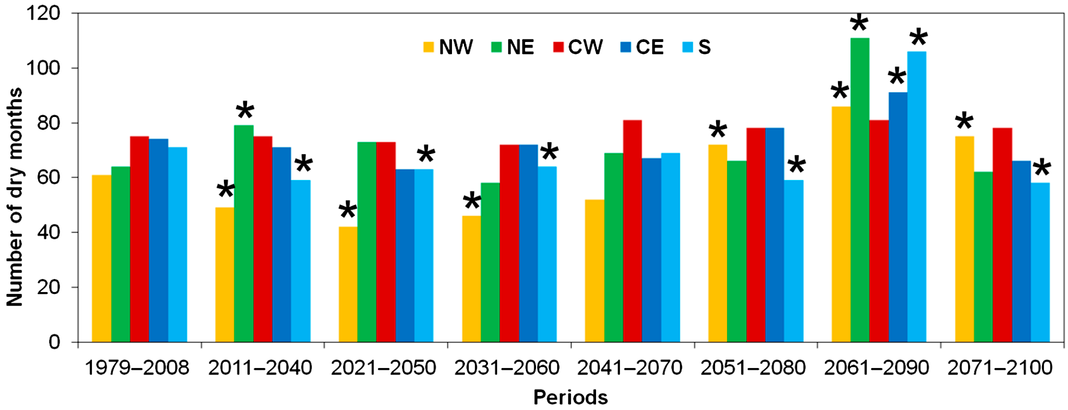

Figure 6. Number of critical dry months (months with more than 30% of the regions affected by drought conditions) based on the SPI12 time series from the multi-model ensemble mean precipitation outputs, for the baseline period and for seven 30-year periods between 2011–2040 and 2071–2100. Asterisks indicate significant changes with respect to the 1979–2008 period under the RCP4.5 scenario.

each region and period of time, based on the multi-model ensemble mean SPI12 under the RCP4.5 scenario. The months were calculated based on the SPI12 time series in order to avoid high-frequency variations that can hide significant differences in the area affected with drought conditions. Except for 2041–2070, projections indicate that in all the periods at least two regions will experience significant changes in the number of critical dry months with respect to the baseline values. A significant decrease is expected during the 2011–2040 to 2031–2060 period in both the NW and S regions. The first half of the 21st century shows also significant increases in the NE region for the 2011–2040 period. Significant increases in the number of critical dry months are expected during the 2061–2090 period in all the regions except for the CW. In the case of the NE region, 5 of the 30 years between 1979 and 2008 are affected by drought conditions that spans more than 30% of the grid points, while the number critical dry months for the 2061–2090 period constitutes almost 10 years. It is evident a multi-decadal variation in the NW region, from significant decreases in the first three 30-year period to significant increases in the second half of the 21st century. Finally, significant decreases are projected for the 2051–2080 and 2071–2100 periods over the S region.

5. Discussion and conclusions

This article addressed the regional aspects of future precipitation and meteorological drought characteristics over SSA through a CMIP5 multi-model ensemble based on 15 GCMs forced under two future radiative forcing scenarios (RCP4.5 and RCP8.5). Two periods were selected for the evaluation of significant changes in precipitation and drought parameters: 2011–2040 (early 21st century) and 2071–2100 (late 21st century). Meteorological drought conditions were defined through the SPI for time scales of 3 and 12 months, in order to evaluate the effect of climate change upon the characteristics of short- and long-term droughts, respectively. This is extremely important given the implications that agriculture and water resources have on the society and economy of SSA. Other aspect that is valuable for the decision-making process is the seasonality of the changes in precipitation, that could affect the activities during particular periods of the year, like the crops planting, the cattle raising and the hydropower generation. All these aspects have to deal with the uncertainty of future projections, which also needs to be evaluated to give a complete panorama of the expected changes.

The findings of this study indicate that future climate conditions will modify the regional characteristics of both precipitation and droughts over SSA, although the range of uncertainty in the values of the expected changes is high and in some regions depends on the season considered. There is no single model or group of models that represents in an accurate way the precipitation characteristics in the five regions considered for the study. This was evaluated through a comparison of the model outputs and the GPCC gridded database during the 1979–2008 period. For example, the performance of the MPI-ESM-LR model is remarkable in the NE and CW regions, but has a bias of near 200 and 50% in the NW and S regions, respectively. In the case of the NW region, all the models possess a wet bias, which in most of the cases is above 100% of the mean precipitation. The best models over this region are the IPSL-CM5A-LR, the INMCM4 and the CSIRO-MK3-6-0, with an average overestimation of approximately 50%. The larger dispersion values are observed during the wet season, although during the dry season the low precipitation values recorded give enormous percentage errors. Precipitation outputs over the CW region have a dry bias during the autumn-winter season, with the multi-model ensemble mean error above 20%. The multi-model ensemble mean tends to reproduce the annual cycle over the CW region in a good way, i.e. over central Chile, the Andes ranges and the central-west portion of Argentina. Over the CE region most of the models have a dry bias in all the months, and the semi-annual cycle is poorly reproduced by the multi-model ensemble mean. The best models are the ACCESS1-0 and the CCSM4, with less than 10% mean error. Finally, a wet bias is evident in all the models over the S region, with a mean error of nearly 40%, although the

annual cycle is well reproduced. These results prevent the use of individual model outputs for the assessment of the future changes given that the model skills have a regional variation. However, the study allowed the identification of GCMs that have a good performance on a regional basis and can be useful for future research.

Regarding the future changes in precipitation, we calculated the precipitation change during the periods 2011–2040 and 2071–2100 with respect to the 1979–2008 averages. Based on the multi-model ensemble mean, an increase in the annual precipitation totals is projected for most of the regions, and seasonality changes are likely to increase (decrease) the amplitude of the annual cycle over the CE, CW and NE (NW) regions. This result can increase the occurrences of winter droughts, although can be helpful for the water storage during the summer, which could prevent water shortages. Nevertheless, two aspects must be considered: the uncertainty attributed to the dispersion of the GCMs outputs and the interannual variability, which plays a great role in the timing and amount of precipitations and has to be assessed for future water management purposes. One key to estimate and understand future precipitation variability is the assessment of the changes in the future drought characteristics. A common aspect in all the regions is that the multi-model ensemble mean projections indicate a significant increase in the number of drought events during the 21st century in comparison with the 1979–2008 baseline. This increase is in line with a decrease in drought durations, and it is independent upon the scenario, sub-period or SPI window considered. This result is indicative of an increase in precipitation variability at seasonal and interannual scales during the 21st century. In the case of the NW region, multi-model ensemble mean projections indicate that a significant increase in the number of drought events will be likely during both early and late 21st century under both climate change scenarios. The decrease in drought durations was significant only for the 2071–2100 period under the RCP8.5 scenario. Mean drought severity will decrease, with significant changes during the early 21st century for the short-term droughts. A multi-decadal oscillation could be responsible for the expected changes in the number of critical dry months – i.e. months with drought conditions affecting more than 30% of the grid points of each region – in this region, given the projected differences between the first and second half of the 21st century. Projections for the NE region shows some differences between SPI3 and SPI12 regarding the magnitude and significance of the changes. This could be indicative of the different future evolution of the process that controls drought occurrences at different time scales. RCP4.5 scenario shows significant increases (decreases) in the long-term drought events (duration), with also a non-significant increase in the severity. These results possess immediate impact over the water resources storage and hydropower generation, mainly during the low-flows season. Long-term droughts over the CW region are projected to have a significant increase over time, with higher number of events for the late 21st century, and a slight increase in its severity. A decrease in the mean duration of long-term droughts is projected but the maximum duration is expected to increase. Taking into account the future evolution of temperature over the region, these projections shows a real challenge for the hydrological droughts management, given strong dependence of streamflows to snowpack variations. In the case of the CE region, the pattern of long-term drought severity shows an increase with time, although the number of events and their duration will have no significant change during the late 21st century. Regarding short-term droughts, a decrease in the mean duration and an increase in the mean severity are likely. Multi-model ensemble mean projections for the S region show an increase in the number of droughts during the early 21st century under the RCP4.5 scenario. A decrease in the mean severity is likely for the long-term droughts, while the opposite occurs for the short-term droughts. In both early and late 21st century it is expected a significant decrease in the number of critical dry months. Therefore, although the occurrence of an increase in the number of drought events is projected, these will affect a smaller percentage of the region.

Uncertainty in the model outputs prevents a direct application of these results, for example for drought contingency plans; however, it shows a panorama of expected changes and can give insight into the evolution of drought hazard and its implications.

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