Received: 6 June 2022 | Revised: 19 October 2022 | Accepted: 6 November 2022

DOI: 10.1002/joc.7924

International Journal of Climatology RMetS

RESEARCH ARTICLE

Evaluation of long-term changes in precipitation over Bolivia based on observations and Coupled Model Intercomparison Project models

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Funding information
European Commission; Ministerio de Ciencia y Tecnología; Spanish Ministry of Science and FEDER; AXIS (Assessment of Cross(X)-sectorial climate impacts and pathways for Sustainable transformation)

Abstract

Using observations and model simulations from the 5th and 6th phases of the Coupled Model Intercomparison Project (CMIP5 and CMIP6, respectively), this study evaluated changes in monthly, seasonal, and annual precipitation over Bolivia from 1950 to 2019. Results demonstrate that observed precipitation is characterized by strong interannual and decadal variability. However, long-term precipitation trends were not identified on the annual scale. Similarly, changes in seasonal precipitation were almost nonsignificant ($p > .05$) for the study period. Spatially, albeit with its complex orography, no substantial regional variations in observed precipitation trends can be identified across Bolivia. In contrast, long-term precipitation trends, based on CMIP5 and CMIP6 models, suggest a dominance of negative trends, mainly during austral winter (JJA) (−10%) and spring (SON) (−15%). These negative trends were more pronounced in the lowlands of Bolivia (−20%). Overall, these contradictory results highlight the need for validating precipitation trend outputs from model simulations, especially in areas of complex topography like Bolivia.

KEYWORDS
Bolivia, CMIP5, CMIP6, precipitation, trends

1 | INTRODUCTION

Water availability is a major constraint for both natural and human environments worldwide. For this reason, the variability and trends in precipitation are strongly relevant in the current climate change context and several global studies have therefore analysed the possible trends in precipitation over the past decades (e.g., Knutson and Zeng, 2018; Dai, 2021). These assessments are usually based on low spatial resolution gridded datasets that have been developed using a low number of meteorological stations, particularly in regions with sparse networks of observations. This introduces uncertainties in the assessment of precipitation trends. Long-term time series of meteorological variables are scarce in large areas of southern America, and few studies have examined recent changes in precipitation on national and regional scales (López-Moreno *et al.*, 2014; Morán-Tejeda *et al.*, 2016; Marengo *et al.*, 2017; Garreaud *et al.*, 2020). Due to its complex topography, Southern America's assessment of precipitation trends is particularly important to better understand the varying responses of precipitation regimes to local and large-scale atmospheric mechanisms (Singh and Kumar, 1997; Salerno *et al.*, 2015; Vicente-Serrano *et al.*, 2017; Espinoza *et al.*, 2019a), as well as the differential influence of climate change processes on precipitation trends (Giorgi *et al.*, 1997; Luce *et al.*, 2013).

Bolivia is a country characterized by strong elevation gradients, varying between the lowlands (Amazon and Paraná-Paraguay basins) and the Andean plateau whose elevation almost exceeds 4,000 m a.s.l. The elevation gradient in Bolivia has a major impact on the region's complex climate patterns (Abadi *et al.*, 2018). Bolivia's annual precipitation varies widely by region, from 400 mm on the Andean plateau to more than 1,500 mm in the lowlands (Ribstein *et al.*, 1995; Francou *et al.*, 2003; Vuille and Keimig, 2004; Ronchail and Gallaire, 2006; Vuille *et al.*, 2008; Villar *et al.*, 2009; Vicente-Serrano *et al.*, 2016). Also, climate is characterized by strong intra-annual variability, with marked dry and humid seasons (Hardy *et al.*, 1998). Previous research indicates that the Andean plateau and the lowlands have experienced different climate evolution over the last few decades, particularly for drought (Ronchail, 1995; Seiler *et al.*, 2013a; 2013b; Vicente-Serrano *et al.*, 2015). The decrease in precipitation could have direct implications on human activities and the environment in the lowlands and the Andean plateau regions as well.

Precipitation in the lowlands is expected to decline as temperatures rise in future climate, particularly in scenarios with high greenhouse gas emissions (Douville *et al.*, 2021). Nevertheless, findings based on precipitation scenarios must be evaluated carefully, recalling that numerous studies have warned that long-term trends, provided by models, during the historical period are generally inconsistent with those based on observations (i.e., either overestimated or underestimated observed precipitation; van Oldenborgh *et al.*, 2013; Zebaze *et al.*, 2019; Peña-Angulo *et al.*, 2020; Vicente-Serrano *et al.*, 2021).

The assessment of long-term precipitation trends in Bolivia is lacking. Using data from 1965 to 1985 and 1985 to 2005, Seiler *et al.* (2013a) found that the Pacific Decadal Oscillation (PDO) had a significant impact on precipitation trends in DJF (December, January, and February) and JJA (June, July, and August) over Bolivia. Also, Villar *et al.* (2009) analysed trends of precipitation in the entire Amazon basin, including Bolivia. They found a general decrease from 1975 to 2003, albeit with much stronger decline since 1982. More recently, Canedo-Rosso *et al.* (2019) analysed precipitation variability in the Andean plateau of Bolivia using data from six meteorological stations. They looked at precipitation frequencies and their association with the main low-frequency atmospheric mechanisms affecting climate of the region (Garreaud *et al.*, 2003; Espinoza *et al.*, 2019b).

Given the strong interannual variability of precipitation in Bolivia and its distinct spatial patterns, it is necessary to analyse long-term precipitation trends from observations and climate model simulations. This assessment is important to determine the possible attribution of precipitation changes to anthropogenic climate change. Overall, the main aim of this study is to assess—for the first time—long-term (1950–2019) precipitation trends and variability in Bolivia based on a quality-controlled and homogenized data set and compare the spatial and temporal patterns of observed precipitation trends with trends suggested by the Coupled Model Intercomparison Project (CMIP), that is, the CMIP5 and CMIP6 experiments, outputs. The CMIP experiments use observed changes in radiative forcing in a multimodel context to simulate the whole climate system. Specifically, we aims to (a) examine the variability and trends of precipitation in Bolivia and (b) evaluate the performance of CMIP models in reproducing the sign, magnitude, and spatial patterns of observed precipitation trends.

2 | DATA AND METHODS

2.1 | Dataset description

We used data from 29 series of monthly precipitation totals (in mm) provided by the Bolivian Meteorological Service (SENAMHI) for the period 1943–2019. Due to the presence of high percentage of missing values and gaps in the series, we excluded five observatories and kept only data from 24 observatories for further analysis. The location of the selected 24 precipitation series is illustrated in Figure 1. Herein, it is noteworthy to indicate that although some series were available from 1943, our decision was made to restrict the analysis to the data dating back to 1950. This is simply because observations were mostly complete from 1950. The series were subject to a rigorous quality control and homogenization procedure. The quality control procedure was based on a rank data comparison considering the adjacent stations (Vicente-Serrano *et al.*, 2010). Then, a relative homogeneity test, Standard Normalized Homogeneity Test (SNHT; Alexandersson, 1986), was applied to identify possible inhomogeneities presented in the series. Specifically, we used CLIMATOL (https://www.climatol.eu/) to compare each candidate precipitation series with a reference one. The reference series was created using the means of the weighted average of the neighbour series. SNHT was applied to identify possible artificial steps in the series. This procedure includes the detection and correction of possible inhomogeneities and completes the missing values (<10% of the whole series). Based on this procedure, we found a total of nine inhomogeneities in eight stations that were corrected.

Also, we employed the available historical monthly data from a set of CMIP5 (Taylor *et al.*, 2012) and CMIP6 (Eyring *et al.*, 2016) members spanning the period 1950–2006 and 1950–2014, respectively. The list of models used in this study can be found in Table S1, Supporting Information and we used a single member in each model. In order to match the study period for both observations and CMIP data from 2006 to 2019, we used the data from the representative concentration pathway (RCP) 8.5 experiment for CMIP5. On the other hand, for CMIP6, we employed the shared socioeconomic pathways (SSP) 585 experiment from 2015 to 2019. Our decision was based on the notion that CO_2 concentrations considered in these scenarios match well with the observed concentrations for the years considered (Schwalm *et al.*, 2020). The spatial resolution of the CMIP models varies considerably, with CMIP6 models having improved spatial resolution over CMIP5 models (Table S1). In the same context, recalling that the spatial resolution of the CMIP5

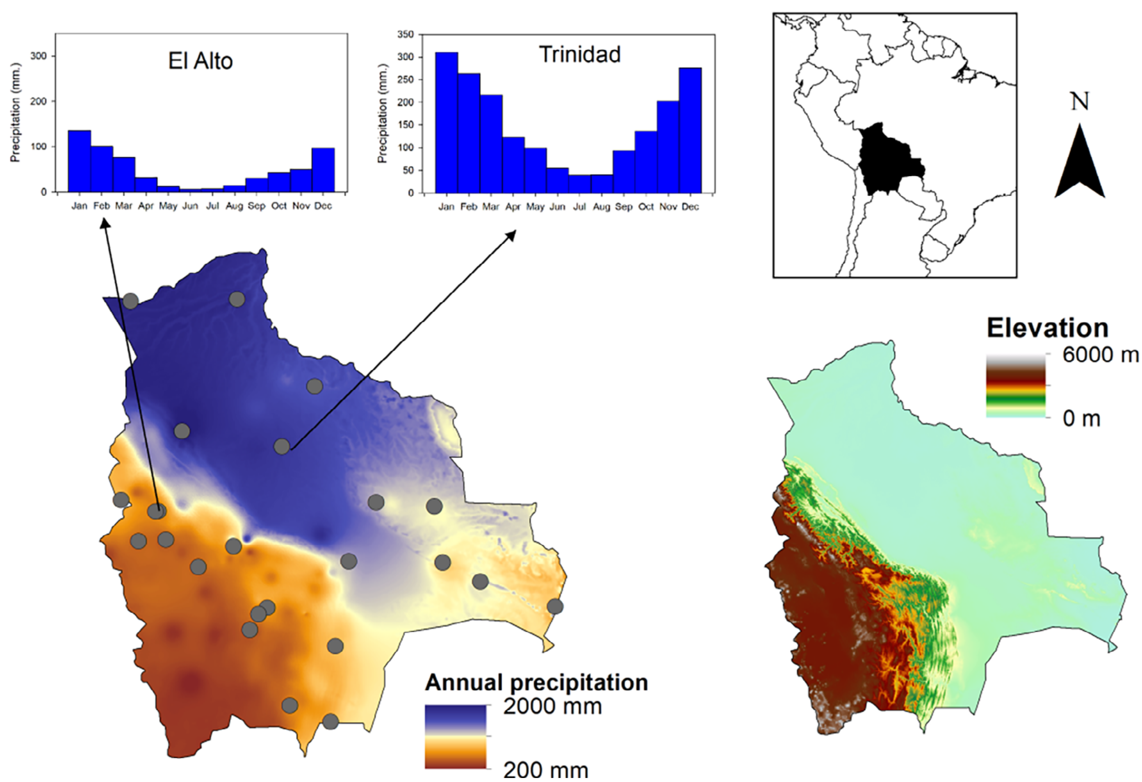

FIGURE 1 Location, relief, and climatology of annual precipitation over Bolivia [Colour figure can be viewed at wileyonlinelibrary.com]

and CMIP6 models varies considerably among different models, model data were resampled to a common grid interval (2.5° for CMIP5 and 1.25° for CMIP6 models) using a bilinear interpolation.

As it is difficult to establish a robust comparison between trends of the observation series and a group of model simulations, some studies considered the observation series as a member of each of the group of models (e.g., Nasrollahi *et al.*, 2015; Knutson and Zeng, 2018). This method is advantageous in the sense that it allows to determine the position of the trends in the observations with respect to the trends in the members. Nevertheless, because observations lack the same spatial structure and resolution as model simulations, this approach does not allow for robust comparisons with punctual observations. For this reason, in order to establish a quantitative comparison between observations and model simulations, we used series of multimodel averages following several

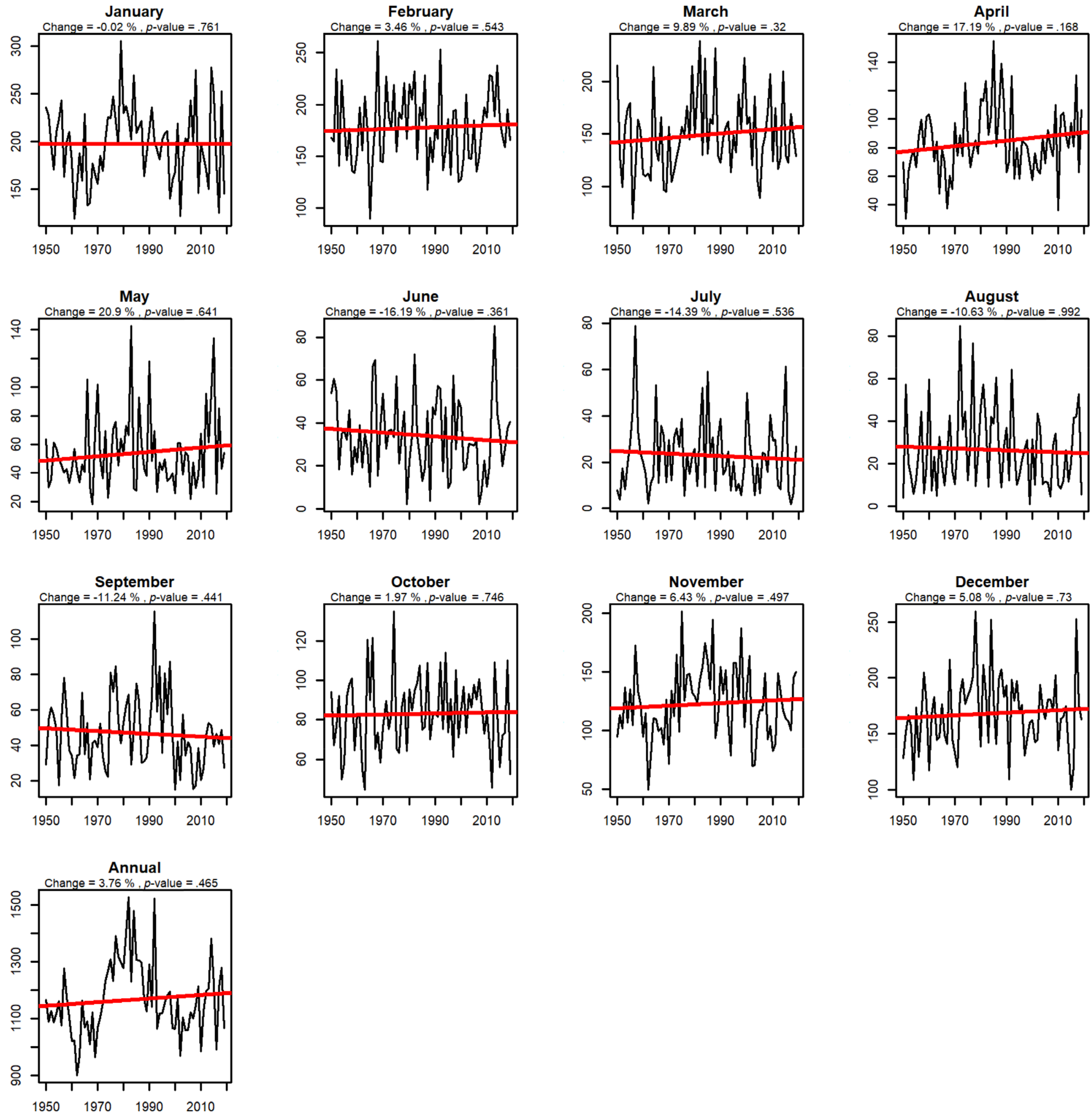

FIGURE 2 Evolution of the average monthly and annual precipitation series (in mm) for Bolivia [Colour figure can be viewed at wileyonlinelibrary.com]

previous studies (e.g., Kumar *et al.*, 2013; Orlowsky and Seneviratne, 2013; Sillmann *et al.*, 2013; Dai and Zhao, 2017). This ensemble mean can reduce the internal variability and the standard deviation of the resulting average series from a group of members. Moreover, the approach allows to reduce the strong variability introduced in different model simulations, providing an overall picture of the general pattern of trends from the different models, irrespective of their natural variability.

2.2 | Methods

To analyse changes in precipitation series from both observations and model outputs, we employed a modified version of the nonparametric Mann–Kendall statistic (Hamed and Ramachandra, 1998; Yue and Wang, 2004). This statistic accounts for the possible effect of autocorrelation on trend detection by returning the corrected p values after accounting for temporal pseudoreplication. Herein, we present the trend results using four categories of trends: positive and significant ($p < .05$), positive and nonsignificant ($p > .05$), negative and nonsignificant ($p > .05$), and negative and significant ($p < .05$). The magnitude of trends was assessed by means of linear regression analysis between the series of time (independent variable) and precipitation series (dependent variable). The slope of the regression indicates the amount of change (precipitation change per year), with higher slope values indicating greater change. As the magnitude and seasonality of precipitation varies considerably among regions of Bolivia due to the complicated topography (Figure 1), we presented the magnitude of change in percentages, allowing for direct comparison between different regions across the country.

The seasonality of precipitation in both observations and model simulations was determined by calculating the contribution of each month/season to the annual

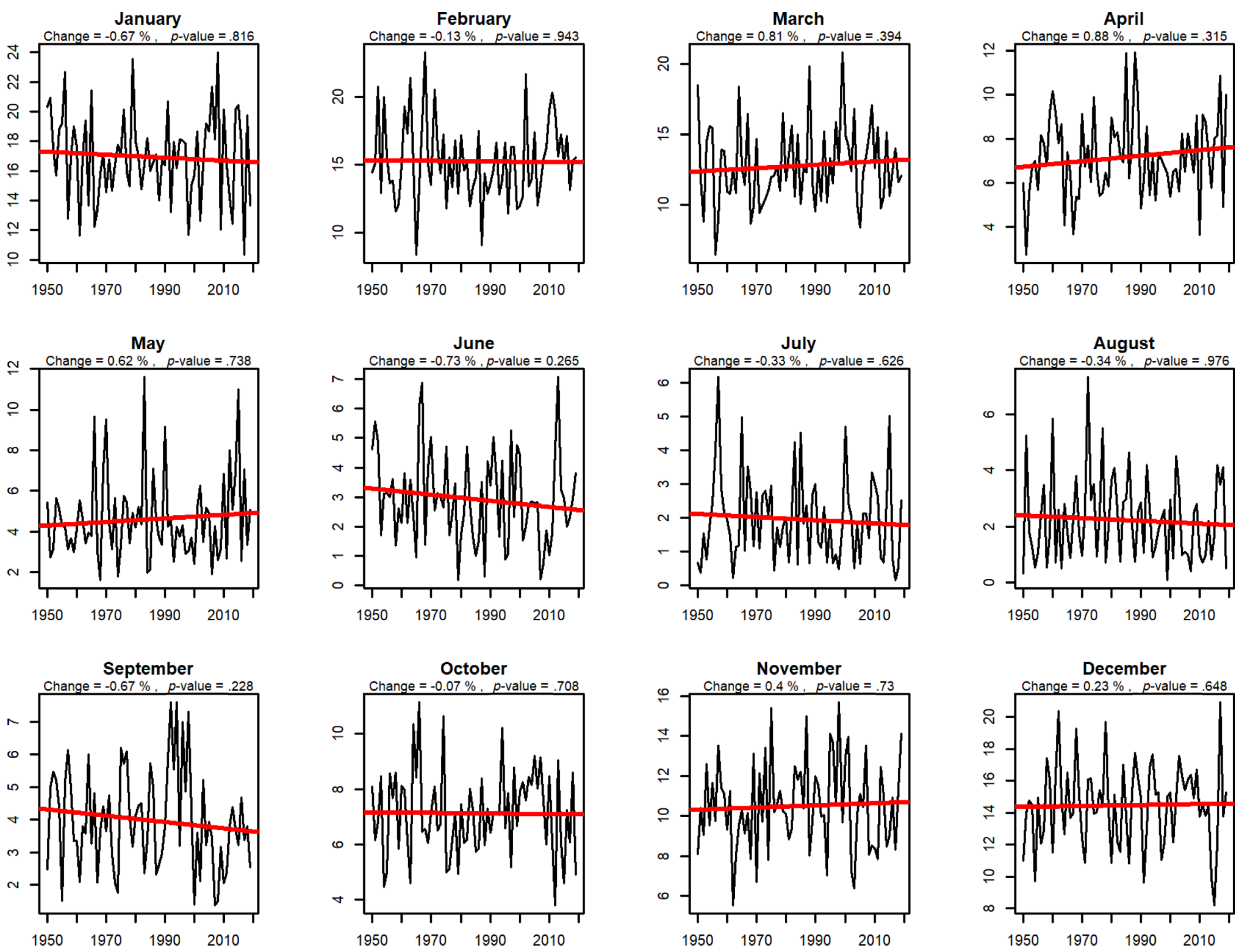

FIGURE 3 Evolution of the series characterizing the monthly contribution to annual precipitation totals [Colour figure can be viewed at wileyonlinelibrary.com]

rainfall totals. The least squares regression method and the Mann–Kendall statistic were used to assess changes in these relative contributions and the statistical significance of their trends. Also, we assessed the spatiotemporal variability of precipitation by means of a principal component analysis (PCA). Specifically, in order to determine the general temporal patterns of precipitation in Bolivia, we applied a PCA in S-mode to the annual precipitation data (Serrano *et al.*, 1999), in which observatories are represented as variables, while years were represented as cases. The S-mode allows determination of consistent regions where the structure of evolution of annual precipitation is similar. Moreover, this analysis can reflect the distinguished temporal behaviour of precipitation in the Andean plateau and the lowlands (see below), allowing for generating representative regional series for each region. Changes in precipitation were also analysed by means of a temporal spectral analysis to determine short and long-term periodicities in order to determine the importance of the interannual and decadal variability in the series. We obtained information about the dominant timescales of underlying processes and

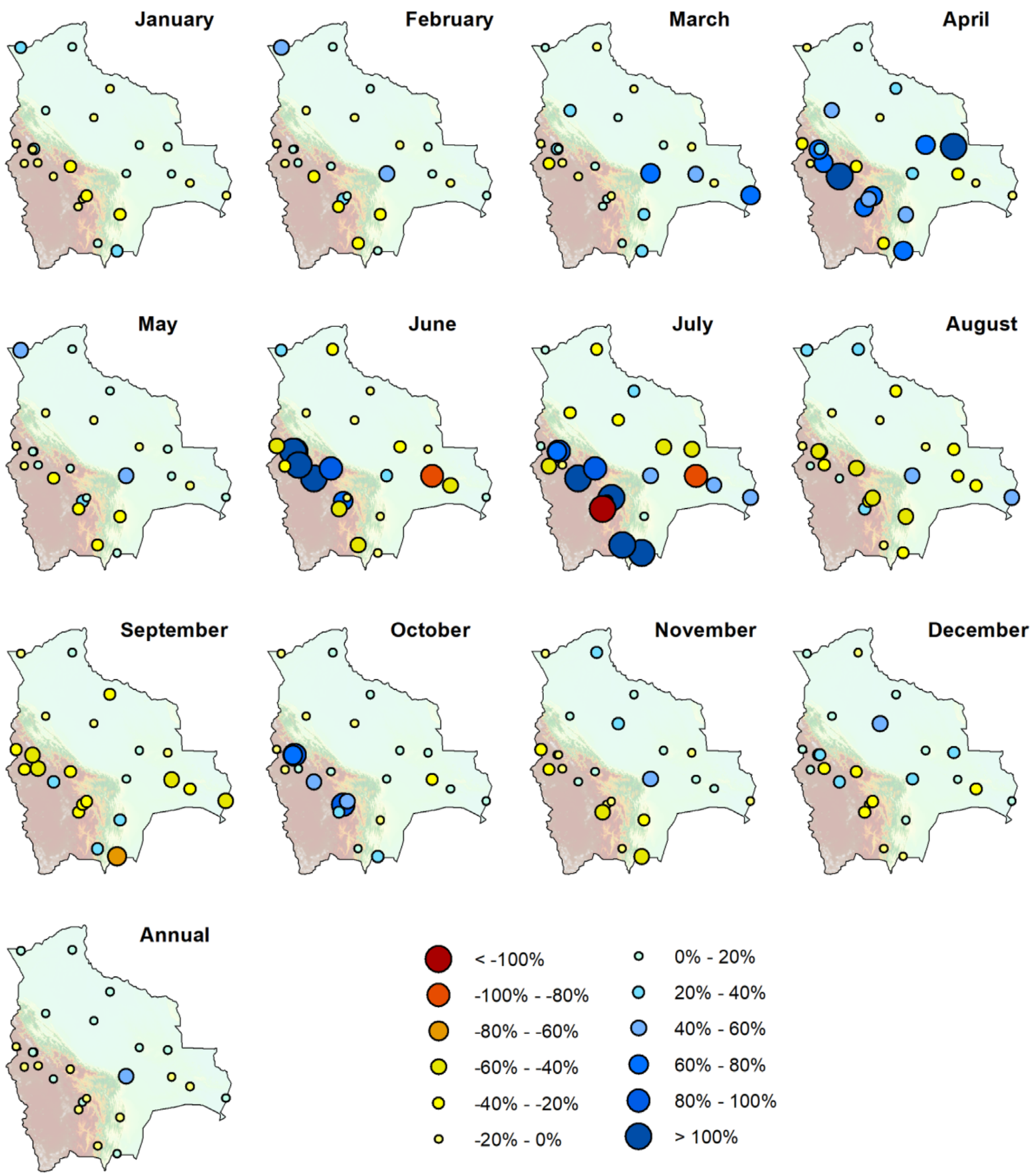

FIGURE 4 Magnitude of change of monthly and annual precipitation in Bolivia (1950–2019) [Colour figure can be viewed at wileyonlinelibrary.com]

hence sources of variability across timescales. We used the Morlet wavelet, which has been successfully used to analyse hydrological time series (Labat *et al.*, 2005; Juez *et al.*, 2021). Time series were standardized (zero mean, unit standard deviation) before applying the spectral analysis.

Considering the whole country, regional series were created by means of the average of monthly records in each station, weighted by the area it represents relative to the whole territory of Bolivia, as suggested by the Thiessen polygons method (Jones and Hulme, 1996).

3 | RESULTS

Figure 2 depicts the evolution of the monthly and annual precipitation in Bolivia considering a regional series for the whole country. The monthly average series show that changes between 1950 and 2019 were statistically nonsignificant ($p > .05$) on both monthly and annual timescales. Rather, the monthly and annual series were characterized mostly by high interannual variability. The stationarity and nonsignificant behaviour of precipitation was reflected in annual and seasonal precipitation, as

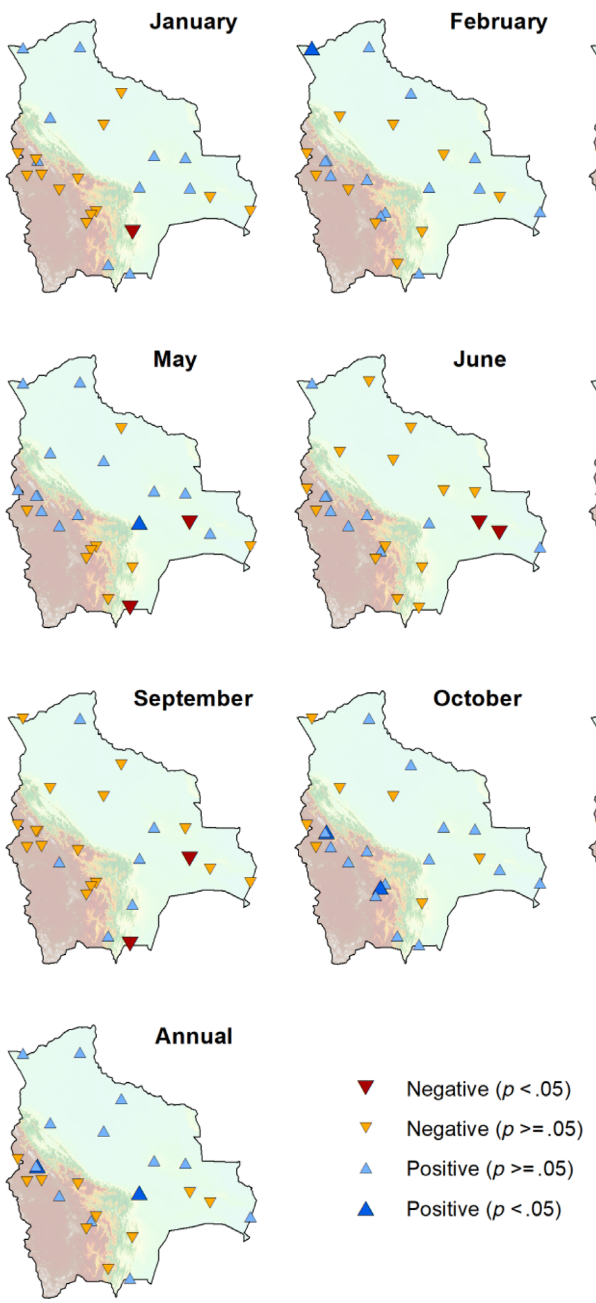

FIGURE 5 Sign and significance of changes in monthly and annual precipitation over Bolivia (1950–2019) [Colour figure can be viewed at wileyonlinelibrary.com]

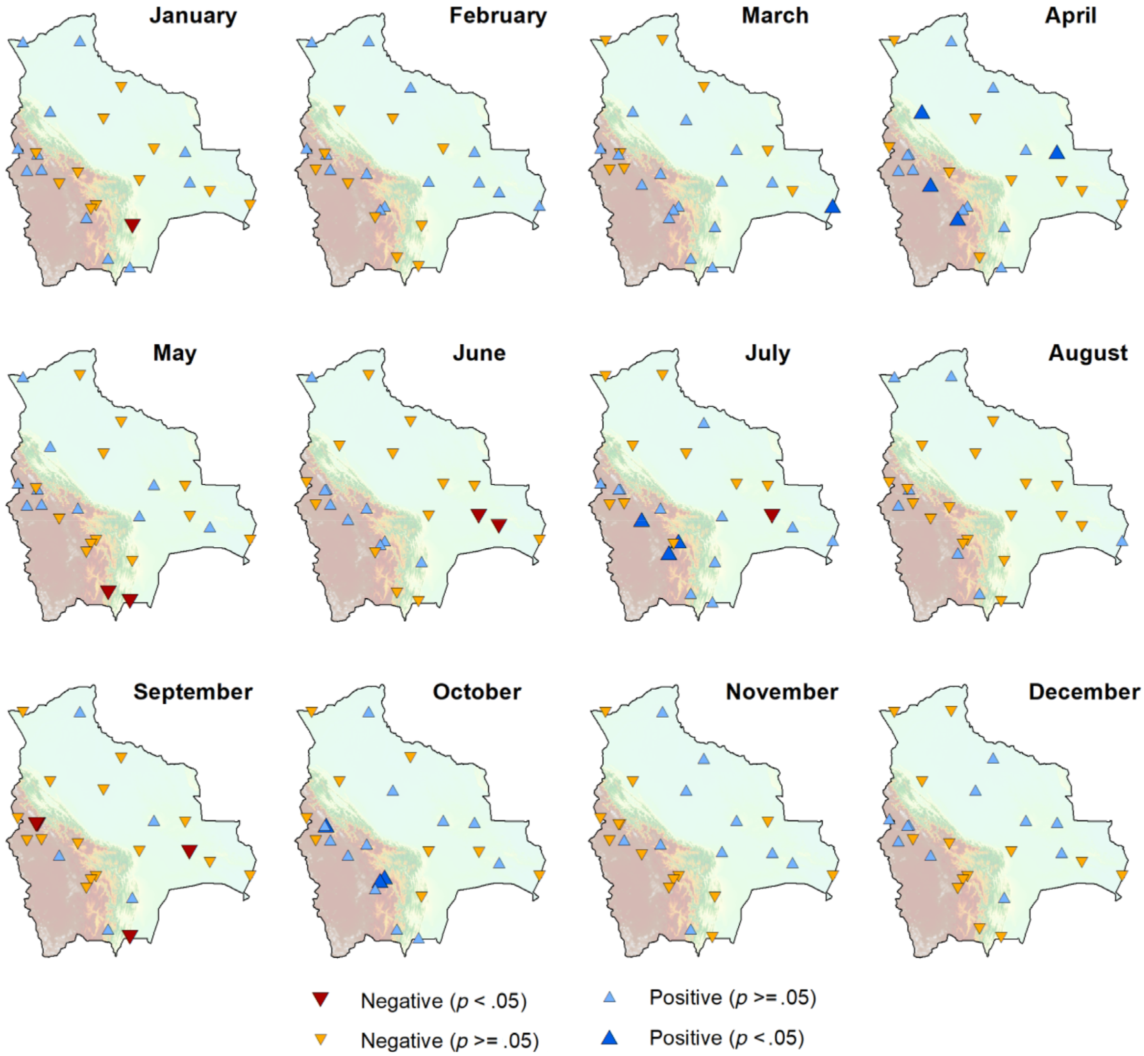

FIGURE 6 Sign and significance in the trend of the series characterizing the contribution of monthly precipitation to annual precipitation in Bolivia (1950–2019) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Results of the principal component analysis applied to the annual precipitation series

Principal component	Total	% of the variance	Cumulative
1	6.376	26.567	26.567
2	4.193	17.472	44.039
3	1.741	7.253	51.292
4	1.456	6.065	57.357

well as for the series characterizing the contribution of monthly precipitation to annual totals for the period 1950–2020 (Figure 3).

Spatially, there were some differences in the magnitude of change of precipitation in some of the months. These differences were observed particularly in April, June, and July, with some stations exhibiting a noticeable increase of precipitation. These stations are mostly located in highly elevated areas of the Andean plateau (Figure 4). On the contrary, a decline in precipitation was noted in some stations of the eastern area, mainly in June and July. Nevertheless, the total magnitude of these changes was generally small, given that they were recorded during the dry season and in arid and semi-arid regions. Overall, the majority of stations in the region showed statistically nonsignificant changes both on the monthly and annual scales (Figure 5), with small spatial changes in the contribution of the monthly precipitation to annual totals (Figure 6).

Table 1 summarizes results of the principal component analysis (PCA) applied to the annual precipitation series. The first three components accounted for more than 50% of the total variance, demonstrating the high spatial and temporal variability of precipitation in the region. The retained components reveal homogenized patterns, with good spatial coherence. While the first component was mostly represented in the highly elevated sites of the Andean plateau, the second component denoted low-elevated areas of the Amazon basin and the eastern region (Figure 7). On the other hand, the third component showed a more random behaviour, with localized patterns. Interestingly, the temporal evolution of annual precipitation indicates an increasing trend in the lowlands and conversely a decline in the Andean plateau, although trends were statistically nonsignificant in both regions (Figure 8). Similarly, changes in monthly precipitation over these two regions were almost

TABLE 2 Magnitude of change (%) of monthly precipitation trends in Bolivia

Month	Lowlands	Andean plateau
January	24.7	6.8
February	40.6*	−29.7
March	8.7	11.5
April	−16.6	−27.6
May	13.1	−14.0
June	37.0	−55.1
July	5.2	42.4
August	25.8	−11.3
September	−5.7	25.4
October	−2.3	16.7
November	−3.2	−8.2
December	2.8	−9.4

Note: Asterisk (*) indicates statistically significant trends ($p < .05$).

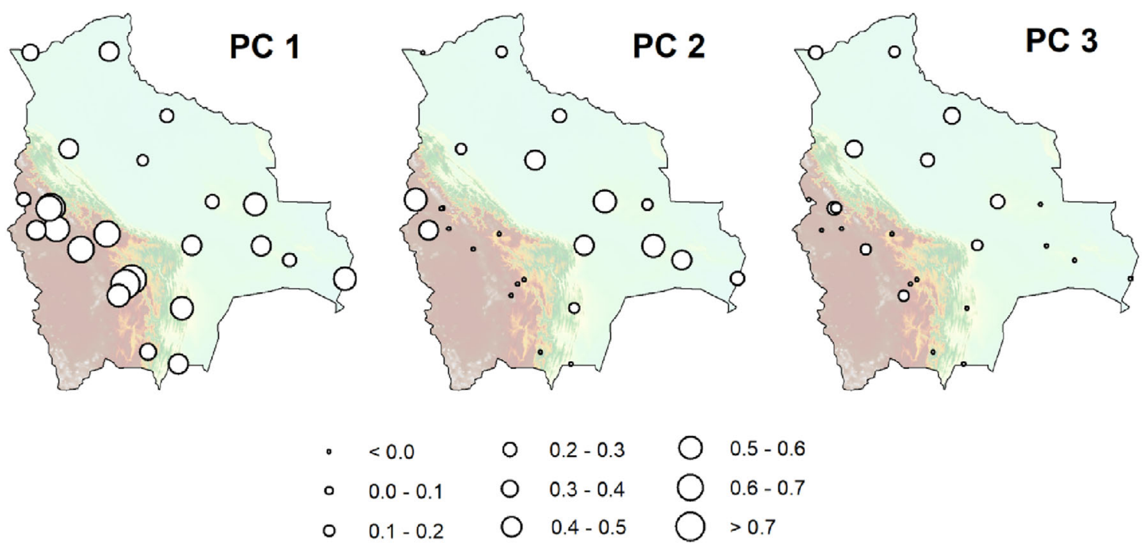

FIGURE 7 Spatial distribution of the PC loadings based on annual precipitation series [Colour figure can be viewed at wileyonlinelibrary.com]

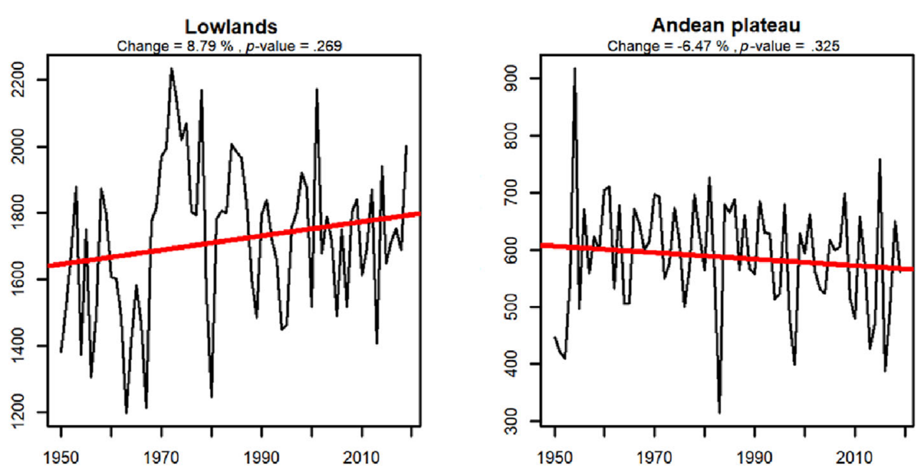

FIGURE 8 Evolution of the regional annual precipitation series in the lowlands and the Andean plateau [Colour figure can be viewed at wileyonlinelibrary.com]

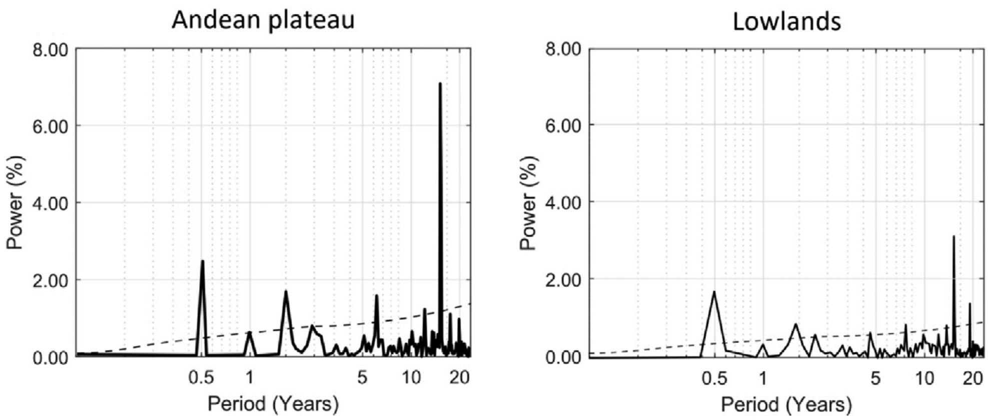

FIGURE 9 Results of the spectral analysis obtained from the series of the Andean plateau and the lowlands showing the power (%) corresponding to different periods (years). Dashed line represents the confidence level at 95%

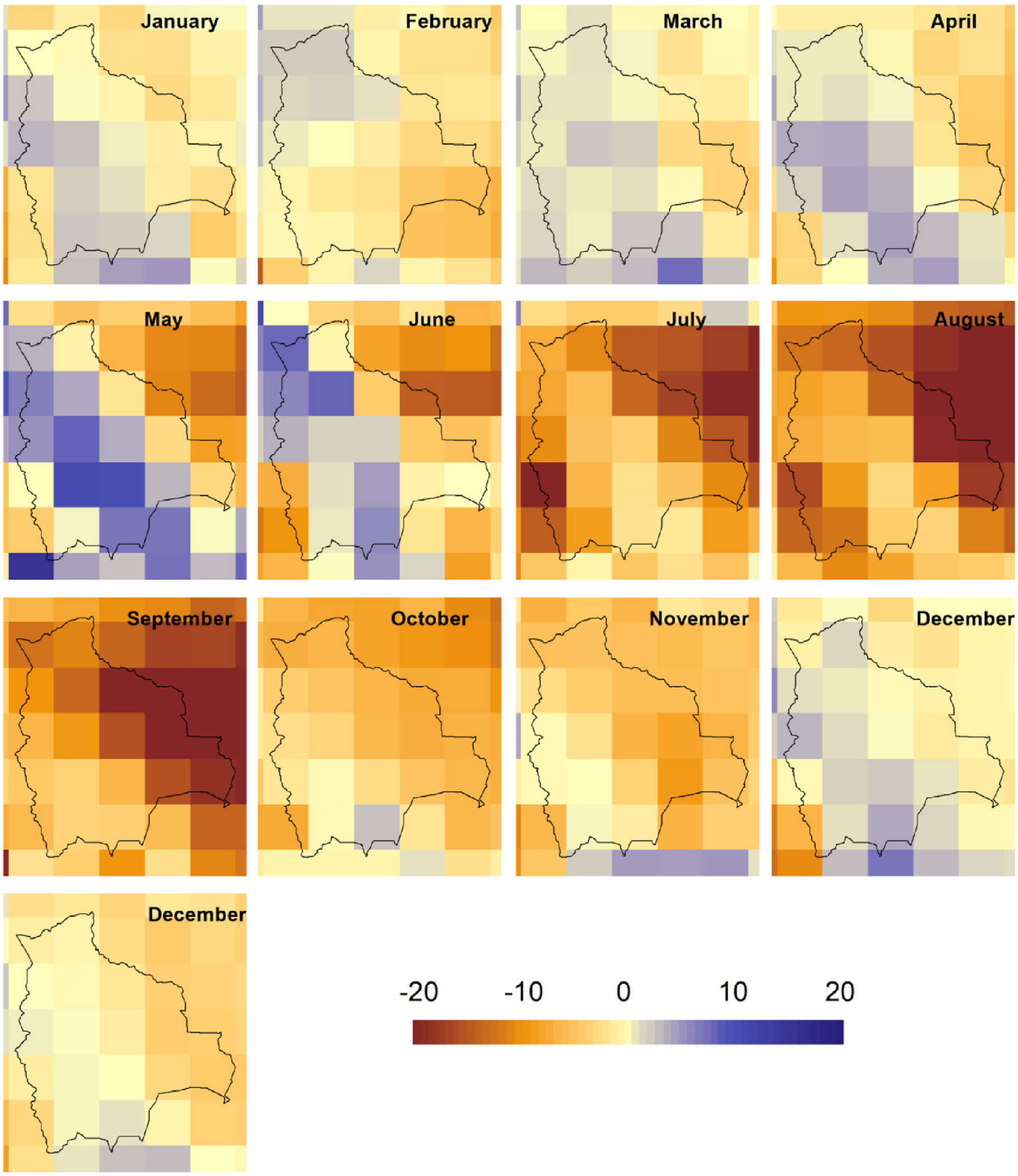

FIGURE 10 Magnitude of change (%) in monthly and annual precipitation based on a multimodel ensemble of CMIP5 between 1950 and 2019 [Colour figure can be viewed at wileyonlinelibrary.com]

statistically nonsignificant, with few exceptions (e.g., increase of precipitation in the lowlands in February) (Table 2). Overall, considering monthly and annual changes in precipitation over Bolivia, results indicate that observed precipitation showed a stationary behaviour, with strong interannual and decadal variability. This is reinforced with the results of the spectral analysis both in the Andean plateau and in the lowlands (Figure 9) since there is a peak at the cycle of 0.5 years, which characterizes the wet and dry seasons and at 1 year, which characterizes the interannual variability. Moreover, in both regions also there is a high power at the temporal scales of 2–7 years and 14 years, which indicates a high variability at the quasi-decadal scale.

For outputs from the CMIP5 and CMIP6 models, results are contradictory with those suggested by observed data. In particular, CMIP5 models suggested a dominant increase in precipitation over the Andean plateau between December and June, with much stronger changes in May (Figure 10). In the same context, model simulations also suggest a statistically significant decrease in precipitation in the majority of the lowlands

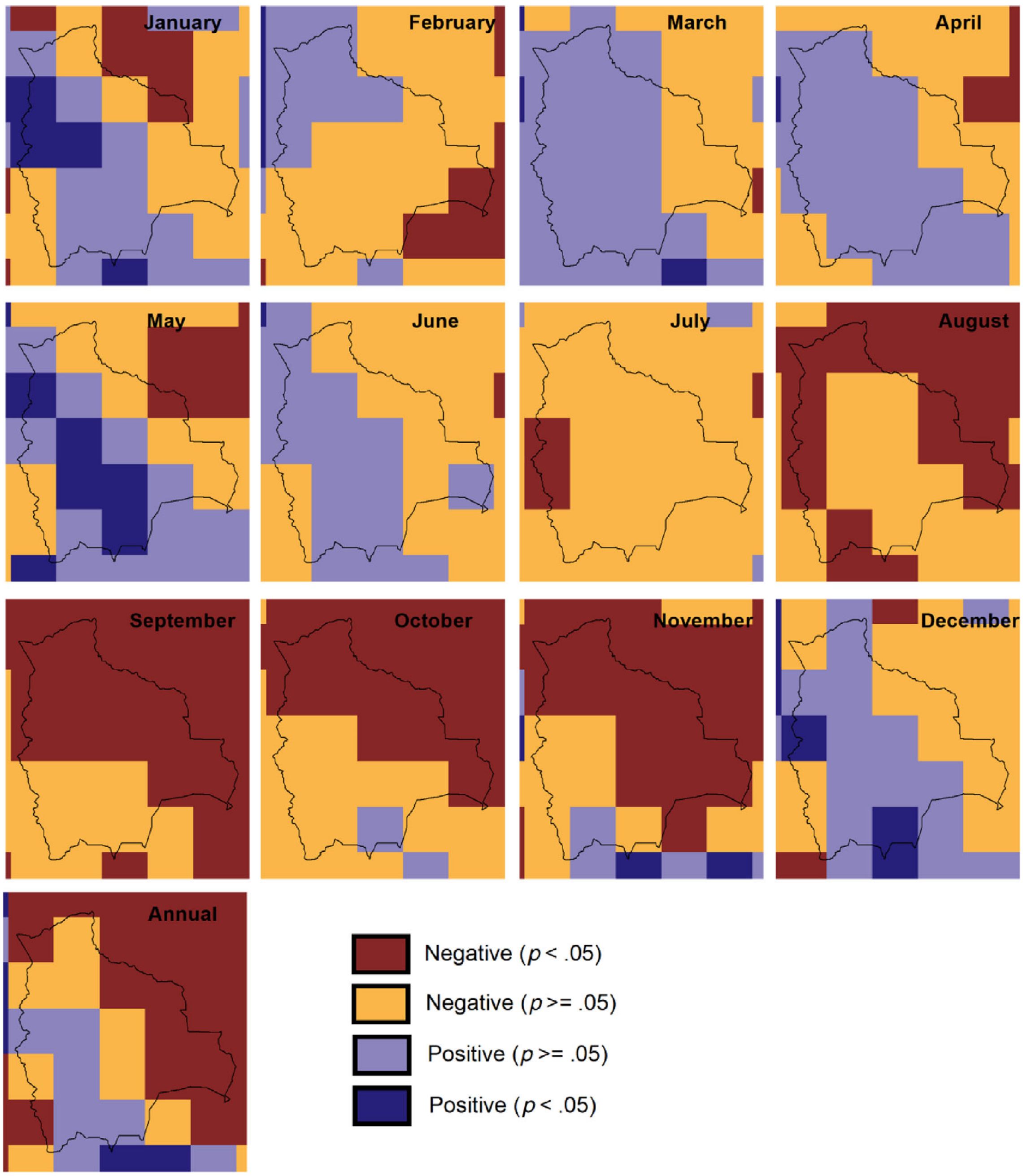

FIGURE 11 Significance and sign of trends in monthly and annual precipitation based on a multimodel ensemble of CMIP5 between 1950 and 2019 [Colour figure can be viewed at wileyonlinelibrary.com]

between August and November, and annually (Figure 11). A comparison of trend results for CMIP5 and CMIP6 outputs reveals some considerable differences. CMIP6 models showed a general increase in precipitation between December and February, although trends were statistically significant in few cases. Also, CMIP6 outputs suggest a decrease in precipitation between July and November, particularly in the lowlands of the Amazon and the eastern region and conversely an increase was noted in September and October in the elevated areas of the Andean plateau (Figures 12 and 13). These monthly trends contributed to the dominant and statistically negative trend of the annual precipitation in the low-elevated areas of Bolivia.

4 | DISCUSSION AND CONCLUSIONS

This study analysed long-term monthly and annual precipitation trends over the whole Bolivia. Nonsignificant trends in monthly and annual precipitation from 1950 to

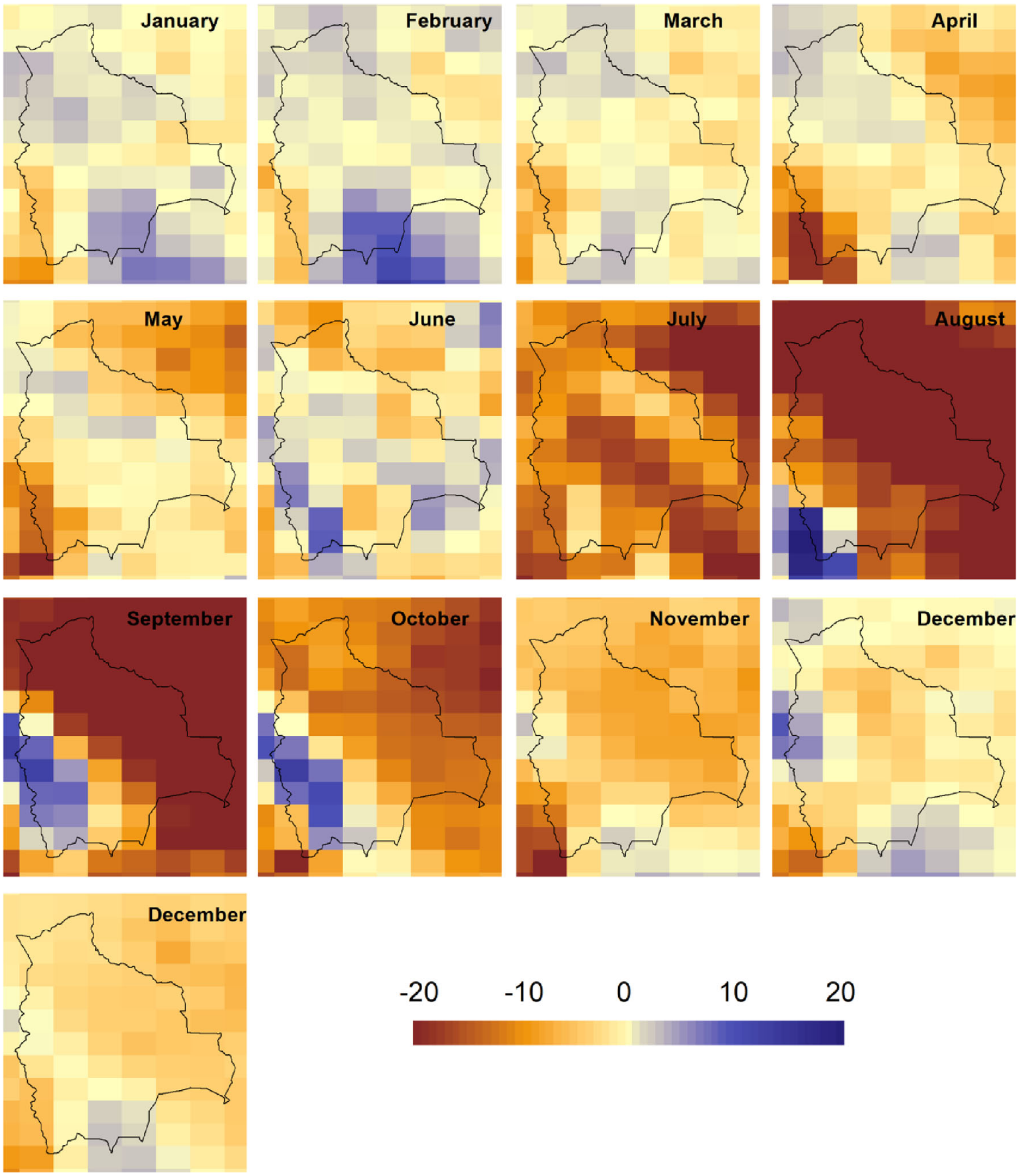

FIGURE 12 Magnitude of change (%) in monthly and annual precipitation based on a multimodel ensemble of CMIP6 between 1950 and 2019 [Colour figure can be viewed at wileyonlinelibrary.com]

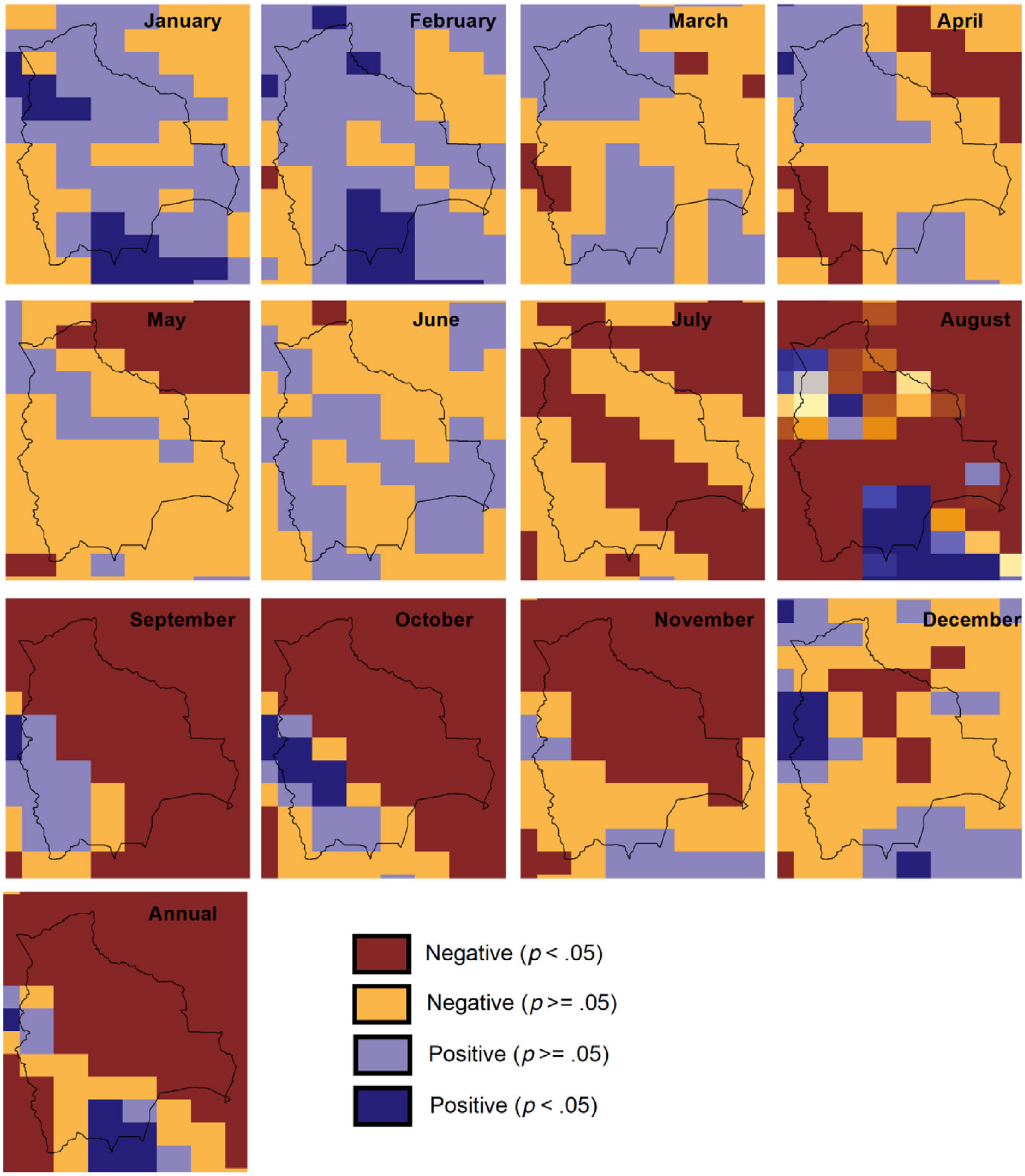

FIGURE 13 Significance and sign of trends in monthly and annual precipitation based on a multimodel ensemble of CMIP6 between 1950 and 2019 [Colour figure can be viewed at wileyonlinelibrary.com]

2020 were the most prevalent across the country. Thus, our results support the notion that precipitation was dominantly stationary, with only very few stations experiencing statistically significant trends either on the monthly or annual scale. The main characteristic of precipitation evolution in Bolivia was its strong interannual and intra-annual variability, characterized by well-defined cycles that explain a high percentage of the total variance of the series. This finding demonstrates that it may be possible to identify short-term trends for periods of 15–20 years across Bolivia, while long-term precipitation trends remain stationary. Also, our findings suggest that there were no significant changes in precipitation seasonality and regimes. The dry (April–September) and humid season (October–March) remained stable during the last 70 years. Therefore, the dominant decline identified in the Bolivian glaciers over the last decades might be attributed to air temperature increase, with small contribution of recent precipitation changes (Soruco *et al.*, 2009).

These results obtained by means of long-term quality controlled and homogenized series from Bolivia suggest that natural precipitation variability is the dominant pattern in comparison to the possible influence of anthropogenic forcing. Our study agrees with other previous studies that showed dominant humid conditions in Bolivia during the 1970s and 1980s, followed by a significant decrease in precipitation during last decades (Villar *et al*., 2009). In this sense, the decades of 1950 and 1960 were also dry (Seiler *et al*., 2013b), so it cannot be argued a dominance of precipitation decrease in the region, rather than an alternation between humid and dry periods. These results stress the need of using long-term series to assess possible anthropogenic forcing influence on precipitation trends as suggested in recent global assessments (Vicente-Serrano *et al*., 2021).

The strong decadal and interannual variability of precipitation identified in Bolivia seems to be strongly connected with anomalies in the dominant air flows (Thibeault *et al*., 2012), as well as mechanisms like the Pacific Decadal Oscillation (PDO; Seiler *et al*., 2013a; Veettil *et al*., 2016; Kayano *et al*., 2019), the El Niño–Southern Oscillation (ENSO; Vuille, 1999; Francou *et al*., 2003; Villar *et al*., 2009; Jonaitis *et al*., 2021), and the atmospheric conditions in the North Atlantic region (Canedo-Rosso *et al*., 2019). Thus, these patterns were likely the dominant drivers of precipitation variability in Bolivia over the past 50,000 years (Baker *et al*., 2001).

Global climate models produce a reasonable agreement with the spatial distribution of precipitation in the region (Abadi *et al*., 2018). Nevertheless, as opposed to trends suggested by observations, CMIP5 and CMIP6 simulations for the historical period (1950–2020) suggest considerable changes in precipitation, mainly a decrease in precipitation during the dry season (August–November) in the lowlands. This pattern contributed to the dominant decline in annual precipitation in this area. Also, CMIP5 and CMIP6 experiments show a decline in precipitation across the Andean plateau in some months of the year, which was not noted in observations. Paradoxically, the overestimation of the negative precipitation trends in the lowlands of Bolivia is more acute in the most recent CMIP6 experiments, characterized by higher spatial resolution and improved physics (Eyring *et al*., 2016). The uncertainty in reproducing long-term precipitation trends using of climate models has been already documented in previous studies on the global and regional scales (van Oldenborgh *et al*., 2013; Abadi *et al*., 2018; Peña-Angulo *et al*., 2020), as well as some subtropical regions of the North and South hemispheres and in high latitudes of the North hemisphere (Kumar *et al*., 2013; Vicente-Serrano *et al*., 2021) and in South America (Varuolo-Clarke *et al*., 2021). In other regions of the world characterized by data scarcity, the assessment of the goodness of the model performance is much more difficult. For this reason, our study in Bolivia has a double value since it assesses model performance of long-term precipitation trends in a region in which there were not previous comparative studies. Moreover, it also compares observed and modelled precipitation trends in a region of particularly complex terrain, with elevation gradients larger than 4,000 m within few kilometres. It is expected that climate models might fail to identify the physical processes responsible for precipitation changes in this complicated region and according to the large differences in precipitation trends between high elevated areas and the lowlands.

The decrease in precipitation in the CMIP5 and CMIP6 models also agrees with the dominant projection of precipitation in the simulations of the models by high greenhouse gases emission scenarios, which show a dominant decrease of precipitation (Douville *et al*., 2021). This suggests that the possible effect of forcing could be overestimated by the ensemble of models, or may be biased by some individual members, which finally overestimate the effect of global warming on a multitude of impacts (Hausfather *et al*., 2022).

The implications of these scenarios are relevant as a precipitation reduction in the lowlands of Bolivia might have key environmental and socioeconomic impacts, affecting humid ecosystems that are strongly vulnerable to water deficits (Duffy *et al*., 2015; McDowell *et al*., 2018), including crop yields in the semiarid regions of the Andean plateau (Escurra *et al*., 2014). Moreover, these projections might affect the Andean glaciers and consequently streamflow changes, with a general decrease of water availability downstream during the dry season (Vuille *et al*., 2008). The results of our study suggest that these scenarios should be carefully assessed and uncertainties in precipitation projections in countries with complex orography like Bolivia should be considered when applying socioeconomic and environmental impact models for future climate scenarios.

AUTHOR CONTRIBUTIONS

Sergio M. Vicente-Serrano: Conceptualization; methodology; investigation; resources; writing – original draft. **Oswaldo Maillard:** Conceptualization. **Dhais Peña-Angulo:** Methodology; visualization. **Fernando Domínguez-Castro:** Resources. **Iván Noguera:** Visualization; methodology. **Jorge Lorenzo-Lacruz:** Methodology; visualization. **César Azorin-Molina:** Formal analysis; visualization. **Carmelo Juez:** Resources. **José Antonio Guijarro:** Data curation; software. **Amar Halifa-Marín:** Resources; methodology. **Ahmed El Kenawy:** Writing – original draft; methodology; formal analysis.

ACKNOWLEDGEMENTS

We thank the National Service of Meteorology and Hydrology (SENAMHI) for all the help provided to access the data from the weather stations. This work was supported by the research projects CGL2017-82216-R, PCI2019-103631, and PID2019-108589RA-I00, financed by the Spanish Ministry of Science and FEDER, the CROSSDRO project financed by the AXIS (Assessment of Cross(X)-sectorial climate impacts and pathways for Sustainable transformation), the JPI-Climate co-funded call of the European Commission, and the LINCGLOBAL-CSIC project (INCGLO0023, RED-CLIMA). A. Halifa-Marín gratefully acknowledges the Ministerio de Ciencia, Innovación y Universidades of Spain for his predoctoral contract FPU18/00824.

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How to cite this article: Vicente-Serrano, S. M., Maillard, O., Peña-Angulo, D., Domínguez-Castro, F., Noguera, I., Lorenzo-Lacruz, J., Azorin-Molina, C., Juez, C., Guijarro, J. A., Halifa-Marín, A., & El Kenawy, A. (2022). Evaluation of long-term changes in precipitation over Bolivia based on observations and Coupled Model Intercomparison Project models. *International Journal of Climatology*, 1–17. https://doi.org/10.1002/joc.7924