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RESEARCH ARTICLE

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Long-term observed changes of air temperature, relative humidity and vapour pressure deficit in Bolivia, 1950–2019

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Abstract

This study analyzes the long-term observed changes of mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperatures, relative humidity (RH) and vapour pressure deficit (VPD) at different elevation ranges across Bolivia from 1950 to 2019. The linear trends in air temperature series present a significant increase, with no substantial seasonal or spatial differences. On an annual basis, RH exhibited a non-significant decrease (−0.08% decade^{-1}), while VPD showed a significant increase (0.01 hPa decade^{-1}) ($p < 0.05$). Although prior research has suggested that highland elevations experience faster warming than the global average, we have not identified a distinct correlation between elevation gradients and differential warming rates in Bolivia. Future research could investigate elevation-dependent climate trends by examining seasonal and monthly patterns of climatic variables in relation to topographical gradients in various highland regions.

KEYWORDS

climate change, in-situ weather observations, South America, spatio-temporal variability, topographical gradients, trend

1 | INTRODUCTION

Mountainous and highland regions are among the most sensitive and vulnerable areas to climate change and its impacts since these ecosystems support a remarkable level of biodiversity (Dimiri et al., 2022; Gottfried et al., 2012). Small changes in air temperature (Diaz & Bradley, 1997) and precipitation (Dimiri et al., 2022; Giorgi et al., 1997) with elevation could have major implications for hydrology (Beniston et al., 2018) and for animal and plant species living in upper mountain environments (Diaz & Bradley, 1997), leading to severe social and economic consequences. Mountains function as hydrological reservoirs for adjacent low-lying regions, accumulating and retaining water via snowpack, glaciers and rivers. As such, climate variability can impact water availability in terms of quantity and timing, thereby affecting agriculture, hydropower generation, drinking water supplies and water resource management. Moreover, mountainous locations are good indicators of global warming (Pepin & Lundquist, 2008) since they are less affected by emission sources, so their responses could be used as an early detection tool for global warming (Keiler et al., 2010; Sorg et al., 2012).

Altitude is the main factor that controls the climate in mountain regions (Fan et al., 2015). In fact, several observational and modelling studies have argued that climate warming depends on elevation, with certain elevation ranges experiencing enhanced warming relative to others. This phenomenon is commonly referred to as elevation-dependent warming (EDW) (Minder et al., 2018). However, previous studies have not reached a consensus about whether high elevations worldwide have been warming faster than nearby lower elevations or global averages. On the one hand, there are authors who have found increasing air temperature rates with elevation in Asia and Europe (e.g., Diaz & Bradley, 1997), over the Alps (e.g., Giorgi et al., 1997), in Tibet (e.g., Thompson et al., 2003) and worldwide (e.g., Ohmura, 2012) among others (Navarro-Serrano et al., 2020). Other studies have reported reduced warming trends with increasing elevation (e.g., Vuille and Bradley (2000) in the tropical Andes and Pepin and Losleben (2002) in the North American Rocky Mountains). Finally, many authors have shown that there is no clear (significant) relationship between warming magnitude and elevation (e.g., Dimiri et al., 2022 in the Indian Himalayan region for observations and modelling fields from 1970 to 2099; Oyler et al., 2015 in the western United States from 1991 to 2012; Wang et al., 2016 within the Arctic over 1961–2010 or Pepin & Lundquist, 2008 over 1000 high elevation stations across the globe). In addition, at the global scale, there is abundant literature analysing the influence of elevation on mean air temperature trends (e.g., Bradley et al., 2004; Knight, 2022; Moradi & Darand, 2022; Pepin et al., 2015; Pepin & Lundquist, 2008; Rangwala, 2013), whereas a smaller number of studies focusing on maximum and minimum air temperature trends have been conducted (e.g., Liu et al., 2009; McGuire et al., 2012). For example, Pepin et al. (2015) investigated global air temperature variations in mountainous regions, highlighting their trends, spatial distribution and seasonal variations. They emphasized the increased warming trends at higher altitudes relative to low-lying regions. In the same context, several studies have examined precipitation patterns, trends and variability in mountainous regions, including the Alps, Andes, Himalayas, Rocky Mountains and the Tibetan Plateau, among others (e.g., Salzmann et al., 2013; Vicente-Serrano et al., 2015). For example, recent changes in precipitation and drought indices in the Bolivian Andes were the focus of Vicente-Serrano et al. (2015). EDW requires more in-depth studies to ensure that potentially large changes in high-mountain environments are adequately recorded by the global observational network.

While scientific studies have paid considerable attention to the effect of elevation gradients on air temperature in the context of climate change, there is a notable lack of research on other crucial climatic variables such as relative humidity (RH) and vapour pressure deficit (VPD). You et al. (2015) state that RH and VPD play crucial roles in determining changes within the hydrological cycle, including aspects such as moisture content, precipitation patterns, condensation and evaporation. In addition, they are necessary for understanding water and terrestrial carbon fluxes (He et al., 2022) and assessing plant productivity and drought stress in terrestrial ecosystems (Breshears et al., 2013; Grossiord et al., 2020).

In addition to the small number of studies on climate trends in areas of complex relief, few studies have addressed the spatio-temporal evolution of different climatic variables over South America and more specifically in Bolivia, which presents big challenges for the analysis of climatic processes (Andrade, 2008). The high spatial heterogeneity of mountain climates and the lack of climate records over most of these areas (Pepin et al., 2015) challenge the ability to analyse the rates of change in different climatic variables (Dimiri et al., 2022; Minder et al., 2018). The marked topographical gradients and the influence of different atmospheric circulation mechanisms make the Bolivian climate highly complex (Escurra et al., 2014; Garcia et al., 2007; Seiler et al., 2013). Moreover, Bolivia is exposed to extreme weather events (e.g., droughts, storms and heat waves) resulting in large economic and human losses (Blunden & Boyer, 2020; Winters, 2012).

In-situ weather observations are often short and sparse, inhomogeneous or even unavailable (Zhang et al., 2023) especially in regions with complex terrain (Bengtsson et al., 2004; Engdaw et al., 2022), making climatological studies a challenging task (Lawal et al., 2021). As such, many research efforts have employed global reanalysis datasets (e.g., Bengtsson et al., 2004; Li et al., 2023) as a surrogate for the restricted accessibility of direct observations. However, it is important to note that reanalysis products have certain limitations when compared to in-situ observations. These limitations could potentially impact the reliability of findings and lead to increased uncertainty in assessments (Pepin et al., 2015; Zhang et al., 2023). For these reasons, the current study analyzes the spatio-temporal variability and trends in air temperature (T): mean (Tmean), maximum (Tmax) and minimum (Tmin); relative humidity (RH) and vapour pressure deficit

(VPD) based on in-situ weather observations using the most complete register of meteorological records for Bolivia from 1950 to 2019.

Specifically, the main aims of the study are to (i) improve existing knowledge concerning the temporal patterns of the different climatic variables at annual and monthly time scales and (ii) to analyse the possible influence of elevation gradients on the long-term changes found in T, RH and VPD. To our knowledge, there have been no previous studies concerning EDW on long-time series in Bolivia so this dataset represents a unique and valuable climate resource. It can enhance our understanding of the characteristics and dynamics of recent climate change processes in Bolivia.

2 | DATA AND METHODS

2.1 | Study location

Bolivia is a tropical country with an approximate surface area of almost 1,100.000 km^2. Moreover, it is a country with marked geographical contrast (Figure 1) that can be briefly summarized in the following regions: (i) lowlands (800 m a.s.l.) that cover around 60% of the surface, (ii) Andean slopes (800–3200 m a.s.l.) that cover around 28% of the surface and (iii) highlands (Altiplano, 3200–6500 m a.s.l.) that span more than 10% of the surface (Seiler et al., 2013). This marked orography influences the climate of the country. However, despite being located in tropical latitudes, the climatic conditions of Bolivia vary from tropical regions in the lower parts to mountain climates in the highest parts of the Andes. According to Seiler et al. (2013), the annual mean maximum temperatures vary across different regions, ranging from 32°C in the lowlands to 16°C in the highlands. The wet period occurs during the warm austral summer (i.e., from December to February), whereas the dry period occurs during wintertime (i.e., from June to August) (Seiler et al., 2013). Rainfall varies from <250 mm yr^{-1} in the lowlands and the Andean slopes to >2000 mm yr^{-1} in the highlands (Seiler et al., 2013). Furthermore, climate in Bolivia is influenced by atmospheric configurations associated with the Pacific Decadal Oscillation (PDO), the El Niño-Southern Oscillation (ENSO), the Antarctic Oscillation (AAO), the Inter Tropical Convergence Zone (ITCZ) and the South American monsoon system (SAMS) (Del-Jesús et al., 2020; Escurra et al., 2014; Seiler et al., 2013). Overall, Bolivia's climate is influenced by the intricate interactions between the Andes and the Amazon basin. These climatic variations have substantial effects on the country's ecosystems, agriculture, water resources and population welfare.

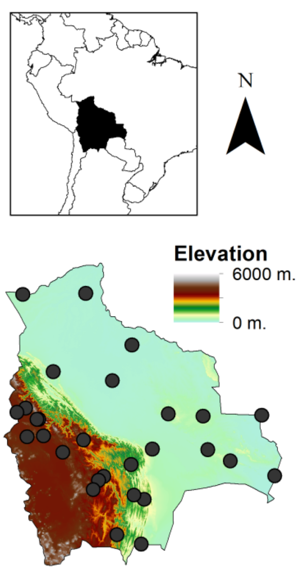

FIGURE 1 Location and relief of Bolivia and spatial distribution of the available monthly air temperature and relative humidity stations. [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Dataset description

Long-term data series of (i) monthly air temperatures: that is, mean (Tmean), maximum (Tmax) and minimum (Tmin), (ii) relative humidity (RH) and (iii) vapour pressure deficit (VPD) were used in the current study. The database comprises 28 stations across Bolivia spanning the years 1950–2019. Air temperatures and relative humidity data series were directly measured and supplied by the Bolivian Meteorological Service (SENAMHI). Figure 1 shows the location and elevation of the stations. It should be pointed out that the data series contained short gaps (less than 5% of the total records were missing). Besides, the dataset was subject to quality control and homogenization. For this purpose, we used the R-package CLIMATOL (https://www.climatol.eu/), which compares each series with a reference one obtained by means of the weighted average of the neighbour series and uses the Standard Normalized Homogeneity Test (Alexandersson, 1986) to identify possible artificial steps in the series. However, CLIMATOL is less skillful in detecting changes across stations (e.g., changes in practice and/or gauge), which is a limitation of the method. The gaps in the climate time series, almost <10%, were completed based on data from the best-correlated neighbouring candidate series by employing the R-package CLIMATOL. The surface area represented by each station in relation to the total area of Bolivia was used as the weighted factor for calculating the single regional series. To accomplish this task, Thiessen's polygon method was applied, allowing to define weighted average of monthly records for each station, following the procedure of Jones and Hulme (1996).

2.3 | VPD calculation

VPD was calculated on a monthly basis following Allen et al. (1998), given that:

$$VPD = e_s - e_a, \quad (1)$$

where e_s is the mean saturation vapour pressure, expressed in kPa, and obtained with Equation (2) (Allen et al., 1998):

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2}, \quad (2)$$

where e^0 (Tmax) and e^0 (Tmin) are the saturation vapour pressure, expressed in kPa, using monthly maximum and minimum air temperature, respectively, and expressed in °C.

e_a which is the actual vapour pressure, expressed in kPa, is computed using monthly RH, by Equation (3):

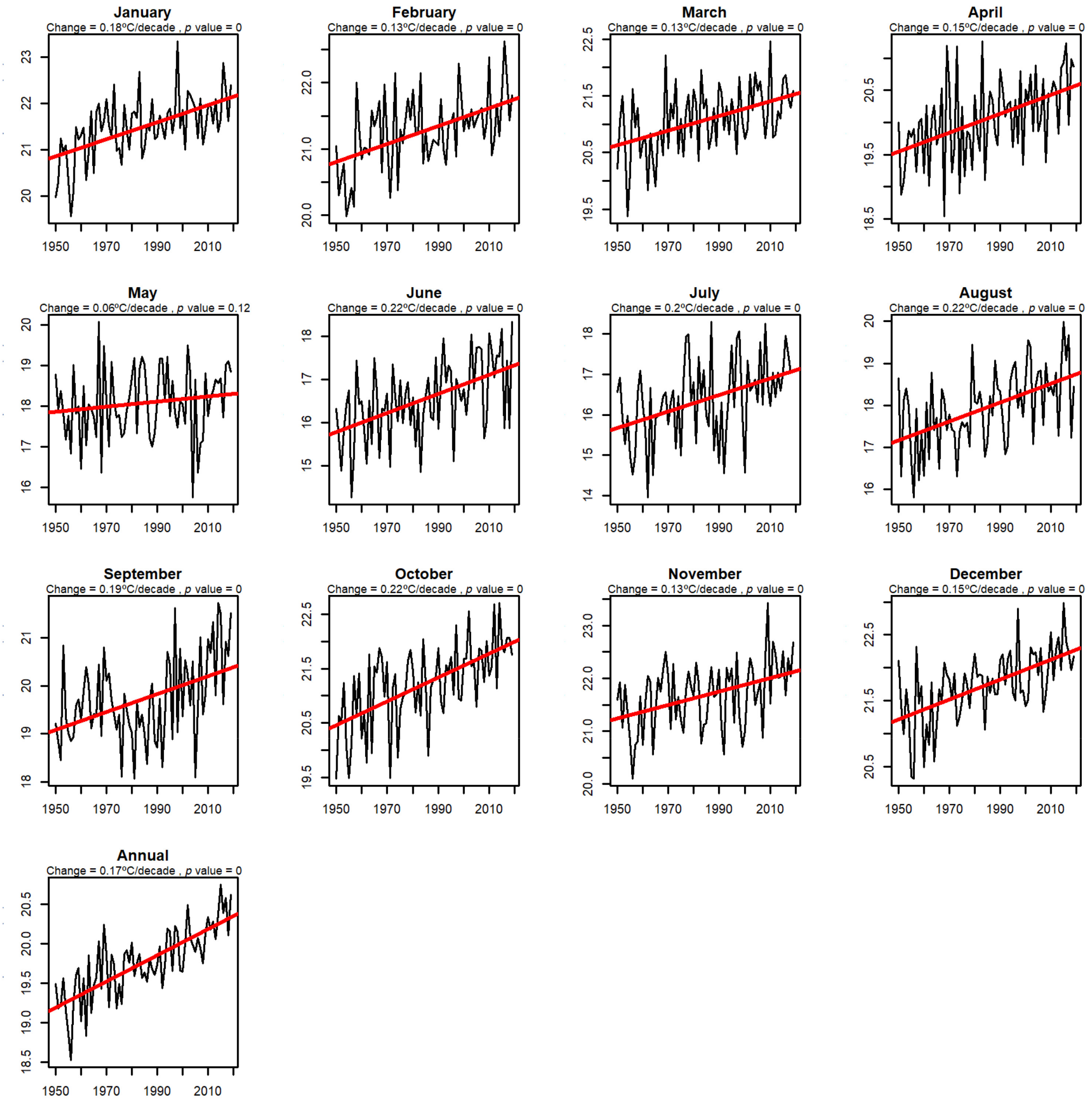

FIGURE 2 Evolution of the country average monthly and annual mean air temperature in Bolivia from 1950 to 2019. The red line shows the trend evolution of the mean air temperature over time. [Colour figure can be viewed at wileyonlinelibrary.com]

$$e_a = (RH/100)^{*}\, e^{o}\,(Tmean), \tag{3}$$

Finally, e^o is expressed as follows:

$$e^o(T) = 0.6108 exp\left[\frac{17.27T}{T + 237.3}\right], \tag{4}$$

where T (°C) is referred to T_{max}, T_{min} or T_{mean} for calculating e^o (Tmax), e^o (Tmin) and e^o (Tmean), respectively.

2.4 | Statistical analysis

The trends in Tmean, Tmax, Tmin, HR and VPD were analysed across Bolivia between 1950 and 2019. The warm season is referred to as that between December and February, whereas the cold season is that between June and August. Trends were calculated on a monthly and annual scale. The magnitude of change was assessed by a linear regression model between the series of time as the independent variable and Tmean, Tmax, Tmin, HR

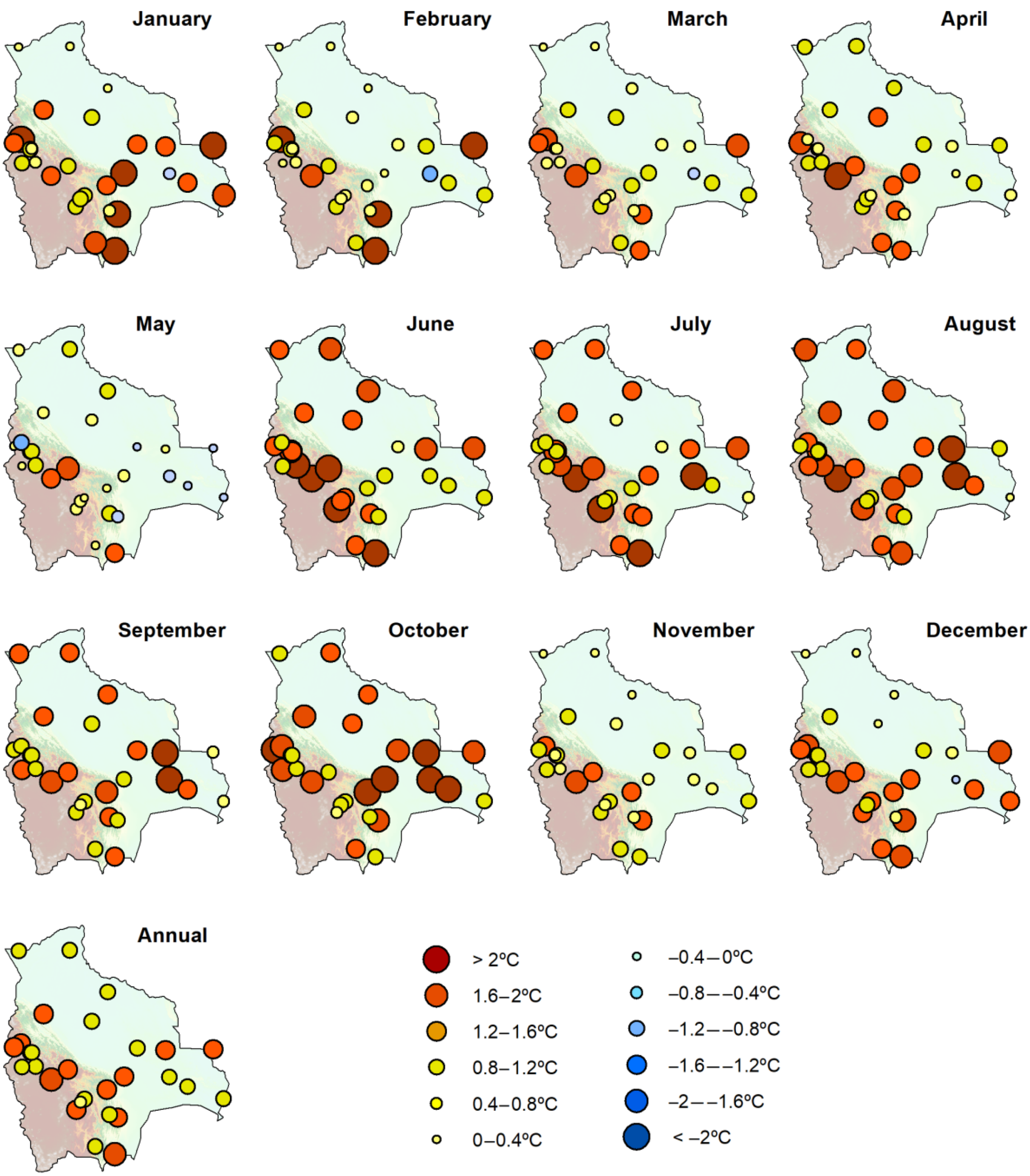

FIGURE 3 Spatial distribution of the monthly and annual changes in mean air temperature in Bolivia from 1950 to 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

or VPD series as the dependent variables. The statistical significance of the trend was assessed using a modified version of the non-parametric Mann-Kendall statistic, which returns the corrected *p* values after considering the temporal pseudoreplication of the variables analysed (Hamed & Ramachandra, 1998; Yue & Wang, 2004). Significant trends were defined as those below the threshold *p* value of 0.05. To facilitate direct comparison between different regions, we presented the trend results using four categories of trends: positive and significant ($p < 0.05$), positive and non-significant ($p > 0.05$), negative and non-significant ($p > 0.05$) and negative and significant ($p < 0.05$). Finally, Pearson's r coefficients for monthly data between the magnitude of change for each climatic parameter (i.e., Tmean, Tmax, Tmin, HR and VPD) with elevation in Bolivia were calculated.

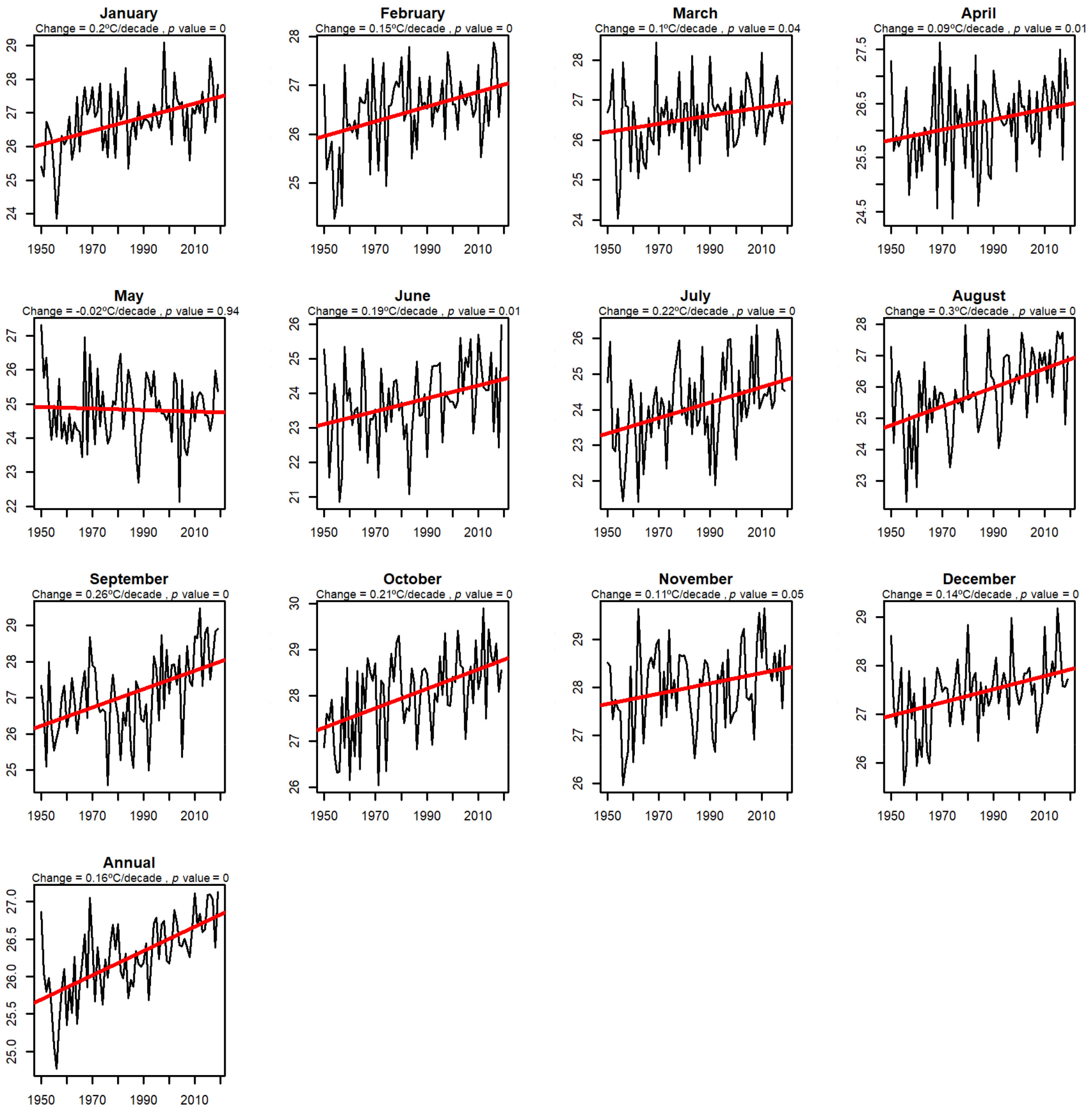

FIGURE 4 Evolution of the country average monthly and annual maximum air temperature in Bolivia from 1950 to 2019. The red line shows the trend evolution of the maximum air temperature over time. [Colour figure can be viewed at wileyonlinelibrary.com]

3 | RESULTS

3.1 | Changes in Tmean, Tmax and Tmin

Figure 2 reveals positive and significant monthly Tmean trends over the year, except for May when the trends, although positive, were statistically non-significant. The annual linear trend in Tmean reached +0.17°C decade^{-1}. Figure 3 shows a strong and significant increase in Tmean from July to October, especially for the highest elevation areas. Significant positive trends predominated across the country at the seasonal and annual scales (Figure S1). In fact, all the meteorological stations showed positive and significant trends at the annual scale for Tmean.

Trends for Tmax also show a predominance of positive and significant values, as displayed in Figure 4, except in May. The largest significant changes (~ +0.25°C decade^{-1}) were reported during the cold season and from September to November, whereas the smallest

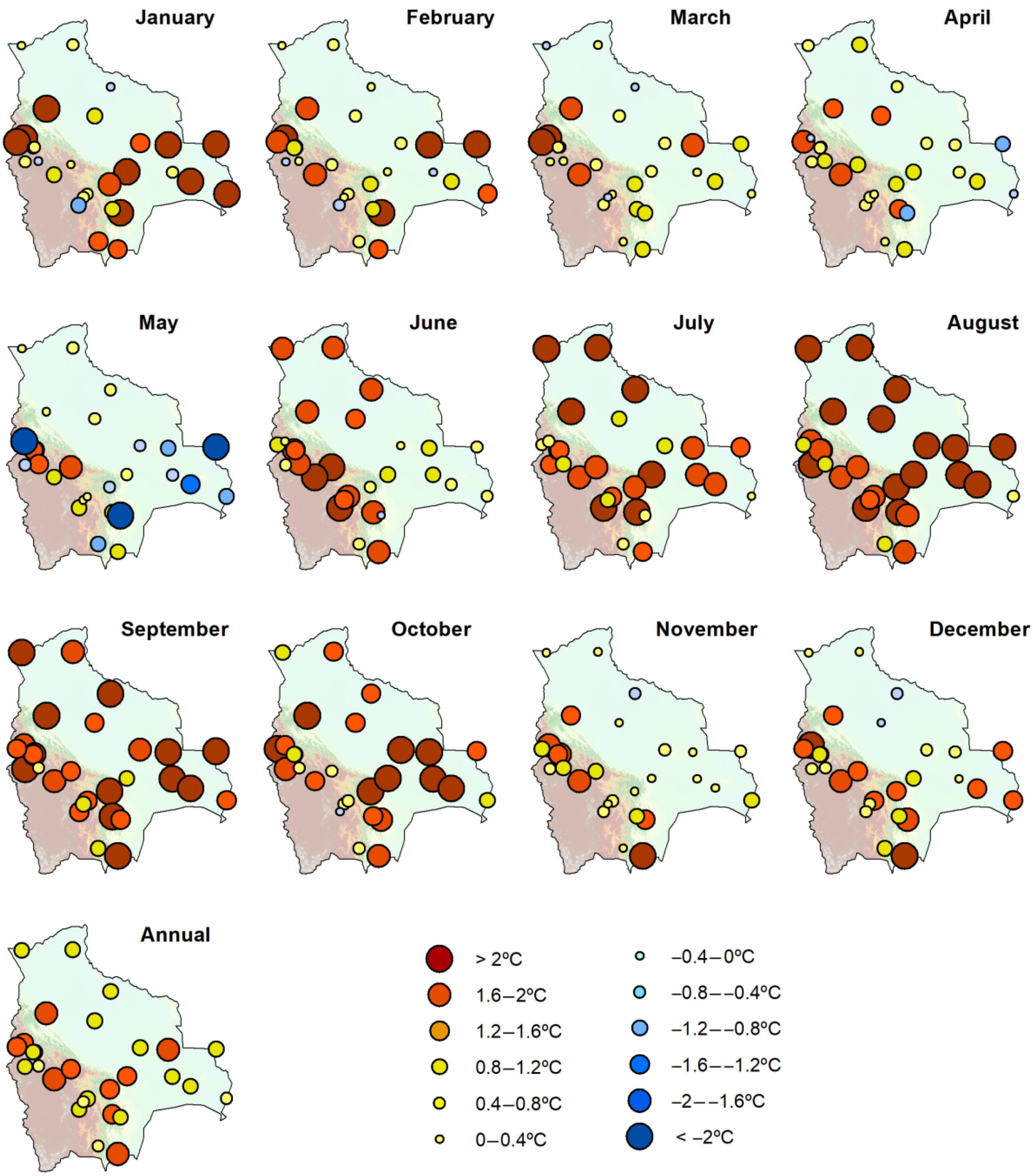

FIGURE 5 Spatial distribution of the monthly and annual changes in maximum air temperature in Bolivia from 1950 to 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

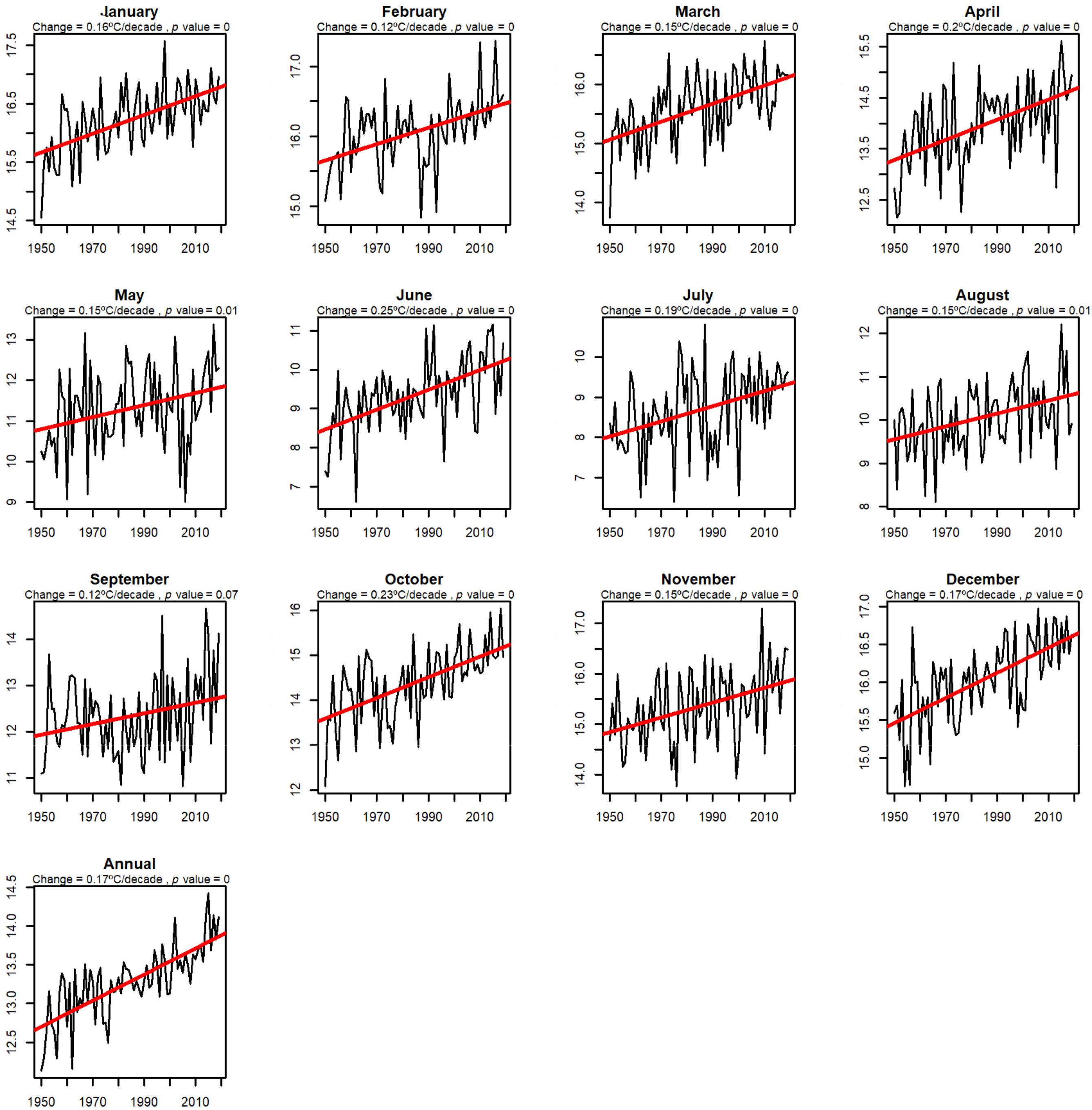

FIGURE 6 Evolution of the country average monthly and annual minimum air temperature in Bolivia from 1950 to 2019. The red line shows the trend evolution of the minimum air temperature over time. [Colour figure can be viewed at wileyonlinelibrary.com]

significant changes were mostly reported from March to April (~ +0.10°C decade^{-1}). The trend in the annual Tmax series was +0.16°C decade^{-1}. From July to October there was a strong and statistically significant increase in Tmax values especially for the lowest areas, whereas in May a strong but insignificant decrease in Tmax records was found (Figure 5). The spatial distribution of the trend significance also showed dominant positive and significant trends across the country, although the significant trends were not as common as observed for Tmax (Figure S2).

Figure 6 shows a widespread positive trend in monthly Tmin with an annual Tmin trend in +0.17°C decade^{-1} ($p < 0.05$). Most of the trends show statistically significant values (p value <0.05) except in September. The largest and most significant positive changes (~ 0.20°C) were found in the cold season and from September to November. The smallest significant positive

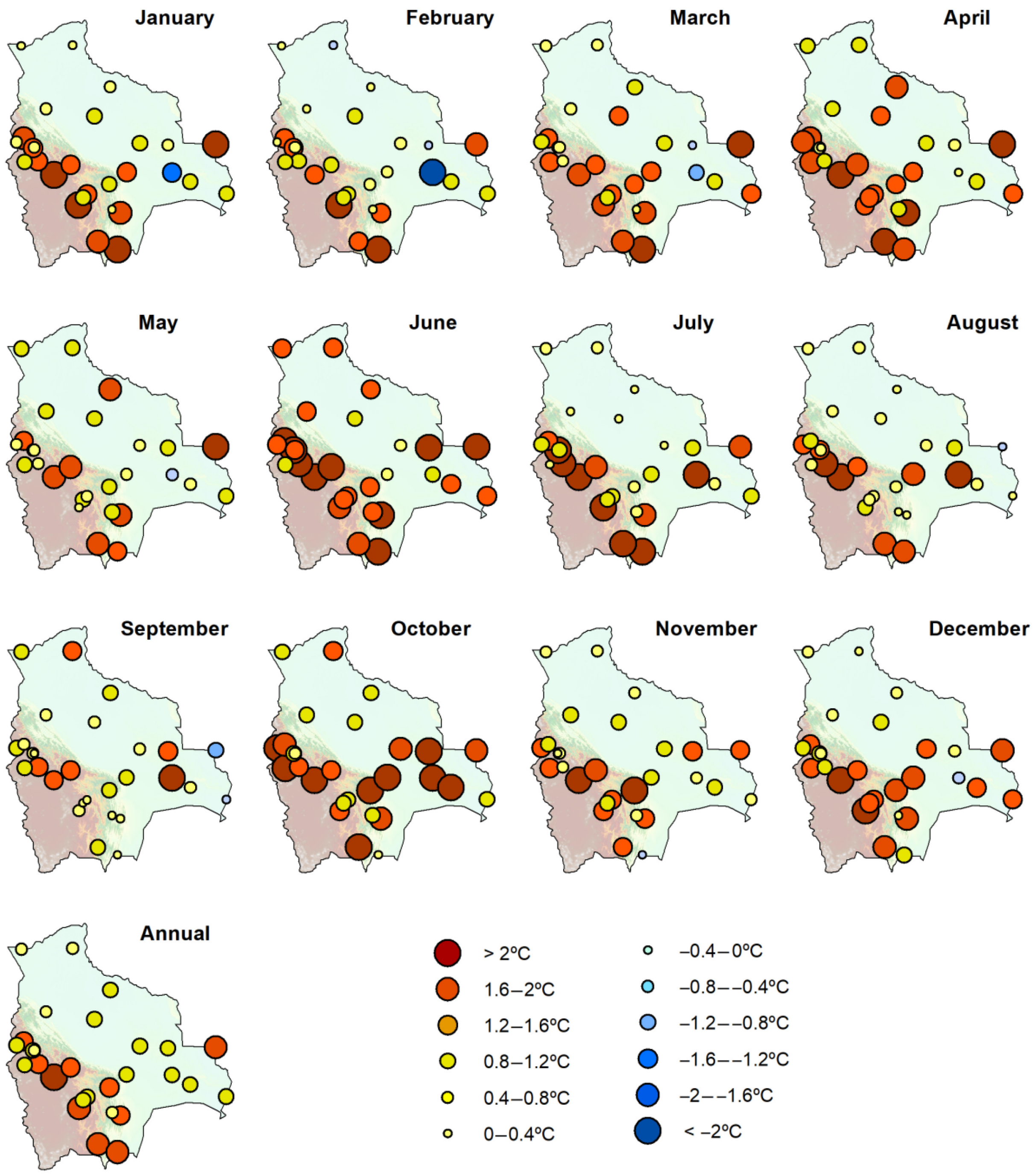

FIGURE 7 Spatial distribution of the monthly and annual changes in minimum air temperature in Bolivia from 1950 to 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

changes in Tmin were mainly reported from March to May (∼ 0.13°C). Figure 7 depicts the spatial distribution of monthly and annual changes in Tmin showing a predominance to positive trends across the country, except for some significant decreases in low areas in January and March. In the sub Andean area, changes for Tmin were around 2°C (p-values <0.05) whereas larger changes were found in the Altiplano (>2°C) in April, June, July and October (p values <0.05) for the study period. The majority of meteorological stations showed positive and statistically significant changes at monthly and annual scales (Figure S3).

Lastly, Figure 8 compares the magnitude of change between Tmax and Tmin at the monthly and annual scales. In general, the changes show higher dispersion for Tmax than for Tmin. The annual median value is the same for Tmin and Tmax although a slightly larger Tmin (Tmax) increase was found from January to June (from July to September). The main discrepancy between Tmax and Tmin trends was found in August and September,

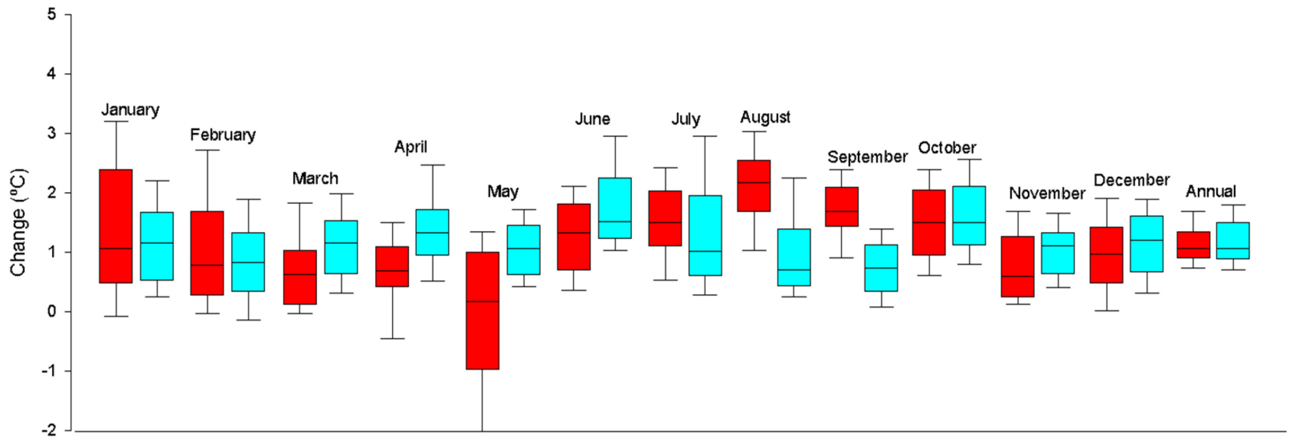

FIGURE 8 Box-plot comparing the magnitude of change in monthly and annual maximum (in red colour) and minimum air temperature (in light blue colour) in Bolivia. [Colour figure can be viewed at wileyonlinelibrary.com]

with more than 1° of difference in the rate of warming from 1950.

3.2 | Changes in RH

The long-term annual mean surface RH was approximately 65%, with a clear peak during the warm season (around 70%), compared to the period from September to November (around 60%). Figure 9 shows monthly and annual RH trends showing positive (negative) changes between December and June (July–November), although no significant values were found for most of the territory. Similarly, the annual RH trend was negative and non-significant ($p > 0.05$). Significant trends were only found from February to April and from August to November. Increases in RH values were found in the warm season and from March to May (~0.35% decade^{-1}, $p < 0.05$), whereas decreases in RH (around 0.60% decade^{-1}, $p < 0.05$) were detected in the cold season and from September to November. The observed pattern in the regional series is caused by all stations having small regional patterns (except in November and December). Annually, a slight decrease in RH and especially at high elevations (around 3%) was observed (Figure 10). The significant decrease in RH was exclusively noted between July and November in the majority of the country (Figure S4).

3.3 | Changes in VPD

Figure 11 demonstrates a predominance of positive monthly VPD trends, although significant trends were only found in May and from July to October. Annually, VPD increased significantly. Moreover, the smallest VPD changes occurred between January and June, being significant at some low elevations from January to April (Figure 12). On a monthly basis, significant positive VPD changes (Figure S5) were reported from July to October across Bolivia, a pattern that is also observed annually.

3.4 | Influence of elevation on trends

Figure 13 shows the relationship between the magnitudes of observed changes in the five climate variables as a function of elevation. As illustrated, there exists a limited relationship over a gradient of more than 4000 metres. The relationship was only significant, although weak, with Tmin. Additionally, Table 1 shows slight differences for the climatic variables studied throughout the year. The strongest positive correlation values were found for (i) Tmin from December to February ($r \sim +0.35$), which means a strong warming trend in Tmin with elevation, (ii) Tmean from November to December ($r \sim +0.40$), (iii) RH in September showed the strongest positive relationship ($r \sim +0.45$) and (iv) VPD values in May ($r \sim +0.40$). The largest negative Pearson's r values were detected for (i) Tmax from August to October ($r \sim -0.40$), (ii) for RH from May to June ($r \sim -0.43$) and finally, for (iii) VPD between August and October ($r \sim -0.40$). This means that the warming associated with Tmax shows higher intensity in low areas between August and October, and this pattern affects the evolution of VPD as it shows a similar geographic pattern.

4 | DISCUSSION

This study analysed long-term changes in air temperature (mean, maximum and minimum), relative humidity and vapour pressure deficit over Bolivia from 1950 to 2019 at an annual and monthly scale using in-situ meteorological

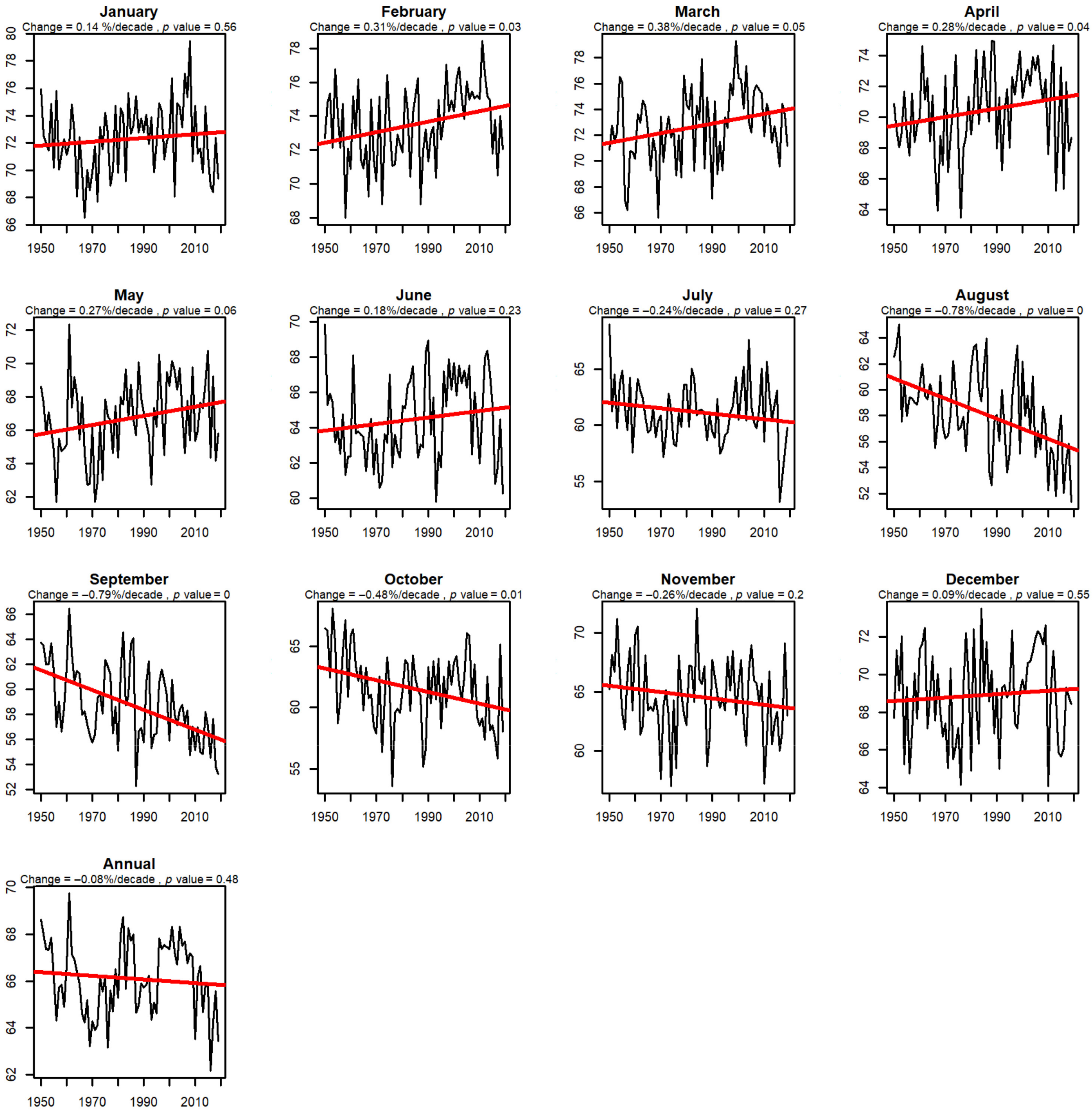

FIGURE 9 Evolution of the country average monthly and annual relative humidity in Bolivia from 1950 to 2019. The red line shows the trend evolution of the relative humidity over time. [Colour figure can be viewed at wileyonlinelibrary.com]

stations. Assessing climate variability in Bolivia using reliable and long-term climate records is crucial, given that this region is sensitive to the effects of climate change, supplies water resources to downstream regions and sustains diverse ecosystems. Research on climate variability in this mountainous region is essential for enhancing our comprehension of these ecosystems, evaluating the effects of climate change and guiding policy formulation and conservation initiatives.

4.1 | Air temperatures

The results show no relevant differences among the trends for the mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperatures. The annual linear trends in Tmean, Tmax and Tmin reached +0.17°C decade^{-1}, +0.16°C decade^{-1} and + 0.17°C decade^{-1}, respectively. These values are in agreement with those reported in the most recent IPCC report (IPCC, 2021) for the

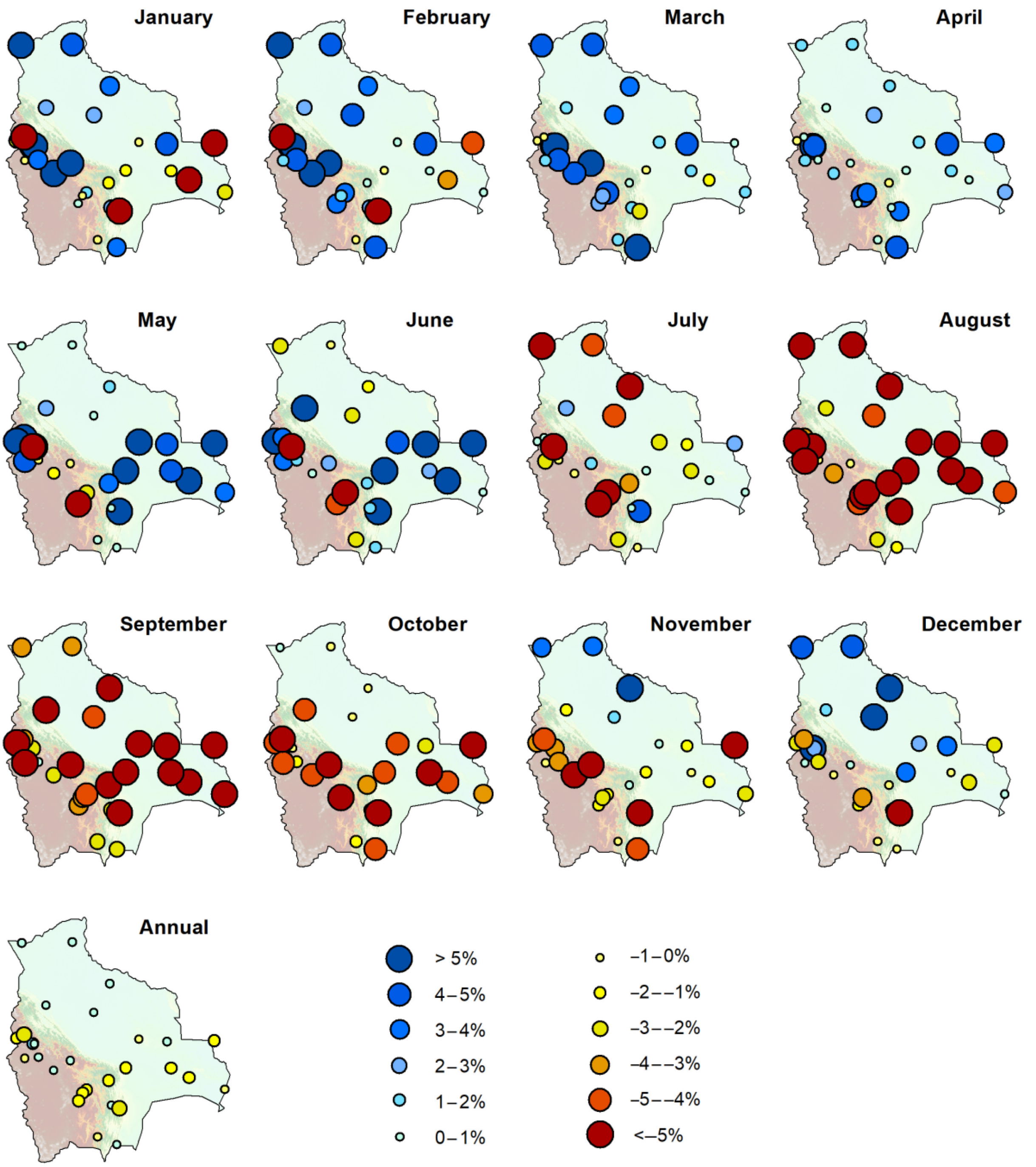

FIGURE 10 Spatial distribution of the monthly and annual changes in relative humidity in Bolivia from 1950 to 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

reference region of South America which is affected by observed increases in mean temperature and experiences the same warming rate with increments of around +0.1°C decade^{-1} between 1961 and 1990 and around +0.2–0.3°C decade^{-1} between 1991 and 2021 (Cavazos et al., 2019; de Barros Soares et al., 2017; Hidalgo et al., 2017; WMO, 2021). We have estimated an increase of +1.12°C for Tmean over the last seven decades that covered the current study. This increment is expected to be higher by 2100 in South America according to different estimations which project an increase of Tmean around +1.9–5°C depending on the model and the emission scenario considered (IPCC, 2021; Llopart et al., 2020). On an annual scale, a positive and significant trend was found as other authors previously reported for Bolivia (e.g., Hagen et al., 2022; Hunziker et al., 2018; Vicente-Serrano et al., 2014). As a result, the predominant loss of Bolivian glaciers during the past few decades (Cayo et al., 2022) may be linked to rising air temperatures (Soruco et al., 2009).

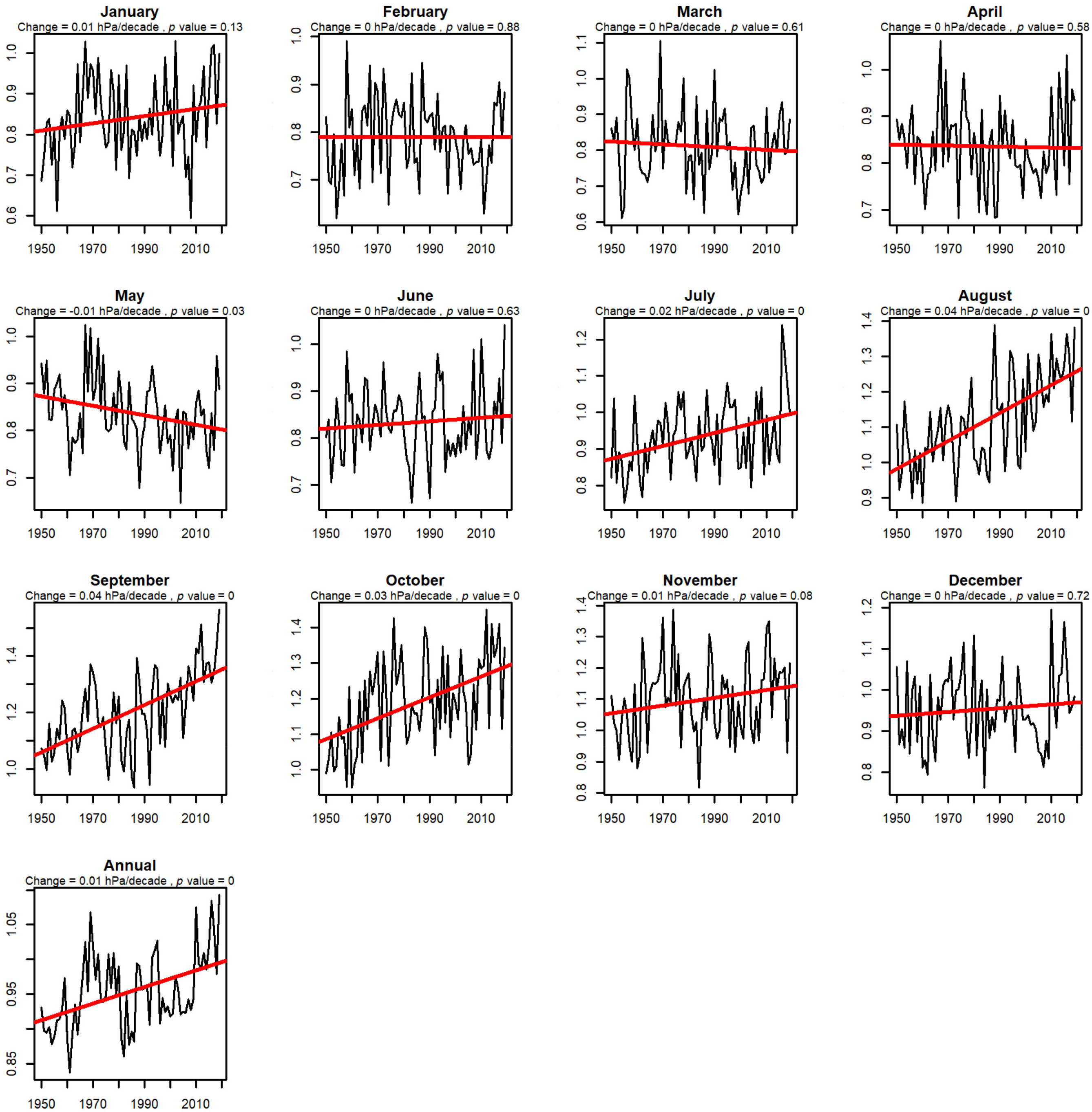

FIGURE 11 Evolution of the country average monthly and annual vapour pressure deficit in Bolivia from 1950 to 2019. The red line shows the trend evolution of the vapour pressure deficit over time. [Colour figure can be viewed at wileyonlinelibrary.com]

In this study, we also reported a direct and significant relationship between the minimum air temperature (Tmin) values and elevation (Figure 13), in agreement with other studies worldwide (e.g., Dimiri et al., 2022; Fan et al., 2015; Liu et al., 2009; Pepin et al., 2015); although this pattern is only identified during 3 months of the year (December–February). According to some authors (e.g., Kirchner et al., 2013; Lareau & Horel, 2015; Moron et al., 2018), the presence of permanent shadows at the valley bottoms usually strengthens the persistence of cold air pools, which partially explains the lower Tmin values found in the lowlands. Besides, we found a decreasing and non-significant pattern for Tmax and elevation, in agreement with Diaz and Bradley (1997) who found decreasing trends, especially above 2000 m a.s.l. Other authors (e.g., Fan et al., 2015) did not always find significant variations between Tmax and elevation, especially at mid-elevations, that is, 2000–3500 m

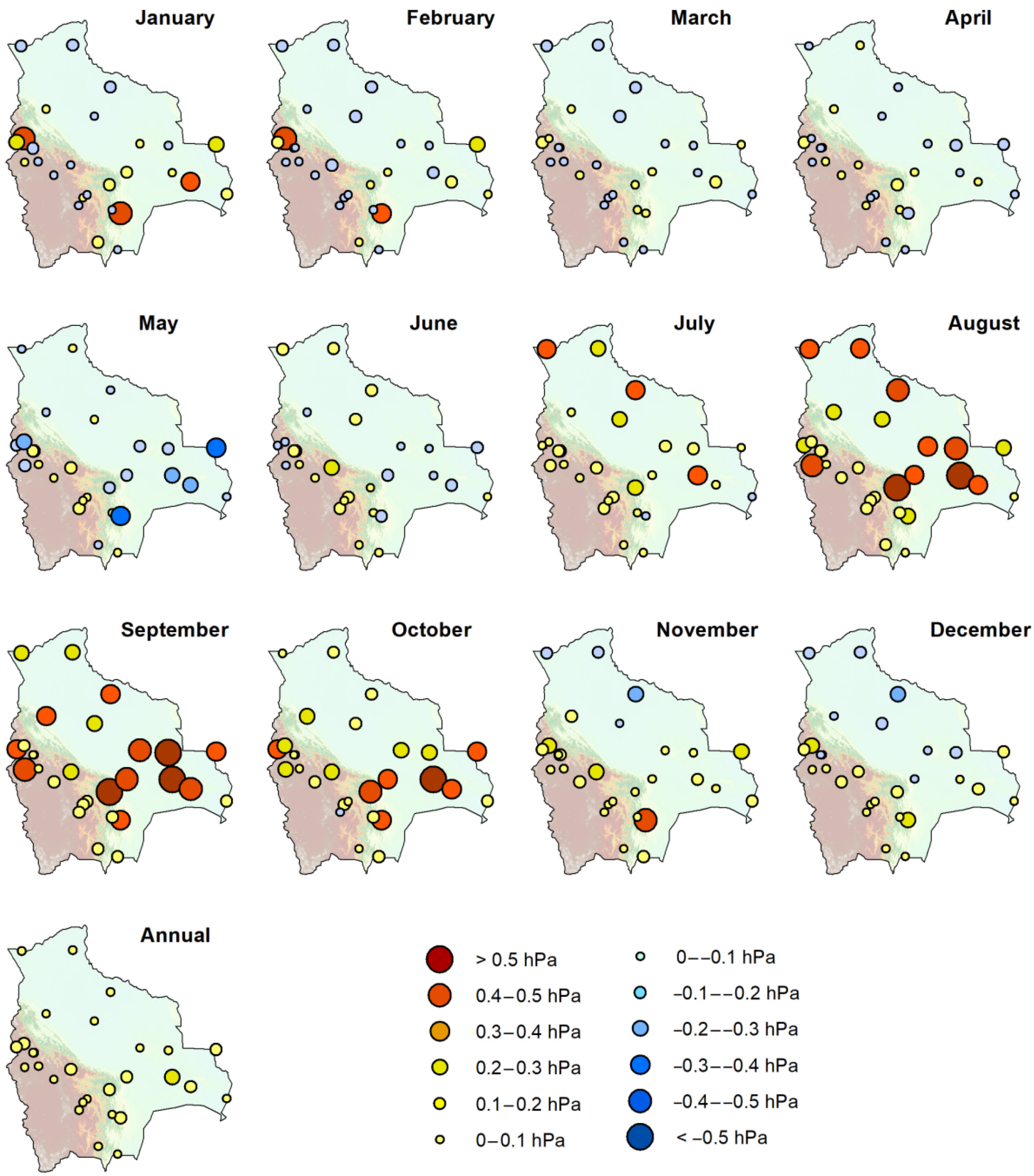

FIGURE 12 Spatial distribution of the monthly and annual vapour pressure deficit changes in Bolivia from 1950 to 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

(Dimiri et al., 2022), in agreement with our results. For mean air temperatures (Tmean), we found an increase in the warming rate with elevation annually (Figure 13), in agreement with previous studies (e.g., Liu et al., 2009; Niu et al., 2021; Pepin et al., 2015).

Niu et al. (2021) pointed out that the relationship between air temperature changes and elevation varies across seasons. In Bolivia, we have found strong seasonal differences in the magnitude of air temperature changes in relation to elevation and they differ between the maximum and minimum air temperatures, with opposite patterns. The warm season showed an increase in minimum air temperatures with elevation, whereas the cold season showed a strong increase in maximum air temperatures in the lowlands. In fact, many authors have not found statistically significant elevation dependency of Tmean (e.g., Liu et al., 2009; Pepin et al., 2015; Zhu et al., 2019), nor did we find them from June to August. However, the cold periods have been suggested to be more affected by an elevation dependency associated

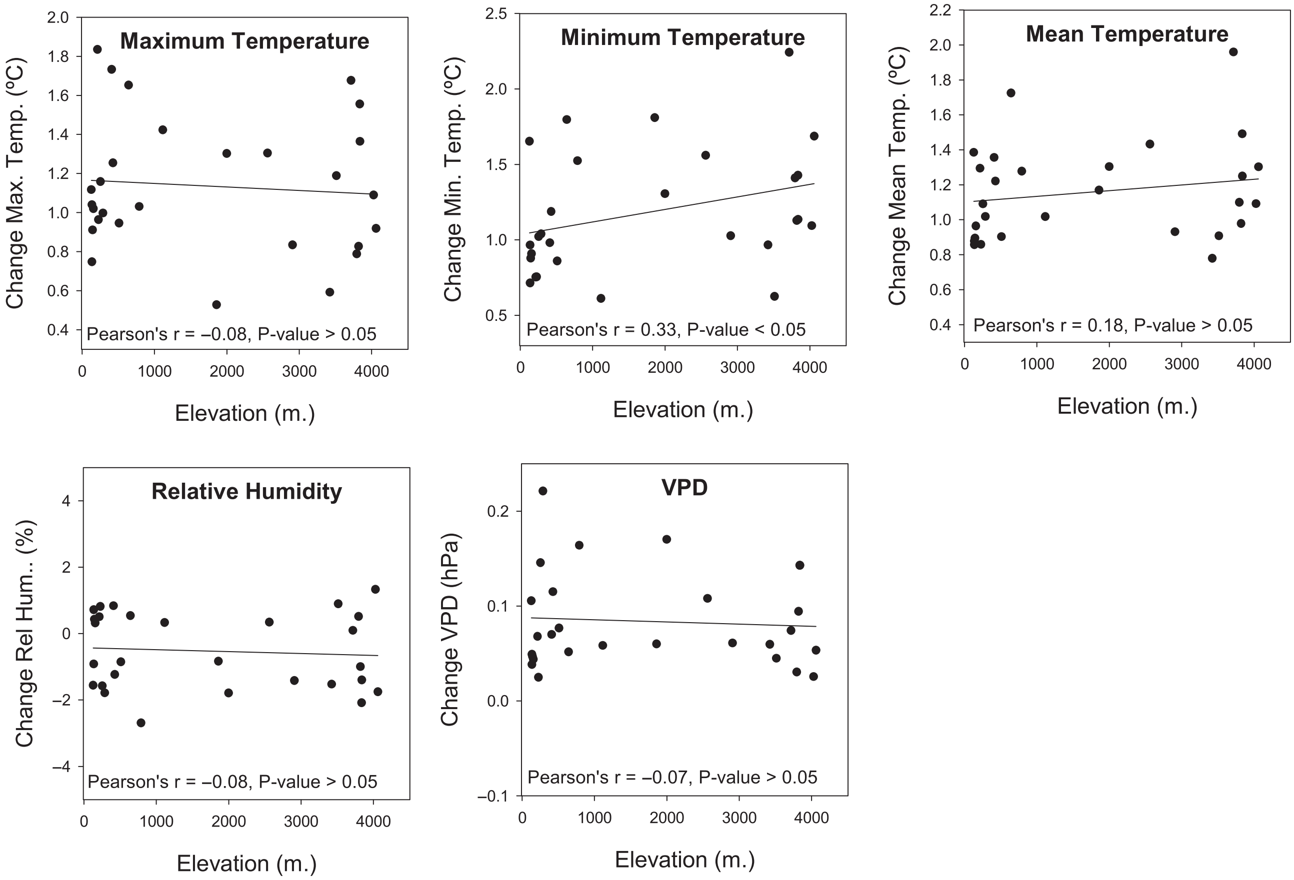

FIGURE 13 Relationship between the magnitude of change in annual air temperature (maximum, minimum and mean), relative humidity and VPD between 1950 and 2019 with elevation in Bolivia.

TABLE 1 Pearson's r coefficients between the magnitude of change in each meteorological station in monthly temperature (mean, maximum and minimum), relative humidity and VPD between 1950 and 2019 with elevation in Bolivia.

	Tmean	Tmax	Tmin	RH	VPD
January	0.03	−0.20	**0.37**	0.20	−0.05
February	0.19	0.01	**0.34**	0.21	0.06
March	0.20	0.10	0.18	0.28	0.14
April	0.09	0.09	0.02	0.02	0.25
May	0.20	0.24	−0.11	**−0.49**	**0.40**
June	0.24	0.20	0.18	**−0.37**	0.29
July	0.13	−0.19	0.27	−0.18	−0.22
August	−0.17	**−0.44**	0.08	0.20	**−0.42**
September	−0.21	**−0.38**	0.00	**0.46**	**−0.47**
October	−0.29	**−0.48**	−0.04	0.13	**−0.32**
November	**0.45**	0.31	0.29	−0.30	0.25
December	**0.36**	0.22	**0.39**	**−0.33**	0.38

Note: Bold values are referred to those which present a highest correlation value between the magnitude of change for climatic variable and the elevation of each meteorological station.

with a decrease in the snow cover, which increases the air temperatures through the snow–albedo feedback (Pepin et al., 2015). In Bolivia, we have shown the opposite pattern, as the minimum air temperatures increase more with elevation in the warm season, while in the cold season, we found the opposite pattern with the maximum air temperature. The mechanisms behind elevation-dependent warming results are difficult to discuss since elevation has a nonlinear effect on air temperature (Navarro-Serrano et al., 2020). Air temperature is the result of an input of energy (i.e., solar radiation) and the way in which that energy is distributed across the territory (Navarro-Serrano et al., 2020). The air temperature change for each elevation unit change (i.e., the elevational lapse rate) is highly variable over space and time in the topographically complex area of the Andean region due to elevation, insolation, vegetation cover and weather conditions, among other factors (Hunziker et al., 2018; Lareau & Horel, 2015; von Arx et al., 2012).

The weak response and complex seasonal patterns of the warming processes with elevation in Bolivia suggest that changes are regionally and seasonally dependent. Nevertheless, the elevation ranges examined, however, might also be a contributing factor to the findings. In fact, Niu et al. (2021) only observed an EDW signal above 4000 m a.s.l. from March to May and from September to November. The meteorological stations analysed in the current study covered elevations below 4500 m a.s.l., which are not sufficient to determine statistical differences when analysing EDW.

4.2 | Relative humidity (RH)

Results indicate a weak annual decrease for the whole country, which was strongest from September to November and during the cold season. Annually, RH decreased, but not significantly, at a rate of −0.08% decade^{-1}. This pattern is consistent with many other regional or global studies that show a weak decrease in RH linked to the increasing air temperature. For example, Isaac and van Wijngaarden (2012) reported a decrease of −0.5% decade^{-1} in North America from 1948 to 2010. Espadafor et al. (2011) reported a significant decrease between −0.01 and −0.23% decade^{-1} in Southern Spain from 1960 to 2005. Vicente-Serrano et al. (2014) revealed an annual significant decrease on the order of −1.02% decade^{-1} in Spain from 1961 to 2011. Finally, global studies conducted by Dai (2006) from 1976 to 2005 and Willet et al. (2008) from 1973 to 2003 reported statistically significant global declines in RH around 0.10% decade^{-1}.

The weak reduction in the annual RH is associated with the above-mentioned increase in annual air temperatures. These results are in agreement with the findings of You et al. (2015), Vicente-Serrano et al. (2014) or the calculations made by Ruosteenoja and Räisänen (2013) that projected a decrease of RH by 8%–12% in Europe from June to August from 2070 to 2099 as a response to global warming. The negative relationship between RH and temperature changes was also observed by Vicente-Serrano et al. (2014) over mainland Spain from 1961 to 2011, explaining the pattern due to the higher maximum air temperatures from June to August over the land surface than over the ocean, which would cause a sub-saturation of the air masses arriving to the continent. According to the Clausius-Clapeyron relationship, the atmosphere is able to exponentially store more moisture with an increase in air temperature (Allan, 2012). However, as also reported by other authors (e.g., Vicente-Serrano et al., 2014; You et al., 2015) this is not the case for Bolivia since we observed a slight decrease in RH trends with an increase in air temperature which could be partially due to a limited moisture supply in the atmosphere, as stated by You et al. (2015). Thus, it seems that RH changes are not just driven by the Clausius-Clapeyron relationship (Vicente-Serrano et al., 2014) but also by processes such as air temperature and precipitation trends or changes in atmospheric circulation patterns (Simmons et al., 2010; Xie et al., 2011). On a seasonal basis, positive RH trends were found from December to June (∼ +0.25% decade^{-1}), while RH trends decreased from July to November (∼ −0.40% decade^{-1}). A similar reduction in RH has been reported from subregional studies in Europe which link the factors causing RH declines to changes in wind direction in Ireland (Butler & García-Suárez, 2012), to atmospheric circulation processes in the Czech Republic (Cahynová & Huth, 2009), to a vapour pressure increase in the Alpine region (Brunetti et al., 2009) or to saturation deficit by evaporation constraints in Poland (Wypych, 2010).

A decreasing pattern of RH values with elevation is in agreement with the inverse relationship between elevation and precipitation (Ghimire et al., 2018; Palazzi et al., 2015), which is usually positively correlated to RH (e.g., Vicente-Serrano et al., 2014). Finally, we highlight the importance of monitoring regional RH levels over time since this parameter can have implications for the severity and intensity of drought events (Karimi et al., 2020), crop yield (Arrizabalaga-Arriazu et al., 2021), pathogen infection rate (Muñoz-Adalia & Colinas, 2021), pollutant concentration levels (Eren et al., 2023) and human health (Kumharn et al., 2023), among other factors. Consequently, the observed decrease in Bolivia during the cold season could have ecological and socioeconomic implications.

4.3 | Vapour pressure deficit (VPD)

Annually, VPD trends slightly increased (+0.01 hPa decade^{-1}, $p < 0.05$) in agreement with global results (Barkhordarian et al., 2019; Yuan et al., 2019). Seasonally, VPD exhibited a more pronounced and statistically significant rise from August to October, with an increase of +0.4 to +0.5 hPa decade^{-1}, particularly noticeable in the lowland regions. Despite a non-significant trend, there was an inverse correlation observed between VPD and elevation. The positive VPD annual trend found could be correlated with the net ecosystem production (NEP) and the terrestrial gross primary production (GPP) and could also substantially impact the interannual variability of the atmospheric CO_2 growth rate as He et al. (2022) pointed out. Besides, VPD also has an influence on terrestrial ecosystem respiration (TER). In fact, He et al. (2022) found a positive (negative) link between VPD and TER in humid (semi-arid and arid) regions. Additionally, atmospheric VPD has been identified as a key driver of plant functioning in terrestrial biomes and has been established as a major contributor to recent drought, which induced plant mortality rates via carbon starvation (Breshears et al., 2013; Hartmann, 2015), irrespective of other drivers associated with climate change (Allen et al., 2015; Eamus et al., 2013; McDowell et al., 2018). The higher VPD values reported in some parts of Bolivia and during some time periods could induce plant stomata closure to prevent extensive water loss (Novick et al., 2016; Sulman et al., 2016; Williams et al., 2013), which subsequently suppresses photosynthesis, decreasing productivity and growth (Barkhordarian et al., 2019; Ding et al., 2018; Grossiord et al., 2020; Konings et al., 2017; McDowell & Allen, 2015; Novick et al., 2016). Moreover, the weak annual increase of VPD detected could induce a shift in vegetation greenness from greening to browning, as also found by Yuan et al. (2019). Finally, the analysis of VPD trends in semiarid and subhumid regions is crucial since they are expected to increase the severity of drought events as well as climate aridity and water stress under climate change (Noguera et al., 2023).

5 | CONCLUSIONS

This study has assessed changes in air temperature, relative humidity and vapour pressure deficit series across Bolivia from 1950 to 2019. To our knowledge, this is the first long-term study analysing the spatio-temporal changes in the magnitude and significance of the climate variables above mentioned in this region. The major findings of this study can be summarized as follows:

i. On an annual scale, positive and significant trends were reported for minimum, maximum and mean air temperatures.
ii. Relative humidity decreased, though not significantly, with the increasing air temperature rates.
iii. A weak but significant increasing trend in vapour pressure deficit was found across Bolivia, suggesting a positive tendency of atmospheric drying and drought events, which could partially limit plant growth and therefore crop production.
iv. Significant relationships between climate variables and elevation were not found. However, minimum air temperatures revealed an inverse and significant relationship with elevation, showing a decrease in the trend at higher elevations. Nevertheless, different seasonal patterns and opposing trends in maximum and minimum air temperature changes and elevation emerge.

In regions with complex topography and high elevation gradients, the changes in the climate variables reported here could help reduce the uncertainties derived from climate model predictions. In addition, this analysis can be used to develop appropriate plans and strategies for risk management and mitigation of negative environmental effects on the human population, as well as for planning activities and biodiversity conservation actions in Bolivia.

AUTHOR CONTRIBUTIONS

B. Fernández-Duque: Conceptualization; data curation; writing – original draft; investigation; visualization. **S. M. Vicente-Serrano:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; supervision; writing – original draft; software. **O. Maillard:** Visualization; writing – review and editing; resources. **F. Domínguez-Castro:** Conceptualization; visualization; writing – review and editing. **D. Peña-Angulo:** Conceptualization; visualization; writing – review and editing. **I. Noguera:** Writing – review and editing; visualization; conceptualization. **C. Azorin-Molina:** Conceptualization; visualization; writing – review and editing. **A. El Kenawy:** Conceptualization; visualization; writing – review and editing.

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