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The Brazilian Cerrado is becoming hotter and drier

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Abstract

The Brazilian Cerrado is a global biodiversity hotspot with notoriously high rates of native vegetation suppression and wildfires over the past three decades. As a result, climate change can already be detected at both local and regional scales. In this study, we used three different approaches based on independent datasets to investigate possible changes in the daytime and nighttime temperature and air humidity between the peak of the dry season and the beginning of the rainy season in the Brazilian Cerrado. Additionally, we evaluated the tendency of dew point depression, considering it as a proxy to assess impacts on biodiversity. Monthly increases of 2.2–4.0℃ in the maximum temperatures and 2.4–2.8℃ in the minimum temperatures between 1961 and 2019 were recorded, supported by all analyzed datasets which included direct observations, remote sensing, and modeling data. The warming raised the vapor pressure deficit, and although we recorded an upward trend in absolute humidity, relative humidity has reduced by ~15%. If these tendencies are maintained, gradual air warming will make nightly cooling insufficient to reach the dew point in the early hours of the night. Therefore, it will progressively reduce both the amount and duration of nocturnal dewfall, which is the main source of water for numerous plants and animal species of the Brazilian Cerrado during the dry season. Through several examples, we hypothesize that these climate changes can have a high impact on biodiversity and potentially cause ecosystems to collapse. We emphasize that the effects of temperature and humidity on Cerrado ecosystems cannot be neglected and should be further explored from a land use perspective.

KEYWORDS
absolute humidity, climate change, dew, dew point, ecosystem collapse, global biodiversity hotspots, MODIS, Reanalysis II, savanna, temperature

1 | INTRODUCTION

Climate change represents one of the greatest challenges in recent human history, due to its wide range of socio-economic and environmental impacts (Pecl et al., 2017; Tol, 2009; Wheeler & von Braun, 2013). In 2018, the Special Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that the change in global mean surface temperature is likely to reach 1.5℃ above pre-industrial levels between 2030 and 2052 (IPCC, 2018). These changes are mainly attributed to anthropogenic emissions of greenhouse gases, particularly carbon dioxide (CO_2), whose concentration increased from 280 ppm during the pre-industrial period to 400 ppm in the first half of the 2010s (NOAA, National Oceanic and Atmospheric Administration, 2019; Ramanathan et al., 2001). Greenhouse gases act as a positive radiative forcing within the Earth's climate system due to the absorption of infrared radiation, which traps thermal energy and re-radiates heat back to the Earth's surface (Farmer & Cook, 2013). Therefore, the nocturnal warming is one of the most noticeable effects of climate change and has been registered worldwide (Vincent et al., 2005; Vose et al., 2005; Zhai et al., 1999; Zhang et al., 2000). However, the influence of human actions on the Earth's climate system is not restricted to the emission of greenhouse gases into the atmosphere. The conversion of natural landscapes to large-scale permanent croplands or pastures alters the regional climate through its effects on energy and water balances (Foley et al., 2005). These processes are linked to complex soil–vegetation–atmosphere interactions and can attenuate or amplify anthropogenic climate change (Alter et al., 2018; Bonan, 2008). Thus, climatic changes caused by massive suppression of native vegetation can vary among biomes.

Over the past few decades, tropical savannas worldwide have been among the most affected biomes due to the suppression of native vegetation. Tropical savannas are typically located between the equatorial rainforests and subtropical semiarid regions, and coincide with the Aw climate type (tropical with dry winter), according to the Köppen classification (Woodward, 2009). Aw is the second most representative climatic type on Earth (covering 11.5% of continental areas), being characterized by high temperatures throughout the year, with wet and dry seasons occurring in summer and in winter, respectively (Peel et al., 2007). The dry season and the deficiency of phosphorus and other nutrient minerals in the very old soils do not favor forest development, giving rise to landscapes consisting mainly of grasslands with sparse or isolated trees (Walter & Breckle, 1986). Fire and other anthropic activities also play an important role both in the structure and composition of the vegetation in savannas (Graeff, 2015b; Walter & Breckle, 1986). In addition to their intrinsic importance in terms of biodiversity, tropical savannas are also essential in the Earth's climate system, accounting for 21% of global evapotranspiration (Miralles et al., 2011). Therefore, environmental changes resulting from human activities in these ecosystems pose threats to both biodiversity and climate.

Historically, the main environmental impacts on savannas are directly or indirectly associated with food production, such as beef cattle production in northern Australia and South America and mixed grazing and permanent cultivation in Africa (Hoffmann & Jackson, 2000). Additionally, tree felling for firewood and charcoal production is a common practice in all savannas around the world (Hoffmann & Jackson, 2000; Oliveira et al., 2005). Furthermore, in recent decades, agricultural production has severely impacted savannas, particularly in South America, where soybean cultivation has become widespread in the Brazilian Cerrado and in the Gran Chaco (an ecoregion formed by parts of the territories of Paraguay, Bolivia, and Argentina; Fehlenberg et al., 2017; Ratter et al., 1997).

The Brazilian Cerrado (also called Neotropical Savanna) is a global biodiversity hotspot that has already lost 46% of its native vegetation cover (Figure 1; Strassburg et al., 2017). Recent studies indicate a conversion rate of 5000 km² year^{-1}, mainly of grassland and woodland in flat and smooth relief, which have been converted to croplands (Ferreira et al., 2016). However, agricultural production in the region is not performed throughout the year due to the pronounced water deficit between June and September, when the soil is exposed, or covered by summer crop residues (Neto et al., 2010). Except in areas with center-pivot irrigation, most of the cropland areas remain under a fallow system, with large expanses without green vegetation cover throughout the dry season (Figure 1c; Figure S1). In this scenario, theoretical simulations evaluating the climatic effects of savanna suppression have predicted an increase in annual albedo and a consequent reduction of the net radiation incident on the surface (Hoffmann & Jackson, 2000; Snyder et al., 2004). In contrast, they also indicate a latent heat flux decline accompanied by an increase in sensible heat flux, leading to an increase in air temperature and a large reduction in near-surface humidity and precipitation. Indeed, empirical studies conducted in small portions of the Brazilian Cerrado have corroborated the climate projections made by theoretical simulations due to land cover changes (Loarie et al., 2011; Oliveira et al., 2005; Spera et al., 2016).

A second anthropic factor affecting the climate system in the Brazilian Cerrado is the high concentration of aerosol particles in the atmosphere caused by biomass burning in wildfires. Burning is an ancient and widespread practice throughout the Brazilian Cerrado and is used by both traditional communities and ranchers (Eloy et al., 2018; Mistry, 1998). Additionally, fire is used to remove crop residues from some commercial cultures, such as sugarcane (Pivello, 2011; Ratter et al., 1997). In total, more than 68,000 fires are annually detected by satellites throughout the Brazilian Cerrado, of which over 80% occur between July and October (INPE, 2020). Aerosols and particulates from wildfires during the dry season have an average atmospheric residence time of 1 week and, eventually, form a thick smoke layer over large extents of the North and Midwest regions of Brazil (Freitas et al., 2005). The smoke particles from biomass burning can change the local and regional energy budgets through scattering and absorption of solar radiation and, therefore, lead to atmospheric heating and surface cooling (Yamasoe et al., 2006). Consequently, there is a tendency to stabilize the atmosphere due to the inhibition of the turbulent fluxes near the ground (Jacobson, 2002; Liu, 2005). Therefore, given the extent of the Brazilian Cerrado which is already suppressed, and the high concentration of aerosols from wildfires, it is likely that climate change can be detected at both local and regional scales in the biome.

In this study, we used three different approaches based on independent datasets to investigate possible changes in the daytime and nighttime temperatures and air humidity between the peak of the dry season and the beginning of the wet season in the Brazilian Cerrado (July–October). Additionally, as dew can be the only liquid water source for sessile organisms and species with low vagility during the dry season, we also evaluated the trend of dew point depression, considering it as a proxy to access possible impacts on biodiversity (see details in the Section 4). To quantify the magnitude of climate change, we used the climate dataset with the longest available time series (1961–2019). This series spans the period prior to the expansion of agribusiness in the Cerrado, extending to the present. Finally, we projected climate trends for the next 31 years, which permits direct comparison with projections by Strassburg et al. (2017) who suggested that 31%–34% of the remaining Cerrado is likely to be cleared by 2050.

2 | METHODS

2.1 | Study area

The Cerrado is an ecoregion that extends over 2 million km² (i.e., equivalent to the area of Mexico), from the equatorial region to 25°S at its southern limit (in the state of Paraná), and occurring in 10 of the 26 Brazilian states (Figure 1). The altitudinal gradient varies from sea level to 1800 m (Ratter et al., 1997). Based on the Köppen climate classification, the Aw type predominates in the region, except at higher altitudes, with Cwa (subtropical with dry winter and hot summer) and Cwb (subtropical with dry winter and temperate summer), and Am (tropical with monsoon) in the transition zones to the Amazon Rainforest biome (Alvares et al., 2014). The Cerrado vegetation is a mosaic of different phytophysiognomies (Figure S1), in a gradient of grasslands (*campos rupestres* and *campos sujos*), savannas (*cerrado stricto sensu* and *veredas*), and forest formations (*cerradão*, riparian forests and dry forests; Graeff, 2015a). All these vegetation formations are closely related to edaphic characteristics, although they are also strongly influenced by other factors such as fire (including natural fire) and cattle grazing (Graeff, 2015a; Walter & Breckle, 1986).

The Brazilian Cerrado is under a process of land cover and land use change which remounts to more than a half-century and can be split into three main phases. Until the 1960s, the native vegetation suppression was restricted to small plots, especially by the logging of trees for coal production and the use of fire for the creation of pasture areas for livestock (Ratter et al., 1997). Between the 1960s and the 1980s, the process was enhanced by the growth of the new capital Brasilia and by concessions of Brazilian Military Dictatorship to private companies to implement new agricultural projects on the western Brazilian border (Ratter et al., 1997; Silva, 2010). Finally, from the 1990s, native vegetation loss has intensified due to the expansion of soybean plantations over new agricultural frontiers in the states of Maranhão, Tocantins, Piauí, and Bahia (Lahsen et al., 2016; Spera et al., 2016).

2.2 | Local and regional climate changes and projections for 2050

First, we analyzed the trend of four climatic variables: maximum and minimum temperature, absolute humidity, and dew point depression (considered a proxy for dewfall) during the 4 months of the dry season. In this step, our analyses were restricted to data recorded by conventional weather stations (i.e., those in which records are taken by a meteorological observer) because the first automatic weather stations in Brazil were only installed from 2000 onward. We accessed the historical database of the Brazilian National Meteorology Institute (Instituto Nacional de Meteorologia—INMET) from its website at https://tempo.inmet.gov.br/TabelaEstacoes. Climate records of all conventional weather stations in the Brazilian Cerrado biome (1961–2019) were compiled. No weather station with more than 30% of missing values for a given variable was considered for the models shown in Tables S1 and S2. However, in case a weather station contained a good dataset for one or more variables but also many missing values for others, we used all the suitable variables and discarded only the problematic ones (i.e., the NA cases in Tables S1 and S2). A total of 45 weather stations remained suitable for our analysis and their spatial distribution is shown in Figure1 (note that at the western boundary of the Cerrado, no weather station was selected). From Brazilian conventional weather stations, data on the main meteorological variables are available for 00, 12, and 18 h Coordinated Universal Time (UTC), and also the daily maximum and minimum records. Therefore, the only nocturnal meteorological record to evaluate a possible increase in dew point depression was at 00 h UTC (09 PM local time).

Daily values of absolute humidity and dew point depression (at 00 h UTC) used in our models were obtained from the following equations:

$$\mathrm{es}_{\mathrm{u}} = 4.58 \times 10^{\frac{(7.5 \times T_{\mathrm{u}})}{(287.5 + T_{\mathrm{u}})}},$$

where, es_{u} is the saturation pressure for the wet bulb temperature (as defined by the Tetens equation, here presented in a form adapted to atmospheric pressure in mmHg and exponentiation with base 10), and T_{u} is the wet bulb temperature (°C).

$$e = \mathrm{es}_{\mathrm{u}} - (A \times P \times (T - T_{\mathrm{u}})),$$

where, e is the vapor pressure (mmHg; according to Dalton's law), A is the psychrometer coefficient (i.e., $0.0008℃^{-1}$), P is the atmospheric pressure (mmHg), and T and T_{u} are the temperatures of the dry bulb and wet bulb (°C), respectively.

$$\mathrm{AH} = 289 \times \left(\frac{e}{T + 273.16}\right),$$

where, AH is the absolute humidity ($\mathrm{g/m^3}$), e is the vapor pressure (mmHg), and T is the temperature of dry bulb (°C).

$$T_{\mathrm{dp}} = 237.5 \times 10^{\frac{(e/4.58)}{(7.5 - 10^{(e/4.58)})}},$$

where, T_{dp} is the dew point temperature (°C), and e is the vapor pressure (mm Hg).

$$D_{\mathrm{pd}} = T - T_{\mathrm{dp}},$$

where, D_{pd} is the dew point depression (°C), T_{dp} is the dew point temperature (°C), and T is the temperature of the dry bulb (°C).

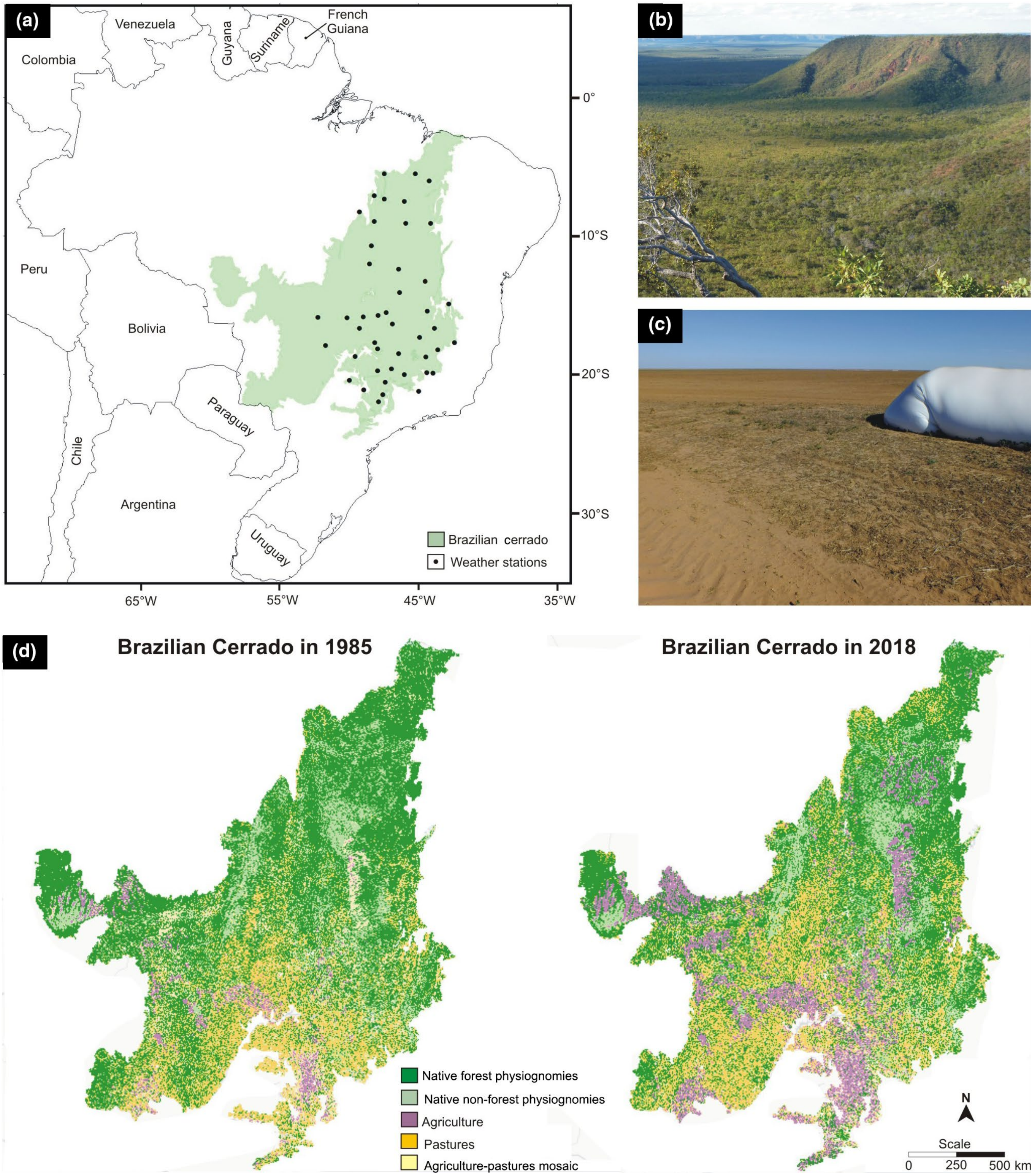

FIGURE 1 Location of the Brazilian Cerrado and its land use/land cover changes in recent decades. (a) Official limits of the Brazilian Cerrado ecoregion (green) and location of the weather stations used in this study (black dots). (b) Intact Cerrado area with Borá peak, a sandstone hill near Mambaí municipality, in the state of Goiás. (c) Extensive cropland area (in fallow stage) and a bag silo for harvest storage in the west of the State of Bahia. (d) Land use/land cover maps of the Brazilian Cerrado in the years of 1985 and 2018 (data source: MapBiomas—Collection 4.1 of Brazilian Land Use Land Cover Map Series, accessed on 28/12/2019 through the link: http://mapbiomas.org/)

Then, we calculated the monthly values of the four variables from the arithmetic mean of the daily values used for two purposes. First, we used the arithmetic mean of monthly values of all 45 weather stations to obtain measures of the four variables that were representative of the entire Cerrado ecoregion (hereinafter referred to as entire Cerrado). For this calculation, we chose not to use the estimated

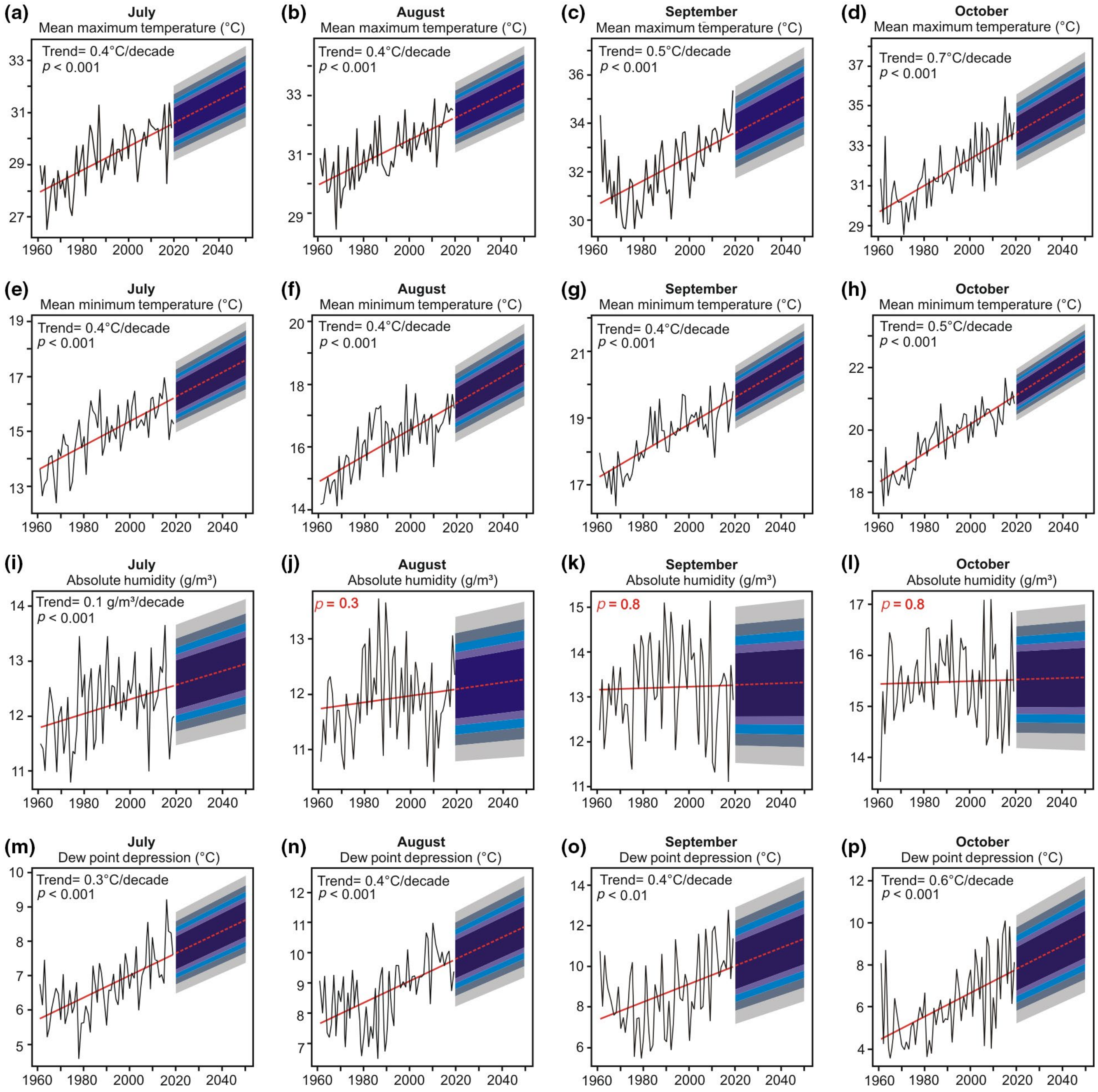

FIGURE 2 Linear regression models between 1961 and 2019 and forecasts until the year 2050 for the entire Cerrado. (a–d) Models considering the mean maximum temperature as the dependent variable for the months of July, August, September, and October, respectively. (e–h) Models considering the mean minimum temperature as the dependent variable. (i–l) Models considering the absolute humidity (estimated at 00 h UTC) as the dependent variable. (m–p) Models considering the dew point depression (estimated at 00 h UTC) as the dependent variable. In all linear models, the time (1961–2019) was considered the independent variable. The black solid lines describe the annual mean of four variables. The red solid lines represent the best-fitting line of each model between 1961 and 2019. The red dashed lines describe projected values until 2050, and the 50%, 60%, 70%, 80%, 90% prediction intervals are represented by the dark-blue to light-gray bands, respectively. UTC, Coordinated Universal Time

data. Therefore, stations lacking data in a specific month were not considered when computing the monthly average for that year. Thus, the monthly values of the entire Cerrado (used in the 16 forecasts from linear regression models shown in Figure 2) were formed only by measured values, so some years did not include data from some weather stations. To evaluate regional climate changes, the forecasts from linear regression time series models were used because of the easy interpretation of trends and because this method also enables data projection for future prediction intervals (for details about this method, see Hyndman & Athanasopoulos, 2018).

Second, to assess the heterogeneity of regional climate change, we also ran a total of 16 forecasts from linear regression models for each weather station (see Table S1). However, contrary to the data of the entire Cerrado, for the models of each weather station, it was necessary to fill the missing values for all months in which the records were not available in the INMET database. Thus, using the entire dataset available, we calculated the monthly deviations of each weather station in relation to the regional mean (entire Cerrado values) for all four variables. The missing values were filled by the difference between the regional mean for that month (the entire Cerrado value) and the weather station monthly deviation value. All linear models were performed using the fpp package for R (Hyndman & Athanasopoulos, 2018).

2.3 | Evaluation of the consistency of the entire Cerrado analysis using MODIS data

In the second step, we evaluated the consistency of the means calculated for the entire Cerrado analysis based on data from remote sensing. Given that most of the weather stations were initially installed in rural areas but eventually became closer to or have been engulfed by towns or villages due to urban expansion, we aimed to evaluate whether the land use and land cover changes around the weather stations could have influenced the measurements, for example, through urban heat-island effects (Gallo et al., 1996; Sati & Mohan, 2018). For that, we compared the monthly values of minimum and maximum temperatures with data detected with the Moderate Resolution Imaging Spectroradiometer (MODIS).

Moderate Resolution Imaging Spectroradiometer land surface temperature data were obtained from the MOD11A2 version 6 product (Wan et al., 2015), provided by the Land Processes Distributed Active Archive Center, managed by the NASA Earth Science Data and Information System project (https://lpdaac.usgs.gov). This product is based on MODIS imagery, onboard Terra (data collected between 00 and 03 h UTC), and Aqua (data collected between 15 and 18 h UTC) platforms, providing an average 8-day land surface temperature globally at 1 km spatial resolution.

From the entire series, we selected the months of July to October, from 2000 to 2019, filtered by a high-quality control flag, covering the official limits of Brazilian Cerrado as defined by the Brazilian Institute for Geography and Statistics (Instituto Brasileiro de Geografia e Estatística). The land surface temperature values (originally supplied in Kelvin) were converted to Celsius for comparison with weather station data. Using all the available records, we generated a monthly value of land surface temperature for all years of the MODIS data collection (2000–2019 for MODIS/Terra and 2002–2019 for MODIS/Aqua) through the arithmetic mean values of all pixels included in the Cerrado area. Then, the monthly values of land surface temperature from MODIS data were compared to the entire Cerrado mean temperatures recorded by weather stations using Pearson's correlation test. Additionally, we examined the homogeneity of the regression slopes of the two datasets through ANCOVA. Both correlations and ANCOVA tests were performed using PAST.4.03.

2.4 | Evaluation of large-scale regional trends with the NCEP/DOE Reanalysis II dataset

Third, we evaluated large-scale regional trends in surface temperature and relative humidity, based on the National Center for Atmospheric Research/Department of Energy Reanalysis II dataset (Kanamitsu et al., 2002). The product reports global data four times daily (00–18 h UTC) at 2.5° lat/lon spatial resolution, and it is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website (https://www.esrl.noaa.gov/psd/). The NCEP Reanalysis II is based on an analysis/forecast system to perform data assimilation by combining observations from satellites and conventional ground-based stations. Data were selected covering all of Brazil territory from July to October, at 06 h UTC and 18 h UTC, starting in 1990, when agricultural processes currently observed in the region started to intensify (Lahsen et al., 2016). We analyzed the large-scale regional trends comparing the surface temperature and relative humidity averages for the years 2014–2019 and 1990–1995, at both nighttime and daytime periods.

3 | RESULTS

Our regression models for the entire Cerrado show maximum temperatures increase, predominantly in October (Figure 2a–d). In this month, the mean maximum temperature increased by 4.0℃ between 1961 and 2019 and, if this tendency persists, the temperature will be 6.0℃ higher in 2050 than in 1961 (Table 1). The same pattern was also observed in most weather stations, with some localities showing trend values higher than 1℃ per decade (Table S1). Minimum temperature values also showed an increasing tendency for both the entire Cerrado and most of the localities (Figure 2e–h), with forecasts for 2050 displaying less uncertainty than the projections for the other variables analyzed (as shown by relatively narrower ranges of 50%, 60%, 70%, 80%, and 90% prediction intervals). For absolute humidity, the trends for entire Cerrado considering a linear fit displayed a slight (and less conclusive) increase in most cases (Figure 2j–l, $p \geq 0.3$), except for July (Figure 2i, $p < 0.01$). Considering the values from 1990, the tendency of absolute humidity records indicates a decline, and suggest an inverted U-shaped pattern (more clearly evidenced in September; Figure 2k). The analysis for dew point depression (Figure 2m–p) showed a pattern similar to that of the maximum temperature, increasing with the succession of the dry months.

The comparisons between monthly values of land surface temperature from MODIS and maximum and minimum temperatures recorded by weather stations for the entire Cerrado are displayed

TABLE 1 Regional climate changes and projections for 2050 in the Brazilian Cerrado. Results of linear regressions between 1961 and 2019 and forecasts until the year 2050 for entire Cerrado, where the variables trend values were calculated by multiplying between slope β and the number of years in each period (i.e., 59 years for 1961–2019 and 90 years for 1961–2050). NA (not available) indicates models whose results were not statistically significant ($p > 0.05$)

	Maximum temperature (°C)		Minimum temperature (°C)		Absolute humidity (g/m^3)		Dew point depression (°C)	
Month	1961–2019	2050 forecast	1961–2019	2050 forecast	1961–2019	2050 forecast	1961–2019	2050 forecast
July	2.6	4.0	2.6	4.0	0.8	1.2	1.9	2.9
August	2.2	3.4	2.5	3.8	NA	NA	2.1	3.2
September	2.9	4.4	2.4	3.6	NA	NA	2.6	4.0
October	4.0	6.0	2.8	4.2	NA	NA	3.3	5.0

in Figure 3. Pearson's correlation coefficients between the monthly values of MODIS and the entire Cerrado ranged from 0.47 to 0.89, and were significant ($p < 0.05$) for all cases analyzed. As shown, the trend values are positive in all cases and, for each month, changes in daytime temperature were always higher than nighttime changes. All ANCOVA tests were not significant ($p > 0.05$); therefore, there was no difference between the slopes of MODIS and those of the entire Cerrado.

Based on the information from the NCEP/DOE Reanalysis II, the average surface temperatures in the months from July to October were higher for 2014–2019 than for 1990–1995, during both nighttime and daytime periods (Figure 4a,b, respectively). In this dataset, the increase in temperature was the highest in the afternoon. The difference between the earlier and later years was approximately 1–2.5℃ for the daytime period (18 h UTC) and 0.5–1℃ for the nighttime period (06 h UTC) in most of the Cerrado. In parallel, relative humidity showed a downward tendency for most of the biome, between 1990–1995 and 2014–2019 decreasing by ~15% for both 06 and 18 h UTC (Figure 4c,d).

4 | DISCUSSION

Here, we present analyses of atmospheric conditions near the surface for the past decades in the Brazilian Cerrado, including data from weather stations, remote sensing, and modeling. When compared to past decades, hotter and dryer conditions have been verified in the study region, both locally and at a regional scale. This overall pattern in the results is supported by all analyzed datasets, which include direct observations from ground station reporting data from approximately 60 years ago. As presented, weather stations showed increases in maximum and minimum temperatures, increases in dew point depression, and decreases in absolute humidity in recent years (except for the July month). There was an important agreement between the ground measurements and remote sensing data revealing a rise in temperature for the entire series of MODIS data. In addition, broad-scale information from NCEP-DOE Reanalysis II was in agreement with these datasets, showing substantially higher temperatures and lower relative humidity near the ground in recent years (2014–2019 compared to 1990–1995) in the study region. These results also corroborated the heterogeneity observed in trends of weather stations, showing variation in changes within the Brazilian Cerrado, where the eastern and central sectors seem to have become warmer and drier than the western one. However, even though this difference may be real, it must be interpreted with caution due to the reduced number of stations in the latter.

In addition to the consistency between the analyzed data, the results we present are also in agreement with those of other studies. First, they are consistent with the observed global warming, which is linked to the increasing concentration of atmospheric greenhouse gases (IPCC, 2018). Second, they corroborate the results of other studies that simulate land use changes in savannas. For instance, the pronounced increase in temperatures during the dry season is consistent with the forecasts from all three theoretical studies that simulated climate change due to savanna removal (Bounoua et al., 2002; Hoffmann & Jackson, 2000; Snyder et al., 2004). However, in terms of intensity, the increase in the maximum and minimum temperatures detected in this study was higher than those projected by previous theoretical studies. Our temperature trends were also considerably higher than that of the global warming of 0.2℃/decade estimated by the IPCC (IPCC, 2018) and by Vose et al. (2005) for the Southern Hemisphere (i.e., maximum and minimum temperature trends between 0.086–0.126 and 0.125–0.14℃/decade, respectively).

Thus, it may seem that our temperature means of the entire Cerrado could be biased by the effect of urban heat islands. However, the comparison of data from weather stations with that of surface temperatures from MODIS was essential to discard this concern. Hence, we considered two possible reasons to explain the difference between the magnitude of our trends and that of the former studies, associated with land use and land cover changes that occurred in the Brazilian Cerrado since the beginning of the records in the datasets that we analyzed.

First, both IPCC projections and the three theoretical models consulted do not consider the synergy between the global increase in greenhouse gases concentration, land use and land cover changes on the local and regional scales. In fact, diurnal local/regional

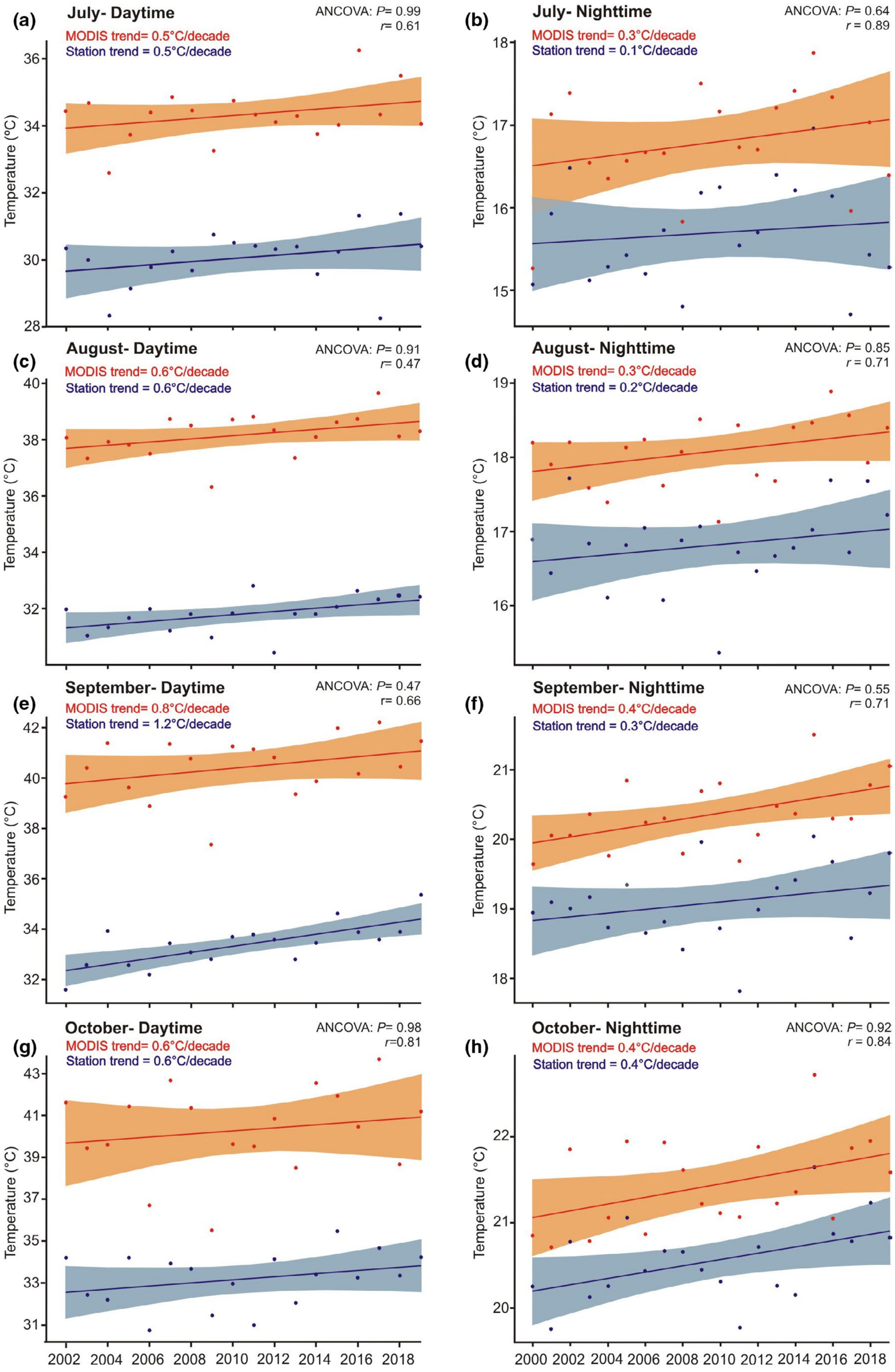
(a)
July- Daytime
ANCOVA: P= 0.99
r= 0.61
MODIS trend= 0.5°C/decade
Station trend = 0.5°C/decade
Temperature (°C)
36
34
32
30
28
(b)
July- Nighttime
ANCOVA: P= 0.64
r = 0.89
MODIS trend= 0.3°C/decade
Station trend = 0.1°C/decade
Temperature (°C)
18
17
16
15
(c)
August- Daytime
ANCOVA: P= 0.91
r= 0.47
MODIS trend= 0.6°C/decade
Station trend = 0.6°C/decade
Temperature (°C)
40
38
36
34
32
(d)
August- Nighttime
ANCOVA: P= 0.85
r = 0.71
MODIS trend= 0.3°C/decade
Station trend = 0.2°C/decade
Temperature (°C)
19
18
17
16
(e)
September- Daytime
ANCOVA: P= 0.47
r= 0.66
MODIS trend= 0.8°C/decade
Station trend = 1.2°C/decade
Temperature (°C)
42
40
38
36
34
32
(f)
September- Nighttime
ANCOVA: P= 0.55
r= 0.71
MODIS trend= 0.4°C/decade
Station trend = 0.3°C/decade
Temperature (°C)
21
20
19
18
(g)
October- Daytime
ANCOVA: P= 0.98
r=0.81
MODIS trend= 0.6°C/decade
Station trend = 0.6°C/decade
Temperature (°C)
43
41
39
37
35
33
31
2002 2004 2006 2008 2010 2012 2014 2016 2018
(h)
October- Nighttime
ANCOVA: P= 0.92
r = 0.84
MODIS trend= 0.4°C/decade
Station trend = 0.4°C/decade
Temperature (°C)
22
21
20
2000 2002 2004 2006 2008 2010 2012 2014 2016 2018

FIGURE 3 Comparison between the temperatures calculated for the entire Cerrado (weather stations data) and land surface temperatures for all pixels of Cerrado recorded by satellites Aqua and Terra (MODIS data) for the same period. (a, c, e, and g) Comparison between mean maximum temperatures for the entire Cerrado (blue dots) and land surface temperature product of MODIS/Aqua satellite between 15 and 18 h UTC (red dots) for the months of July, August, September, and October, respectively. (b, d, f, and h) Comparison between mean minimum temperatures for the entire Cerrado (blue dots) and land surface temperature product of MODIS/Terra satellite between 00 and 03 h UTC (red dots). In all linear models, the time was considered the independent variable (2000–2019 for minimum temperature and MODIS/Terra comparison, and 2002–2019 for minimum temperature and MODIS/Aqua comparison). Solid lines represent the best-fitting line of each model (red lines for satellite data and blue lines for entire Cerrado means) and trend values are showed at each graph (red values for satellite data and blue values for entire Cerrado means). Red and blue bands represent the 95% prediction intervals for satellite and entire Cerrado models, respectively. The Pearson correlation coefficient between both datasets and the ANCOVA results is shown at the top of each graph. UTC, Coordinated Universal Time

warming increases the vapor-pressure deficit, inducing higher release of water vapor into the atmosphere through evapotranspiration (e.g., explaining the absolute humidity trends recorded here in the period between the 1960s and 1990s, when the magnitude native vegetation suppression was still lower). Furthermore, the water vapor added to the other greenhouse gases amplifies regional warming. Therefore, the coupling of the two different radiative forcings and their feedback effects may explain the high warming tendencies in the Brazilian Cerrado.

Second, it was assumed complete savanna vegetation conversion into barren soil (Snyder et al., 2004), grasslands (Hoffmann & Jackson, 2000), and crops (Bounoua et al., 2002), is not the current reality in the Cerrado. Specifically, in the scenario described by Snyder et al. (2004), the removal of the Cerrado could increase the regional albedo, resulting in a reduction of net radiation absorbed and, therefore, attenuating the rise in temperature. However, the albedo increase due to savanna vegetation removal seems to be secondary in regional climate change in the Cerrado. A previous study showed that evapotranspiration reduction is the main factor driving the climatic changes associated with the Cerrado destruction because it potentially consumes almost five times as much energy as the albedo increase reflects under clear sky daytime conditions (Loarie et al., 2011). Field experiments show that, because of a deep root system, even during the dry season, part of the Cerrado vegetation maintains evapotranspiration rates between 1.8 and 2.2 mm day^{-1} (i.e., 216–264 mm of water vapor are potentially added to the atmosphere between July and October; Oliveira et al., 2005). Continuous monitoring exposes the impact of the savanna vegetation removal on local climate. In the first year after a 45 km^2 Cerrado vegetation suppression, Oliveira et al. (2014) reported a decrease of 36% (429 mm) in annual evapotranspiration. Therefore, the Cerrado vegetation conversion is expected to significantly alter the local energy balance, with a reduction in latent heat flux and a consequent augmented sensible heat flux, which leads to a strong increase in air temperature.

Although a reduction in evapotranspiration rates is expected due to the widespread removal of original vegetation in recent decades, Oliveira et al. (2014) found diverging annual tendencies between different portions of the Cerrado. An increasing tendency was observed in the western portion, whereas in the south it tended to decrease, and the east and north presented no tendency (associated with higher errors in evapotranspiration estimates). Yet, the western upward tendency is associated with lower portions of the relief and is possibly a consequence of higher evapotranspiration rates during the wet season, both due to larger and longer water availability. This pattern is consistent with the daytime temperature patterns recorded in this study (Figure 4b), where the western portion has a less pronounced heating than the southern, eastern, and northern sectors of the Brazilian Cerrado. Specifically related to the dry season, our results corroborate those of Spera et al. (2016), who detected pronounced evapotranspiration reduction in croplands when compared with native Cerrado vegetation.

Further evidence reinforces the possibility that the shifts in land use and land cover can be the main radiative force driving climate change in the Brazilian Cerrado. For example, the construction of large hydroelectric dams in the Tocantins and Araguaia river basins over the last decades has significantly altered the extent of water bodies in many localities, affecting radiation and energy balance. This is the case of the Carolina municipality located near the Tocantins River, where the weather station recorded one of the steepest trend values of absolute humidity, probably a consequence of the nearby large water body from a dam constructed in the 2000s (Figure S2; Table S2). Similarly, the expansion of other types of anthropic projects may result in local changes, differing from most of our estimates (e.g., conversion of existing crops into sugarcane crops; Loarie et al., 2011).

Despite contrasting with patterns observed in other regions of South America (Vincent et al., 2005) and of the world (Vose et al., 2005), the most pronounced diurnal warming was consistently detected by the three approaches used in this study except for July and August weather station data. Interestingly, while minimum temperatures rose gradually since the 1960s, the increase in maximum temperatures seems to have been triggered only after the end of the 1970s (pattern more clearly evidenced in September and October; Figure 2c,d). We believe that the gradual rise in minimum temperatures since the 1960s can be an effect of complex synergy between the global increase in greenhouse gases with regional radiative forcings as land use/land cover changes (see the section of the study area) and the progressive increase in wildfires. On the other hand, both the intense daytime warming (started in the 1980s) and the sudden drop in absolute humidity from the 1990s (see next paragraph) are probably related to the massive conversion of Cerrado vegetation into croplands, which remain under a fallow throughout

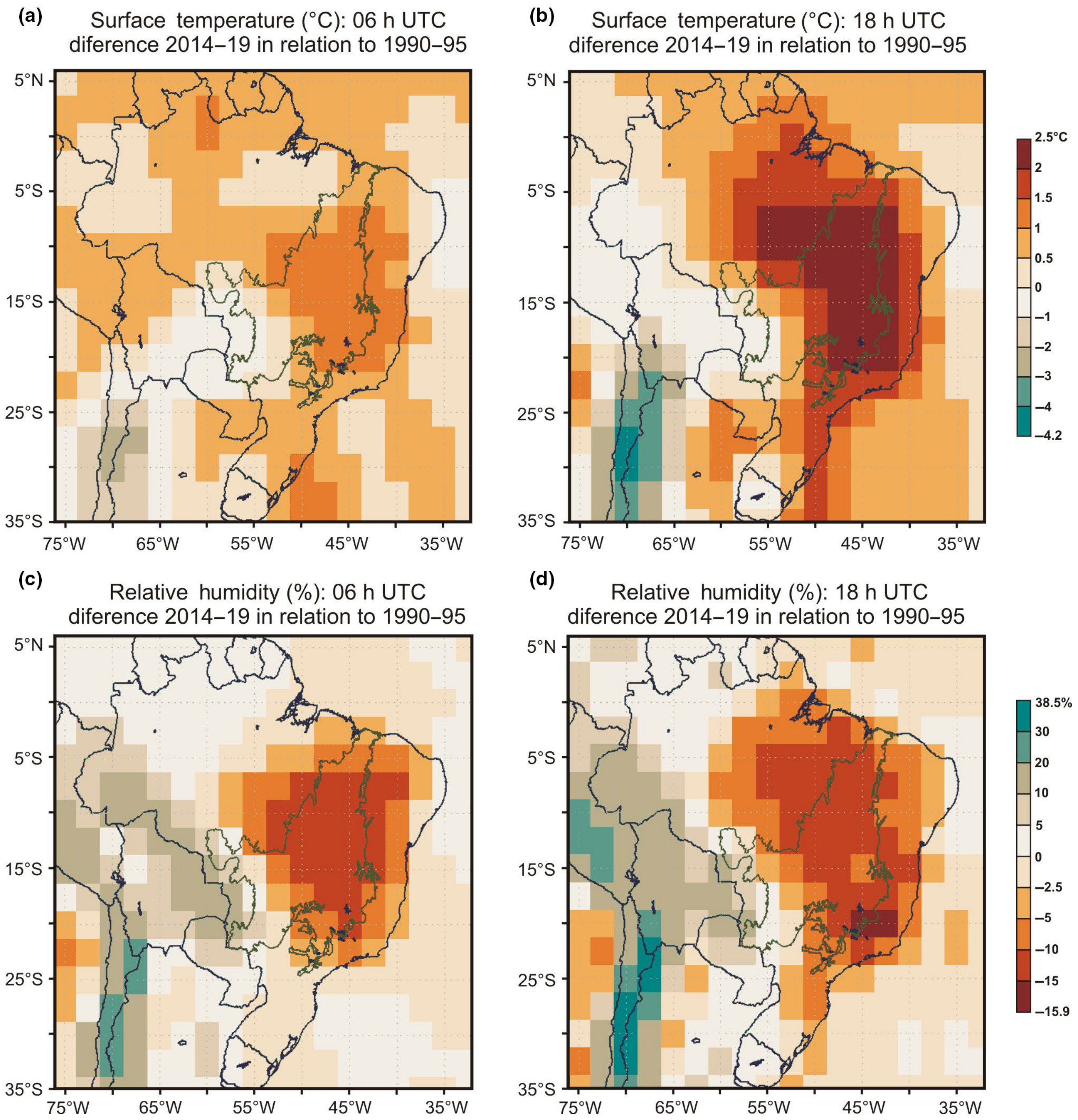

FIGURE 4 Large-scale regional trends for both daytime and nighttime surface temperature and relative humidity in Brazilian Cerrado between 2014–2019 and 1990–1995. (a, b) Difference in mean surface temperature (°C) between 2014–2019 and 1990–1995 at 06 and 18 h UTC. (c, d) Difference in mean relative humidity (%) between 2014–2019 and 1990–1995 at 06 and 18 h UTC. The green solid line represents the official limits of the Brazilian Cerrado. Analyzes generated from the dataset of National Center for Atmospheric Research/Department of Energy Reanalysis II dataset. UTC, Coordinated Universal Time

the dry season. As a consequence, evapotranspiration is widely reduced in extensive areas without green vegetation cover, leading to a sharp increase in diurnal temperatures due to the sensible heat flow enlargement at the expense of the latent heat flux reduction. Furthermore, if the main radioactive forcings behind regional climate change were the increase in the concentration of greenhouse gases or smoke from wildfires, nighttime warming should have been more intense than diurnal and with less variation than of local models (Tables S1 and S2). Yet, we emphasize that the smoke from wildfires probably plays a secondary role in the climate changes observed here (mainly on the local scale and in years with a high number of wildfires).

The daytime and nighttime warming in the Cerrado and the related increase in both absolute humidity and dew point depression can be explained by the Tetens equation (Tetens, 1930), which shows that a linear increase in air temperature raises the vapor pressure deficit exponentially. Although there is an upward tendency of absolute humidity (i.e., water vapor addition in the atmosphere), relative humidity was decreased by a larger proportion, therefore, as a paradox, the air became drier (as shown in the relative humidity trends in Figure 4c,d). In other words, the rising temperature allows the local atmosphere to retain more water vapor than evapotranspiration can supply. Thus, the succession of dry months in the Cerrado progressively reduces the amount of water available for evapotranspiration, which could explain the smaller slope of the absolute humidity trend in the models of September and October compared to July and August (Figure 2i–l). However, the reduction in the rise of absolute humidity for all months analyzed is mainly due to the sudden drop from the 1990s (generating an inverted U-shaped pattern). It is likely that decreases in absolute humidity beginning in the 1990s are associated with native vegetation suppression, which has intensified throughout the Cerrado. However, this humidity reduction may be partly a consequence of the abrupt decrease in global evapotranspiration due to the terrestrial moisture-supply limitation that occurred between 1998 and 2008 and mainly affected the Southern Hemisphere, including a region in the middle of South America that overlaps with the Cerrado (Jung et al., 2010).

Whatever the reason, many weather stations have recently displayed negative trends of absolute humidity, which leads us to project an intensification of regional atmospheric dryness for the next decades. Lastly, our results show that the dew point depression in Brazilian Cerrado nights progressively moves away from vapor pressure saturation. The gradual air warming will cause the night cooling to take longer to reach the dew point temperature and, therefore, will progressively reduce both the amount and duration of dewfall in Brazilian Cerrado nights during the dry season.

4.1 | Implications of rising dew point depression for Cerrado biodiversity

Dew is water vapor condensation on a substrate resulting from radiative deficit between the atmosphere and surfaces (Beysens et al., 2016). Dew formation, normally at night, is favored by windless and clear sky conditions when the temperature of the surface on which condensation occurs reaches the dew point temperature (Agam & Berliner, 2006). Although dewfall represents small amounts of liquid water compared to rainfall, in some regions, it may reach a maximum potential of 0.6 mm (0.6 L/m^2 or 6000 L/ha) per night (Sharan et al., 2017). In dry environments (or in dry seasons as analyzed), dew can be the only liquid water source for sessile organisms and for species with low vagility, thus having a significant ecological importance for biodiversity. Although dew is historically recognized as a fundamental resource for many organisms, its importance as a water source is still undervalued in biology (Tomaszkiewicz et al., 2015).

While dew can potentially form every night in the Cerrado, rain is a rare event during the winter; therefore, several plants and small animals cannot depend on rain as a stable source of water. For instance, epiphytic plants account for 10% of all vascular plant species (Benzing, 1987) and are highly dependent on dew (Schimper, 1888). The number of vascular epiphyte species in the Cerrado is unknown, but it is known that they are abundant in the vegetation of mountains with rupestrian grasslands (*campo rupestre*), where they are pulse supplied. Thus, the reduction in dew availability during the dry season could result in the extinction of the most sensitive species. The climatic changes detected can also cause other impacts to plant species. For example, many plant species usually have their pollen viability reduced due to dehydration when exposed to very low air humidity conditions (Corbet, 1990). As many woody species in the Cerrado flowering during September and October (Batalha & Martins, 2004), the period that we recorded the more pronounced regional climate changes, great uncertainty emerges about the maintenance of the reproductive success of these species in the future. In the Cerrado, the climate patterns also drive the establishment and frequency of mutualistic interactions, such as ant–plant–herbivore interactions through the production and secretion of extrafloral nectar by plants during the beginning of the rainy season (Calixto et al., 2021). Therefore, the impacts of regional climate changes on plant species will probably not be restricted to the organism or population levels (e.g., fitness reduction or local extinction), and their effects may extend to the community level through changes in interspecific interactions. So far, few studies have been able to demonstrate these possible impacts. One exception was a recent work that monitored four Malpighiaceae species in the Brazilian Cerrado for 10 years and showed that variations in temperature and precipitation resulted in shifts in the onsets of flowering and increased the degree of plant phenological overlap, which influenced the herbivory and fruit set of species (Vilela et al., 2017).

Dew is also an important direct water source for insects, such as honeybees, which use dew and raindrops more than other sources (Joachimsmeier et al., 2012). The insects, particularly bees, are the main pollinators of woody and herbaceous Cerrado flora (Oliveira & Gibbs, 2002). Therefore, the reduction in dew represents a serious additional threat to both the pollinator assemblage and the pollination process itself (i.e., another potential impact on a community level). Another example of the potential effect of dew reduction in animals can be seen in the Bolivian savanna, where it is suggested as the main cause of the decline and local species extinctions of rodent populations (Emmons, 2009). In this regard, there are few comparative studies or data available on body water conservation and regulation in South American small mammals (Tirado et al., 2008), particularly regarding the Cerrado fauna, which is one of the most diverse regions in South America (Carmignotto et al., 2012). Seasonal and annual variations in urine concentration and renal expression levels of aquaporins in response to environmental changes associated with El Niño events have been detected in rodents in xeric biomes of South America (Bozinovic et al., 2007; Gallardo et al., 2005), but have not been extensively studied in regions with pronounced climatic seasonality, such as the Cerrado.

To conclude, we emphasize that the effects of temperature and humidity on the properties of the Cerrado ecosystems cannot be neglected and should be further explored from a land use perspective. Due to the massive habitat loss and the resulting deep regional climate changes, ecological studies must begin to assess the synergistic effects of both impacts. We believe that the regional climate changes described in this paper will impact directly or indirectly the biodiversity on different ecological levels (i.e., organism, population, and community), eventually resulting in cascade effects and causing ecosystems to collapse. Therefore, our results reinforce the alert issued by Strassburg et al. (2017) and highlight the need for urgent measures to avoid the collapse of the Cerrado hotspot.

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DATA AVAILABILITY STATEMENT

The authors are committed to providing any information or data related to this study that may be requested in the future.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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