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Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts

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The Pantanal region in South America is one of the world's largest wetlands. Since 2019, the Pantanal has suffered a prolonged drought that has spelled disaster for the region, and subsequent fires have engulfed hundreds of thousands of hectares. The lack of rainfall during the summers of 2019 and 2020 was caused by reduced transport of warm and humid summer air from Amazonia into the Pantanal. Instead, a predominance of warmer and drier air masses from subtropical latitudes contributed to a scarcity of summer rainfall at the peak of the monsoon season. This led to prolonged extreme drought conditions across the region. This drought had severe impacts on the hydrology of the Pantanal. Hydrometric levels fell all along the Paraguay River. In 2020, river levels reached extremely low values, and in some sections of this river, transportation had to be restricted. Very low river levels affected the mobility of people and shipping of soybeans and minerals to the Atlantic Ocean by the *Hidrovia -Paraná-Paraguai* (Paraná-Paraguay Waterway). This study is directed to better understand the hydroclimatic aspects of the current drought in the Brazilian Pantanal and their impacts on natural and human systems. As a consequence of the drought, fires spread and affected natural biodiversity as well as the agribusiness and cattle ranching sectors. While fires had serious socioecological and economic consequences, we do not intend to investigate the effect of the downstream low-level waters on the Pantanal ecosystems or the drought in the risk of fire.

Keywords: Pantanal, drought, river levels, biodiversity, fires

INTRODUCTION

Drought represents one of the most important natural phenomenon that threatens food and water security in many parts of the world. The overall impact of drought on these regions depend on their ability to recover from the resulting social, economic and environmental impacts. As examples, some tropical regions have been affected by drought, as in Southeast Asia (Taufik et al., 2020), tropical Africa (Jiang et al., 2019), Amazonia and Northeast Brazil (Jimenez et al., 2019) and Australia (Freund et al., 2017; King et al., 2020). In this study, we focus on meteorological drought, which is caused by a prolonged rainfall deficit, often enhanced by other meteorological conditions, such as high temperatures, high evapotranspiration rates, and desiccating winds in the Pantanal region, considered as the worse in 50 years. These droughts affected the hydro-climatological functioning in the regions and increased the risk of fire, as well as impacted humans and biodiversity.

The Pantanal region is one of the world's largest wetlands. It is located in a large floodplain in the center of the upper Paraguay River basin in South America (**Figure 1**). It encompasses 179,300 km^2 across Brazil (78%), Bolivia (18%), and Paraguay (4%). In Brazil, the Pantanal is located in the states of Mato Grosso (MT; 35%), and Mato Grosso do Sul (MS; 65%) (Tomas et al., 2020). The Brazilian Pantanal extends over 140,000 km^2 (Pott and Pott, 2004, Alho and Silva, 2012), and it represents a complex of interconnected aquatic, terrestrial, and wetland ecosystems. Its geographical location is of particular relevance since it represents the link between the *Cerrado*, in central Brazil, the Chaco, in Bolivia, and the Amazon region, in the north. The Pantanal works as a large reservoir, causing a lag of up to 5 months between the inflows and outflows. The summer rainfall regime determines the flood season between November and March in the north and between May and August in the south, in this case under the influence of the Pantanal.

Because of its diversity and abundance, the Pantanal's natural resources are essential for local, regional, and global economies (Alho and Silva, 2012; Padovani, 2017). The vegetation of the Pantanal biome is very diverse, mainly due to flooding and varying soil classes. The Pantanal region is considered the center of the greatest diversity of aquatic plants on the planet (Pott and Pott, 2000; Fundación Amigos de la Naturaleza (FAN), 2020). It is home to more than 3,500 species of vascular plants, 300 species of fish, 41 species of amphibians, 177 species of reptiles, around 600 species of birds, and more than 150 species of mammals (Primack and Vidal, 2019).

Changes in rainfall regime and the flood-pulse are likely to disrupt the processes that maintain these landscapes; further, landscape modification may dramatically alter wetlands (Ivory et al., 2019).

Many human activities in the region rely on the ecosystem services provided by the Pantanal, including professional and touristic fishing, and contemplative tourism (Bergier et al., 2018). Cattle ranching in the Pantanal started in the 17th century and is now the principal economic activity (Machado and Costa, 2018). It is conducted by ∼3,000 ranches on the Brazilian side and an unknown number in Bolivia and Paraguay. The total cattle herd in the Brazilian Pantanal has been estimated as 3.8 million heads, producing ∼1 million calves per year (Oliveira et al., 2016). The available land for cattle ranching and farming is dependent on the extent of the flooding during each wet season. These activities threaten the Pantanal's ecological balance (Hamilton, 1999; da Silva and Girard, 2005). Since 2019, the Pantanal is suffering a prolonged drought that has spelled disaster for the region. Subsequent fires have engulfed hundreds of thousands of hectares across the Brazilian Pantanal. Fire is part of the natural dynamics of the Pantanal's or any ecosystem. Fire can renew native pasture, favoring the regrowth of many species. However, the uncontrolled fires occurring in the dry season are of anthropogenic origin. They are directly related to deforestation, cleaning, and reforming pastures. Improper practices and the use of fire as a management practice without control techniques endanger the conservation (Silva et al., 2011; Alho and Silva, 2012; Aragão et al., 2018; Alho et al., 2019).

The drought in the Pantanal and the Upper Paraguay River basin has spread devastation. The dry conditions increased the risk of fires. As a consequence, unprecedented wildfires ripped through the region even in January and February, which is usually the wet season (INPE-www.inpe.br). International media reported the devastating wildfires that burned out of control in late 2019 and 2020 in Brazil's Pantanal wetland, and this generated global concern over the fate of the region's biodiversity. In 1998, INPE initiated fire monitoring in the Pantanal. There have never been as many hot spots between January and August as recorded in 2020. It was 7,727 fires detected, representing an increase of 211% over the same period in 2019. Fires were started by human activity—likely to clear land for agriculture—and are difficult to control due to the inaccessibility of the region and because some fires burn underground. Faced with the surging number of fires in June and July aggravated by the drought, state and federal authorities moved to reinforce bans on burning. Cross-border fires have not been restricted to Brazil, Bolivia, and Paraguay. These spread along the banks of the Parana River in Argentina in the spring. The fire in the Pantanal has not even spared animals that could not escape the flames in time: scenes of alligators, monkeys, jaguars, snakes, and charred tapirs have shocked those who work in the region (https://www.dw.com/pt-br/fogo-j%C3%A1-consumiu-mais-de-10-do-pantanal-em-2020/a-54630524).

The current drought has had severe impacts on the hydrology of the Pantanal. This has serious socioecological and economic consequences. According to the Brazilian Navy (www.marinha.mil.br/chn-6/?q=alturaAnterioresRios), the water level of the Paraguay River at Ladário dropped to 203 cm in June 2020 (mean of 405 cm). June is the month that usually marks the peak of the river throughout the year.

In this paper, we investigate climate and hydrology patterns of the drought affecting the Pantanal in 2019–2020. This study characterizes the climate drivers behind the unprecedented dry conditions over the Pantanal region, in southwestern Brazil, during the last 2 years. We provide a clear description of the interannual variability of rainfall, river streamflow,

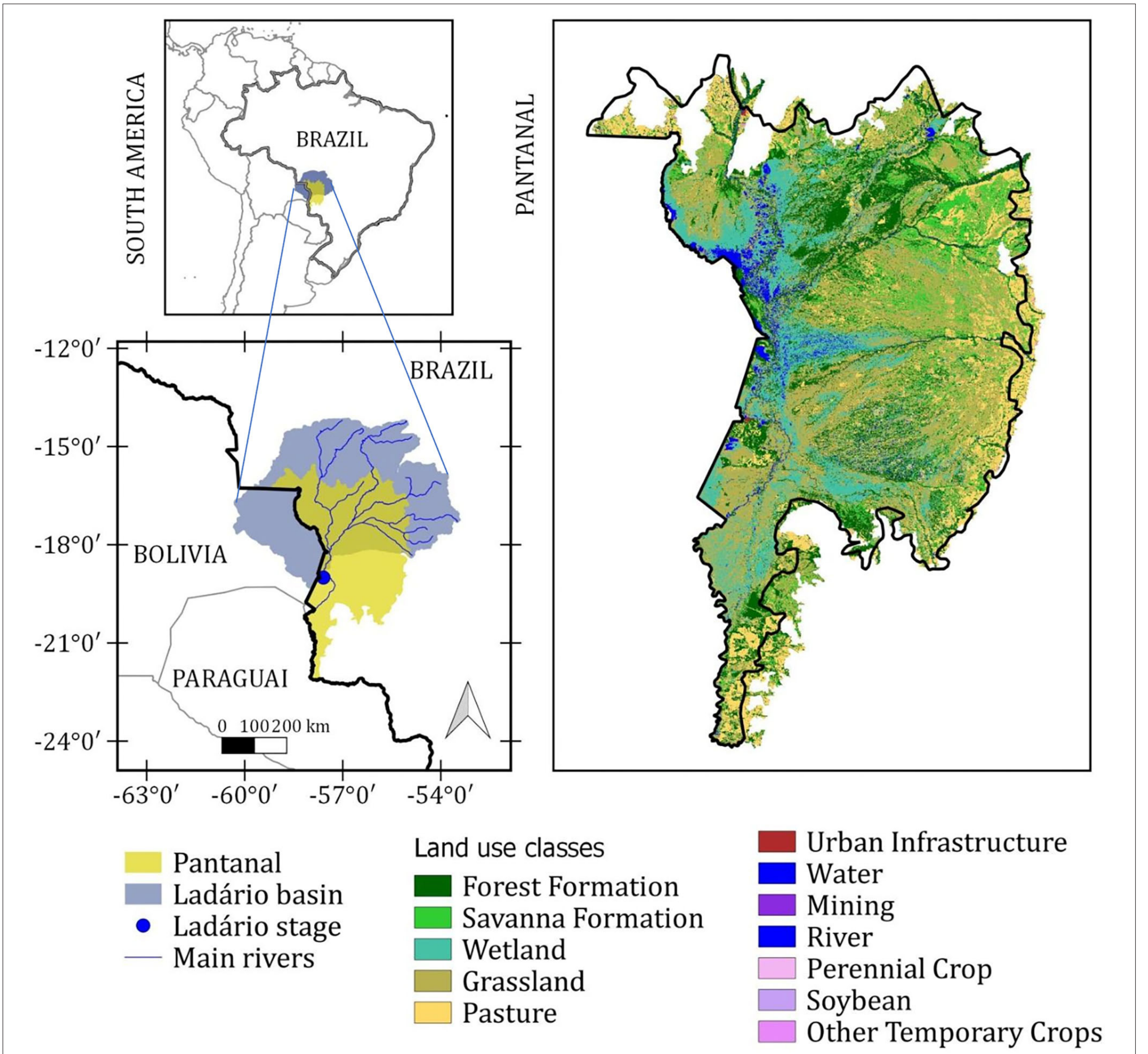

FIGURE 1 | Geographical location of the Brazilian Pantanal. The map on the right shows land use classes, and on the left the map shows the Brazilian Pantanal in yellow, the Upper-Paraguay River basin in gray, and the location of the Ladário gauge station with a blue dot.

and drought-related variables in order to shed light on the exceptionality of the event and also conclude that a complex combination of teleconnections lays behind such drought event. This is done using a combination of climate, hydrology, and land use information. Compared to past drought episodes in the Pantanal, the 2019–20 event shows high vulnerability of population to extreme dry conditions through water stress due to the drought and subsequent increase in the risk of fire.

DATA AND METHODS

The study uses a wide range of data sources, both observational (such as river levels of the Paraguay River at Ladário station), gridded rainfall data, and indices of atmospheric teleconnections to identify changes in circulation during drought events. In addition, indices derived from remote-sensing sources were used to characterize water stress and drought in the Pantanal region.

Blended Vegetation Health Product (VHP)

The Blended Vegetation Health Product (VHP) of the National Oceanic and Atmospheric Administration (NOAA) consists of gridded weekly global vegetation indices. An improved version of the previous VHP data set includes a combination of the indices derived from the Advanced Very High-Resolution Radiometer (AVHRR) from 1989 to 2012 and the Visible Infrared Imaging Radiometer Suite (VIIRS) from 2013 to 2020 (Kogan et al., 2015). It includes the Normalized Difference Vegetation Index (NDVI), brightness temperature (BT), and derived ones, temperature condition index (TCI), vegetation condition index (VCI) and, vegetation health index (VHI).

The combination of satellite visible (VIS) and infrared (IR) images has been widely used to monitor plant changes and water stress. The VHI is based on the Normalized Difference Vegetation Index and Land Surface Temperature (NDVI–LST), which has been related to moisture availability and canopy resistance, indicating vegetation stress or soil water stress. The VHI (Kogan, 1995, 2001; Kogan et al., 2005) is defined as the average of the TCI and VCI, calculated as

$$VHI_i = \alpha VCI_i + (1 - \alpha) TCI_i \tag{1}$$

α and (1-α) are coefficients to determine the contribution of each index, which is usually assigned a value of 0.5, assuming equal contribution of both variables to the VHI. VCI is obtained from the ratio of land surface reflectivity in visible and near-infrared wavelengths, and the NDVI is used to assess the coverage of healthy vegetation, calculated as

$$VCI = 100^* \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{2}$$

where NDVI is the smoothed weekly NDVI, and $NDVI_{max}$ and $NDVI_{min}$ are the multiyear minimum and maximum observed NDVI in the same week. TCI is used to identify vegetation stress caused by high temperature and excessive wetness. It is calculated from thermal emissions measured at infrared wavelengths, according to Equation (3)

$$TCI = 100^* \frac{BT_{\max} - BT}{BT_{\max} - BT_{\min}} \tag{3}$$

where BT is the smoothed brightness temperature for the week and BT_{max} and BT_{min} are the multiyear maximum and minimum brightness temperature observed for that week. Several studies (Quiring and Ganesh, 2010; Pasho et al., 2011; Andujar et al., 2017) have shown that the response timescale to meteorological drought onset is shorter for TCI than for VCI. This is due to the physical and physiological suppression of evaporation and transpiration when less water is available. In addition, the response of remote sensing-based indicators to drought varies depending on the land cover, which is associated with different plant functional types and adaptations needed to endure drought (Andujar et al., 2017).

VHI, VCI, and TCI range from 0 (extreme vegetation stress) to 100 (optimal conditions). Values below 40 indicate stressed vegetation conditions due to water deficit. These indices are obtained from the NOAA STAR Global Vegetation Health Products website (NOAA STAR, 2020), with data since the early 1980s. For drought assessment we use weekly VHI and TCI at 4 km spatial, from 1982 to 2020. As mentioned above, VHI, VCI, and TCI are VHPs derived from remote sensing commonly used for drought assessment. Besides that, the VHI is used to calculate the Integrated Drought Index (IDI, see Section Integrated Drought Index).

Precipitation Data

While previous studies have investigated rainfall variability (Ivory et al., 2019), we find a lack of extensive and reliable precipitation datasets from *in situ* stations in Pantanal. This makes global datasets such as Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and the Global Precipitation Climate Center GPCC (GPCC) the best alternatives available to estimate spatially distributed long-term precipitation trends.

CHIRPS is a rainfall product available at daily to annual time scales with a spatial resolution of 0.05° × 0.05°, starting from 1981 onwards. The dataset includes satellite imagery and rain gauge data to create gridded rainfall time series. The new dataset of CHIRPS version 2.0 has stations worldwide, including more than 11,000 just in Brazil. This new dataset is available on https://data.chc.ucsb.edu/products/CHIRPS-2.0/. The CHIRPS-2.0 dataset has been validated worldwide, including for some Brazilian regions (Baez-Villanueva et al., 2017; Beck et al., 2017; Paredes-Trejo et al., 2017; Anderson et al., 2018; Cavalcante et al., 2020; Paca et al., 2020). Furthermore, it has been used for trend analysis and seasonal drought monitoring (Funk et al., 2015). Beck et al. (2017) evaluate precipitation accuracy and find that CHIRPS-2.0 tends to perform better than other precipitation datasets in central Brazil.

Monthly precipitation from the GPCC Monitoring Product version 7 with 1.0° × 1.0° grid is used to calculate the SPI (Schneider et al., 2017). The GPCC-7.0 global gridded precipitation dataset is developed by combining the precipitation data obtained through the global telecommunication system (GTS), synoptic weather reports (SYNOP), and monthly climate reports (CLIMAT) received via GTS and based on quality-controlled data from 67,200 stations worldwide (Schneider et al., 2017). This dataset is available at https://psl.noaa.gov/data/gridded/data.gpcc.html. Although the GPCC and CHIRPS precipitation products have different spatial resolutions, these differences did not impact the area average precipitation over the Pantanal; both products produced similar seasonal area average ($r^2 = 0.80$).

Standardized Precipitation Index

The Standardized Precipitation Index (SPI) is a drought index proposed by McKee et al. (1993). It is used to quantify the probability of occurrence of precipitation deficit at a specific monthly time scale. In order to calculate the SPI, precipitation data are fitted to a gamma probability distribution function. The inverse normal distribution function is used to rescale the probability values, resulting in SPI values with a mean of zero and a standard deviation of one. More information about the SPI applications for drought studies in Brazil is given by Cunha et al. (2019a,b). Monthly precipitation from CHIRPS (1981–2020) and GPCC (1900–2020) was used to calculate the SPI time series.

SPI is widely used to characterize drought in terms of its duration, intensity, and severity. In general, a drought event starts in the month in which the SPI falls below −1 (and remains negative for at least three consecutive months). It ends when the SPI returns to positive values for at least two consecutive months. Severity is defined as the absolute value of the integral area between the SPI line and the horizontal axis (SPI = 0), from the start to the end month of the drought intensity is the lowest SPI value of the drought event.

In the present study, SPI is used to characterize drought events, and for the calculation of the Integrated Drought Index (IDI, see Section Integrated Drought Index).

Integrated Drought Index

The Integrated Drought Index (IDI) consists of a combination of the SPI with the VHI. The SPI is recommended for drought monitoring due to its simplicity and multiscale characteristic in quantifying abnormal wetness and dryness. On the other hand, the VHI can capture spatial details and is suitable for the monitoring and detection of droughts (Cunha et al., 2019a,b). Since precipitation is the primary cause for drought development, negative SPI anomalies do not always correspond to drought in reality, as it takes no account of impact. Therefore, VHI presents a general picture and perceptions of drought, and we select SPI and VHI to represent the precipitation deficit (drought trigger) and the surface response to soil water deficit. These two indices provide complementary information for identifying areas affected by drought.

Since the IDI is used to assess areas with drought conditions in the Pantanal, it is necessary to consider precipitation data with high spatial resolution; so, the precipitation data from CHIRPS was used to calculate the SPI and, later, the IDI. Quarterly IDI was calculated from December 2018 and with a final spatial resolution of 5 km.

River Data

The stage of the Paraguay River at the Ladário gauge site (19.00°S, 57.60°E) is provided by the Brazilian Navy, and by the National Agency for Water and Sanitation-ANA (www.snirh.gov.br/hidrotelemetria/ and www.snirh.gov.br/hidroweb/). Measurements used in this study are available from January 1900 to December 2020, and absolute maximum and minimum levels of the Paraguay levels at the Ladário gauge station are shown in **Supplementary Material**.

Statistical Analysis

In addition to the SPI, to classify drought years in terms of severity, the precipitation z-score (Z_{ij}) was also calculated as follow (Wu et al., 2001):

$$Z_{ij} = \frac{(X_{ij} - \overline{X})}{\sigma_i} \quad (4)$$

Where Z_{ij} is the z-score for X_{ij} (precipitation) for month j for length i, and σ_i and $\overline{X}$ are the standard deviation of variable and mean in each time scale, respectively. The z-score was then considered based on the significance level from 95% (p-value < 0.05).

For the precipitation z-score calculation, the annual mean and standard deviation of 121 years of the GPCC dataset (1900–2020) and 39 years (1981–2020) from the CHIRPS dataset were used. We also calculated the z-score for river levels at Ladário station, considering 121 years (1900–2020).

In order to identify areas affected by drought, the VHI z-score was calculated pixel by pixel using Equation (4) and the VHI time series from 1982 to 2020. The annual VHI z-score maps were then filtered, considering only pixels with a significance level of 95% ($p < 0.05$). Then, these pixels were used to estimate the annual affected areas by drought.

As a complementary assessment, the precipitation, temperature, fires, and TCI time series over the Pantanal were analyzed for trends detection. For this, a python package for non-parametric Mann-Kendall statistics (Mann, 1945; Kendall, 1975; Hussain and Mahmud, 2019) was used. The Kendall tau correlation coefficient is based on the number of concordances and discordances in paired observations. In the present study, the trend analysis was considered with a significance level of 95% (a = 0.05).

Atmospheric Circulation Fields

We explore upper and low-level circulation changes that lead to anomalous dry conditions during the summers of 2019 and 2020. We also investigate the 200, 500 hPa height anomalies as well as 850 hPa wind. We focus on December-February (austral summer) of 2019 and 2020. Climatologically, these are the wettest months from the mean summer rainy season. During the summer of 2019 and 2020 it rained almost 50–60% of normal (**Figure 2**). We calculate vertically integrated moisture transport between 1,000 and 300 hPa following Rao et al. (1996). Our calculations run from December 2018 to February 2019 and from December 2019 to January 2020, representing the rainy season in the region. All atmospheric fields come from the NCEP/NCAR reanalysis, and anomalies are calculated relative to the 1948–2010 long-term mean.

Various teleconnection indices are considered to analyze the Pantanal drought situation in the context of the large-scale circulation of the Pacific and Atlantic Oceans. The Atlantic Multidecadal Oscillation (AMO); Tropical North Atlantic Sea Surface temperatures SST (TNA); Pacific Decadal Oscillation (PDO) and the Ocean El Nino Index (ONI). The AMO climate index is associated with shifts in hurricane activity, rainfall patterns and intensity, and changes in fish populations (Enfield et al., 2001). The ONI is one measure of the El Niño-Southern Oscilltion (Huang et al., 2017). The PDO is defined by the leading pattern of the Empirical Orthogonal Function (EOF of SST anomalies in the North Pacific basin, typically, poleward of 20°N (Mantua et al., 1997). The TNA index is defined as the anomaly of the average of the monthly SST from 5.5 to 23.5N and 15 to 57.5W (Enfield et al., 1999). These data sets are available from 1950 onwards from the NOAA web site psl.noaa.gov/siteindex.html and are correlated with summertime (January-February) and annual rainfall over the Pantanal derived from GPCC. The AMO

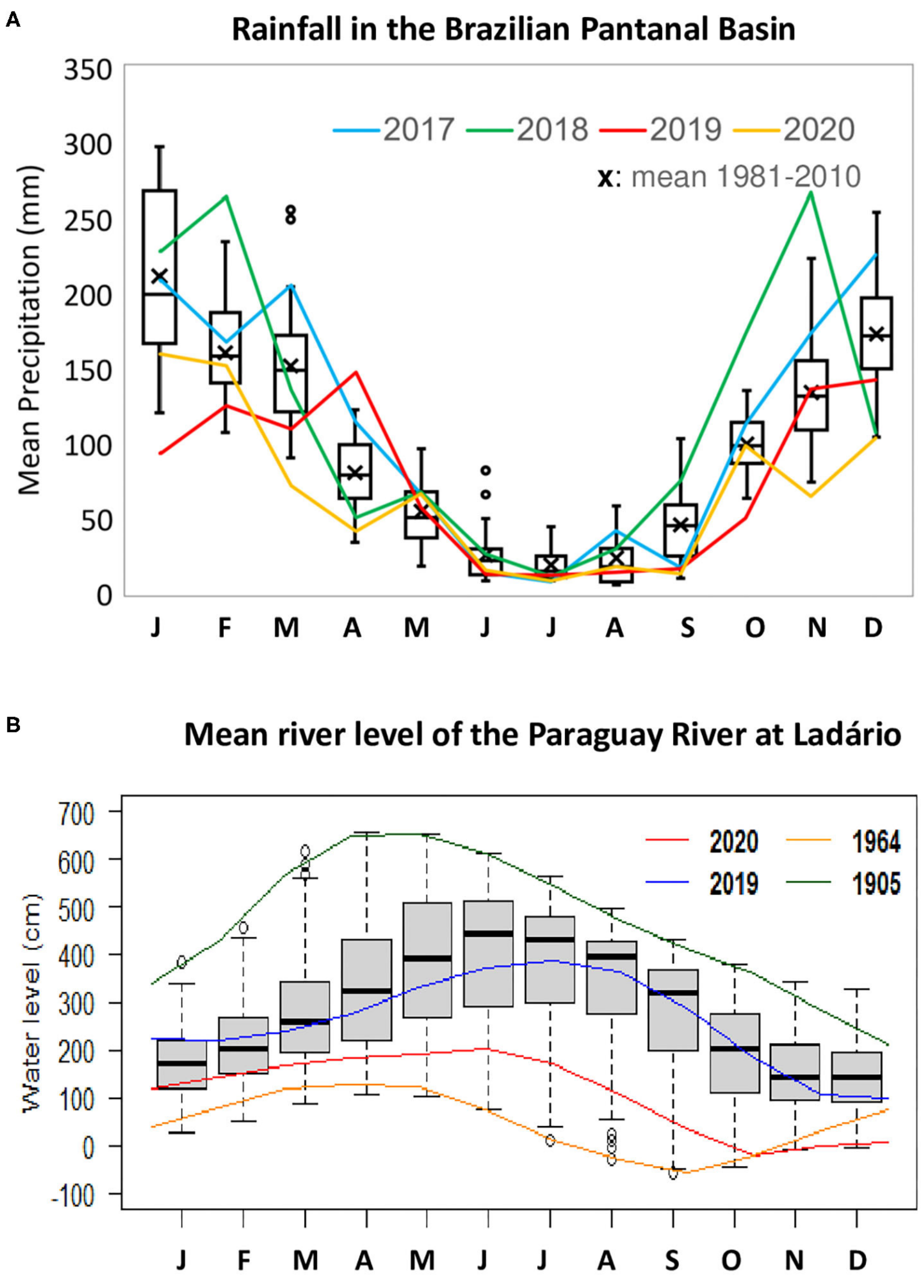

FIGURE 2 | (A) Annual variation of rainfall in the Brazilian Pantanal. Mean is indicated by "x" with the whiskers showing the standard deviation. Long-term mean is from 1981 to 210. The figure also shows rainfall for 2017, 2018, 2019, and 2020. Data is from CHIRPS. **(B)** Annual variation of levels of the Paraguay River at the Ladário gauge station. The figure also shows river levels for 1905, 1964, 2019, and 2020. Source of data: Brazilian Navy.

has a 50–80-year cycle, the PDO has a 15–30-year cycle, and the ONI has a 2–7-year cycle.

Vegetation Data: MapBiomas

The MapBiomas is a multi-institutional project involving universities, NGOs, and technology companies that promotes the annual mapping of land cover and land use in Brazil over the last three decades and provides data and maps in open access (www.mapbiomas.org and Marques et al., 2017). According to the MAPBIOMAS Program data (https://mapbiomas-br-site.s3.amazonaws.com/Infograficos/Colecao5/MBI-Infograficos-pantanal-5.0-BR.jpg), the natural vegetation cover of the Pantanal lowlands fell from 92.65% in 1985 to 84.32% in 2019, with conversion values of natural areas for anthropic use in annual rate with an average of 0.33%. Souza et al. (2020) verify that the expansion of agriculture and cattle ranching was higher between 1985 and 2005, at an annual rate of 5.1%. After that, it fell to an annual rate of 1.2%. According to Coutinho et al.

(2016), agriculture increased by 39% from 2001 to 2013, and sugar cane production expanded by 48% in the same period (**Figure 4F**). Mourão et al. (2010) show that between 1991 and 2004, a sequence of dry years in Pantanal favored the expansion of cattle ranches. The dynamics of livestock moving during dry episodes in 2010 and 2014 was explained by Araujo et al. (2018a), who observed an increase in cattle traffic in periods of drought and pre-flooding.

REVIEW OF CLIMATE AND HYDROLOGY VARIABILITY OF THE UPPER PARAGUAY RIVER BASIN

The Pantanal biome is located in the Upper Paraguay River Basin. The annual average precipitation is 1,400 mm, varying between 800 and 1,600 mm. In some years, it can reach 2,000 mm (Marcuzzo et al., 2011; Marengo et al., 2016). Rainfall is highly seasonal, occurring between December and February with a dry season between June and August (**Figure 2**). In the dry period, monthly precipitation ranges from 0 to 100 mm, with lower year-to-year variability than in the rainy period. Variations occur between the northern and the southern regions in the basin. Between November and March, heavy rains flood the vast majority of this area. The rivers overflow their banks and flood the adjacent lowlands. This inundates as much as 70% of the floodplain by July, forming shallow lakes and innumerable swamps and marshes and leaving island-like areas of higher ground.

Flooding throughout the Pantanal is seasonal. Large sectors of the Pantanal floodplain are submerged from 4 to 8 months each year by mean water depths ranging from a few centimeters to more than 200 cm. This wide fluctuation is independent of the levels established by the Brazilian Navy for navigation along the Paraguay River (Section Review of Climate and Hydrology Variability of the Upper Paraguay River Basin). During the drier winter season (April–September), the rivers withdraw to their banks, but the lowlands are only partially drained (Marengo et al., 2016; Araujo et al., 2018b).

A growing body of literature investigates interannual and multidecadal variations of various surface hydrologic processes. These include precipitation, streamflow, surface-water storage, and flooding in wetlands. In the Pantanal, as well as in Amazonia, rainfall shows interannual variations. This causes either severe floods or pronounced dry seasons that influence the flooding. Hydrological records show that there appears to be no relation between the Paraguay River at Ladário flood peaks and El Niño/La Niña events (Marengo et al., 2016). The occurrence of quasi-periodic heavy rainfall events associated with the South Atlantic Convergence Zone (SACZ), driven by the southern Atlantic and the Madden–Julian Oscillation, were identified by Carvalho et al. (2004, 2011) and de Oliveira Vieira et al. (2013).

Previous studies have detected rainfall trends in the Pantanal. Marcuzzo et al. (2020) and Cardoso and Marcuzzo (2010) analyze the monthly precipitation trends from 1977 to 2006 using data from 12 rain gauge stations in the Brazilian Pantanal. They note a small decrease in precipitation with a pronounced interannual variability. These rainfall variations change in the inter and intra-annual flooding dynamics, drastically affecting the functioning of the Pantanal ecosystem. This affects wildlife diversity and distribution, as well as the sustainability of the ongoing human activity. Bergier et al. (2018) use seasonal rainfall time series from 1926 to 2016 for the Pantanal and find a positive trend in the mean rate of rainy days for all seasons. Lázaro et al. (2020) identify a well-defined water pulse in the northern Pantanal. Over a 42-year historical series, the number of days without precipitation has greatly increased, as well the loss of water mass in the landscape over the last 10 years, specifically during the dry season. Overall, nowadays, the northern Pantanal has 13% more days without rain than in the 1960s (Lázaro et al., 2020).

The river levels at Ladário represent the hydrological regime of the Upper Paraguay River Basin. This enables the characterization of a given period of drought or flood in the Pantanal. The annual mean level at Ladário is 273 cm (1900–2020), ranging from 145 cm in November to 405 cm in June. According to the Brazilian Navy, the level for flood alert is ≥400 cm. The minimum level of 150 cm or below is considered as a limit for navigational alert. This value is based on the danger for navigation and does not represent any minimum ecological value. Considering mean annual levels, **Figure 3A** shows that the region has passed through eight flooding periods in the last decade, with maximum levels of the Paraguay River above 400 cm in Ladário, and eight dry periods with minimum levels below 150 cm.

In terms of daily absolute maximum, the five events with levels above 600 cm were registered in April 1988 (664 cm), May 1905 (662 cm), April 1995 (656 cm), April 1982 (652 cm) and April 1913 (639 cm). The years of 2011, 2014, and 2018 were alarming, with decrees of a state of emergency in Corumbá (the municipality where the Ladário station is located) due to floods. The maximum level in 2011 (562 cm) flooded 23% of the region, and the second flood in 2018 (535 cm) produced losses of the order of R $ 230 million to livestock industry. In April 1988 the river level rose to 664 cm, flooding small communities along the river's shores. The year 1970–1971 recorded the largest number of days with levels equal to or below 100 cm during the observation period.

On the dry side, the 5 years with the lowest minimum levels were detected in September 1964 (−61 cm), September 1971 (−57 cm), October 1967 (−53 cm), September 1969 (−53 cm), and October 1910 (−48 cm). Negative values indicate observations below the zero level of the height stage. The lowest values were detected from 1962 to 1973; all 12 years had levels of 100 cm and below. The most recent minimum level value was −32 cm in October 2020. This is the lowest level in 49 years (**Figure 3A**), with the previous lowest minimum in 1971.

The Ladário river levels reveal multidecadal variability, with breaks in 1936 (from high flows to low flows), 1961 (high/low), 1974 (low/high) and 1999 (high/low) (Santos and Lima, 2016). Araujo et al. (2018b) show that from 1980 onward the multidecadal variability were lower, with a negative trend in the average river levels (−3 cm/year) in the last three decades. Santos and Lima (2016) suggest that the Paraguay River basin in its upper reach, monitored by the Caceres gauging station and Cuiabá river basin, induce low-frequency oscillations in the

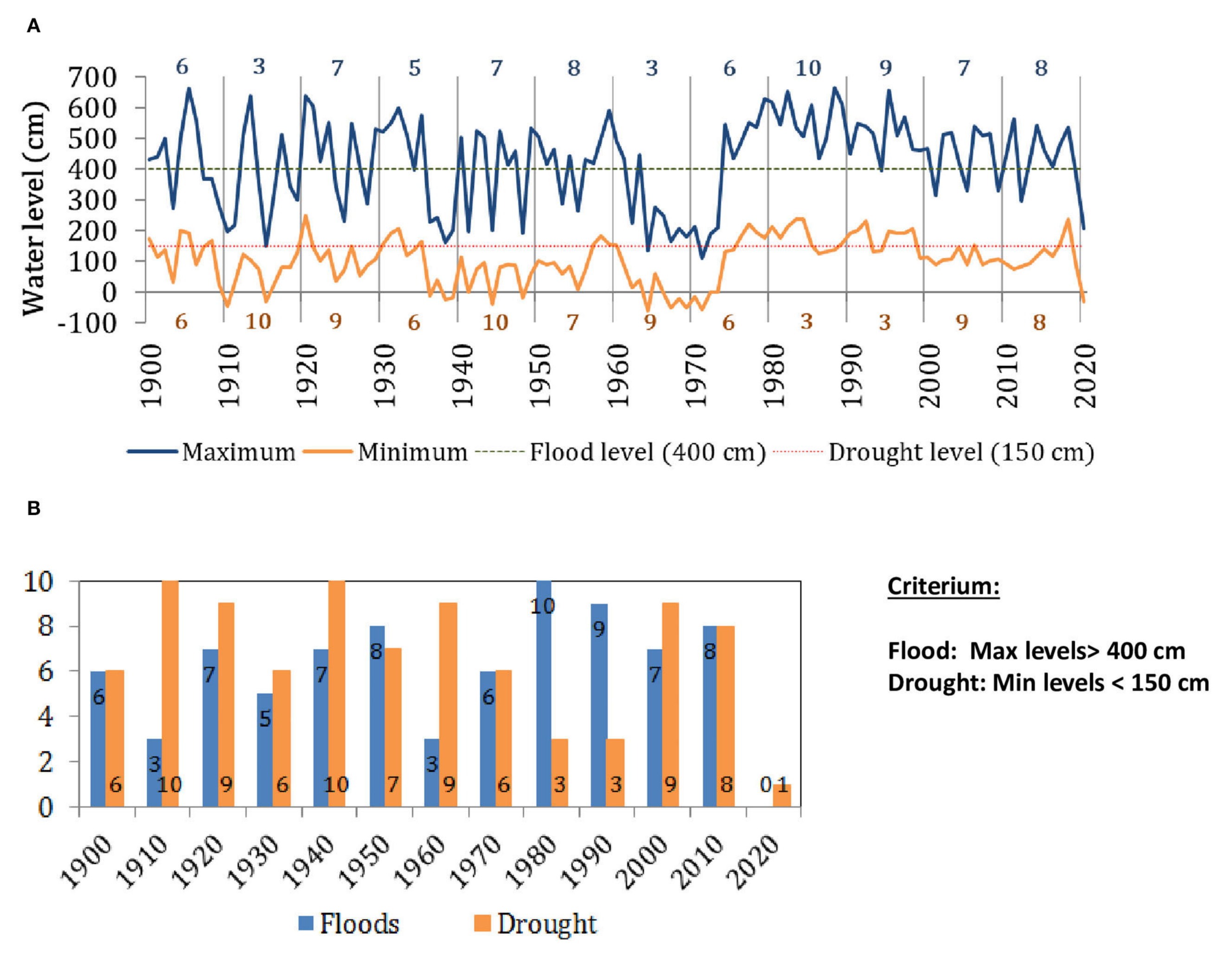

FIGURE 3 | Maximum and minimum levels of the Paraguay River at Ladário, from 1900 to 2020. Numbers indicate the number of droughts and flood episodes at the decadal level. Floods are defined according to the Brazilian Navy when maximum levels are equal or higher than 400 cm, and drought episodes are defined when minimum river levels are equal to or below 150 cm. **(A)** Frequency of floods and droughts for Ladario stage. **(B)** Decadal frequency of floods and droughts from Paraguay River levels at Ladario.

Ladário maxima time series. In both basins, the rainfall records showed a structural break in 1973. These authors show that low-frequency variability is also observed in both rainfall series and may be the main cause of the long-memory persistence and structural breaks in the Ladário gauge station.

LONG TERM VARIABILITY OF HYDROMETEOROLOGICAL PATTERNS IN THE PANTANAL AND ATMOSPHERIC TELECONNECTIONS

The hydrological cycle in the Northern Pantanal is highly related to precipitation. More extended periods without rain tend to decrease the river depth. This consequently affects the floodplain as a total (Lázaro et al., 2020). **Figure 4C** shows the mean water levels of the Paraguay River at Ladário and annual rainfall at this river basin. Variability of the mean levels is similar to that of the maximum and minimum levels from **Figure 3**. It shows the lowest levels in 1910, 1915, 1938, 1967–72, and 2018–2020, with a jump to upper levels from 1974 to 96. This is consistent with rainfall variability, particularly in 2019 to 2020, as shown by various rainfall data sets (**Figure 4C**) and SPI-12 (**Figure 4D**). Rainfall data from GPCC and CHIRPS show reductions consistent with lower river levels at the Ladário stage during 2019–20 and in previous events as 1910, 1936, and 1962–73. In this later, the rainfall reduction was less intense than in reduction in water levels. These reductions in 1962–73 and the jump in the river series after 1974 can be better explained by the SPI-12 (**Figure 4D**), with a period with negative SPI values during the anomalously low levels observed during that decade.

Over the periods between 1962–1965 and 1967–1972, the drought duration was 36 and 62 months, and severity, −43.96 and −53.68, respectively.

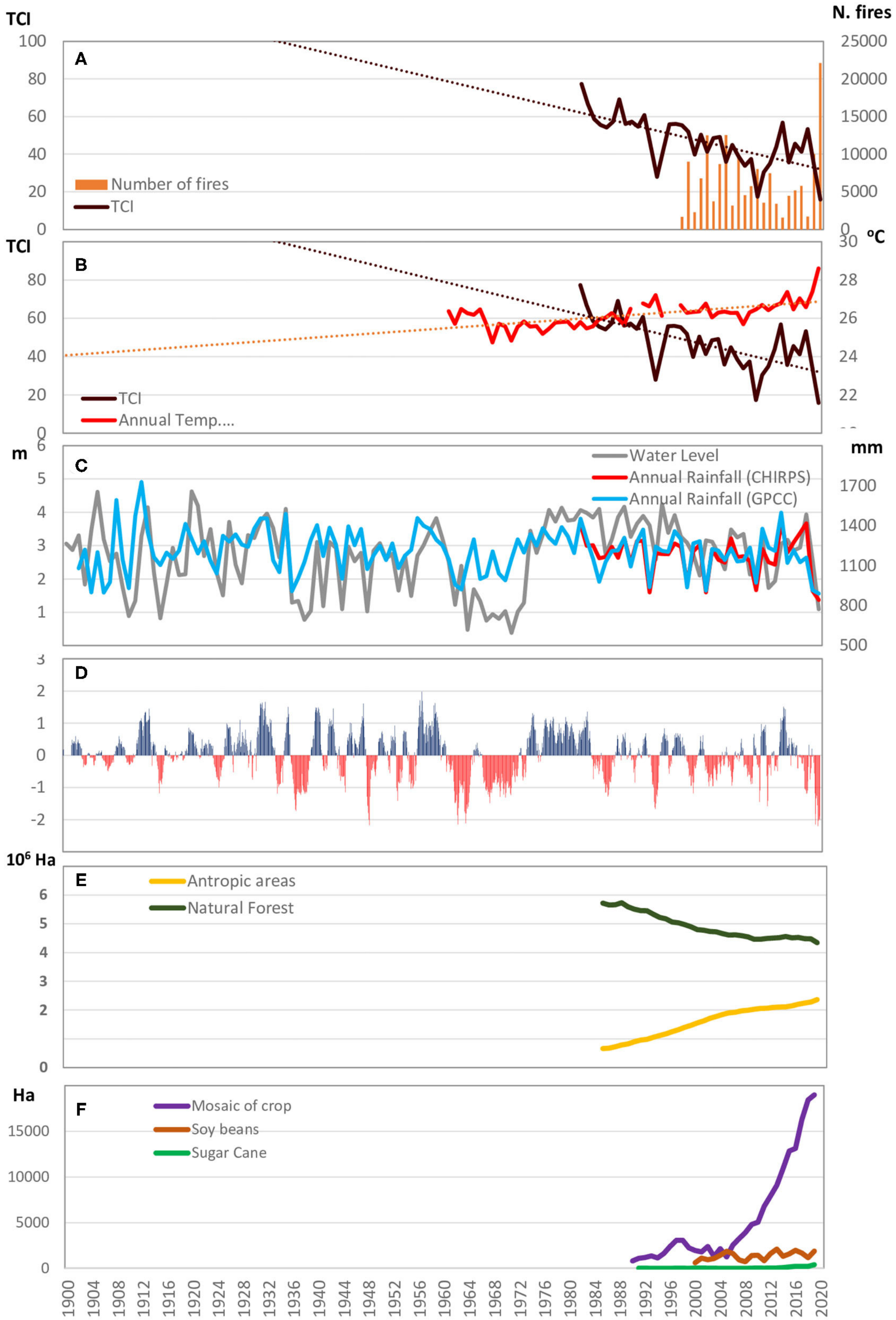

FIGURE 4 | Climate, hydrology, vegetation and land use trends in the Brazilian Pantanal from 1900 to 2020: **(A)** Number of fire episodes (INPE) and TCI; **(B)** TCI and air temperature (at Cuiabá station); **(C)** mean river levels at Ladário, mean annual rainfall from GPCC and CHIRPS, **(D)** SPI-12; **(E)** anthropic and natural vegetation areas; **(F)** area with mosaic of crops, soybean and sugar cane (Sources of data: INPE. Brazilian Navy, INMET, CEMADEN, MAPBIOMAS).

The last drought event that started in 2018 and is still going on in December 2020 already lasted 34 months and registered a severity of −36.37. Considering only the summer period, the summers of 1964 and 2020 registered drought severity of −7.45 and −5.96, respectively. Regarding the 1962–1972 period, the most negative SPI value (drought intensity) occurred in November 1962 (−2.15), and for the 2018–2020 drought, the most negative SPI was in April 2020 (−2.19), being this the driest month since 1,900 (**Figure 4D**).

Records from the Paraguay River at the Porto Murtinho gauge station, located in the section downstream of the Ladário station, within Brazilian territory, show the largest flood ever recorded in this section was in June 1982 when the level reached 952 cm, with the emergency level being 700 cm (CPRM, 2020). In that year, according to data from the National Civil Defense, the damage was recorded in the municipalities of Ladário, Porto Murtinho and Corumbá in Mato Grosso do Sul and in 16 other municipalities in Mato Grosso, including Cuiabá, Várzea Grande, Rondonópolis and Cáceres. It is also worth mentioning the historical importance of the 1974 flood. After a prolonged period of low water levels throughout the 1960s and early 1970s, herds were moved to lower areas of the basins (Marengo et al., 2016). When the flood occurred in 1974, rural properties and herds were submerged, causing great social, economic, and environmental damage. Araujo et al. (2018b) mention that as a consequence of the floods, between 1973 and 1975, the price of meat increased in the domestic market.

Figure 5 shows the climatic indices PDO, AMO, ONI, TNA, annual and summer (January-February) rainfall anomalies over the Pantanal, as well as the SPI-12 and level anomalies at Ladário for 1950–2020. The drought events from 1950 to 2020, defined by the SPI (SPI < −1), are indicated by the red vertical bars. In general, the correlation between rainfall and river with the SST based indices TNA, AMO, PDO, and ONI is very low.

There is no consistency between drought years and El Niño. In fact, while some droughts occurred during El Niño years, there were other events during La Niña. Studies by Allasia Piccilli (2007), Bergier (2010), Marengo et al. (2016), and Thielen et al. (2020) discuss large-scale climate phenomena such as ENSO (El Niño or La Niña), and they did not find a strong ENSO signal in rainfall and river levels in the Pantanal. At interannual time scales, the regional-scale water balance, soil wetness, and soil moisture storage seem to influence the seasonality of floods and droughts in the Pantanal. The best agreement is with the TNA index that shows warming since the middle 1990s. Some drought episodes occurred when the tropical North Atlantic was warmer than normal. This situation induced an anomalously northward position of the Atlantic ITCZ, producing less rainfall in southern Amazonia and the Pantanal during summer, such as in 2005 and 2010. This was better observed during the last two decades. 2016 had a combination between warm TNA and warm ONI.

Aragão et al. (2018) discuss the role of the AMO in decadal rainfall, air temperature, and evapotranspiration in the Amazon. This was better noted during the droughts of 2005, 2010, and 2016. However, not much is known about decadal variability in the Pantanal. Our analysis of rainfall and river data in the Pantanal (**Figures 5E–H**) and SST anomalies in the Atlantic shows that the droughts of 2019 and 2020 occurred in association with the anomalous warming of the Atlantic Ocean captured by the AMO and TNA indices (**Figures 5B,D**). Similar situations were detected during previous droughts in 1993–95 and 1962–73. In the latter, drought occurred with a simultaneous development of anomalous warming of the equatorial and eastern tropical north Pacific, identified by the positive ONI, PDO (**Figures 5A,C**) and cooling in the TNA and AMO.

The TNA and AMO consistently matched the intensification of negative rainfall anomalies in 1986–87. Negative rainfall and river level anomalies in the Pantanal were consistent with negative PDO and ONI indices. This rainfall shortage caused the largest basin-wide mean water deficit (**Figures 5E–H**) observed since 2019 created a widespread drying condition that escalated active and occurrence over the Brazilian Pantanal.

Our results demonstrate that drought in 2019–2020 occurred during a positive AMO phase. Interestingly, the correlations are low between rainfall and river levels in the Pantanal and the anomalous warming of the equatorial and eastern tropical north Pacific and tropical north Atlantic oceans, measured by the PDO, ONI, AMO and TNA. The 2019–2020 drought emerged from a more complex combination of positive anomalies in the three main oceanic modes analyzed here. However, other drought episodes in the Pantanal did not follow this pattern, occurring in years when the AMO and PDO were in the negative phase, such as during the drought of 1961–73, or in 2000 when the PDO and ONI were in the negative phase and the AMO was in a positive phase. Therefore, previous droughts in the region have been triggered by warm surface temperatures in the tropical North Atlantic and North Pacific oceans that created favorable conditions over the Pantanal and some nearby regions, inhibiting rainfall and increased risk of fire. The years 2019 and 2020 saw the worst drought recorded in the Pantanal in 50 years, as shown by the lowest SPI-12 (**Figure 4**). The wet season saw between 50 and 60% less rain than normal, induced by unusually warm waters in the tropical North Atlantic (**Figure 5**).

CLIMATE AND HYDROLOGY IN 2019–2020

Atmospheric Circulation During the Summers of 2019 and 2020

Figures 6A–G shows significant changes in upper, middle and lower-level circulation and moisture transport in South America during both the summer of 2019 and 2020. In addition, the monthly rainfall from October 2018 to December 2020 is compared to the long-term climatology for the Pantanal region. The figure shows the rainfall below normal during the summers of those 2 years, particularly during January 2019 and 2020 (**Figure 6A**). In January 2019, it rained 90 mm, compared with the average January of 210 mm, and rainfall below normal persisted until March 2019. The atmospheric circulation fields (**Figures 6B,C**) for December 2018–February 2019 show a blocking system in the Pacific Ocean. In addition, over subtropical latitudes an anticyclonic anomaly prevailed in the middle levels. This inhibited the typical convection of this time of the year. This fact, adding to the displacement of the

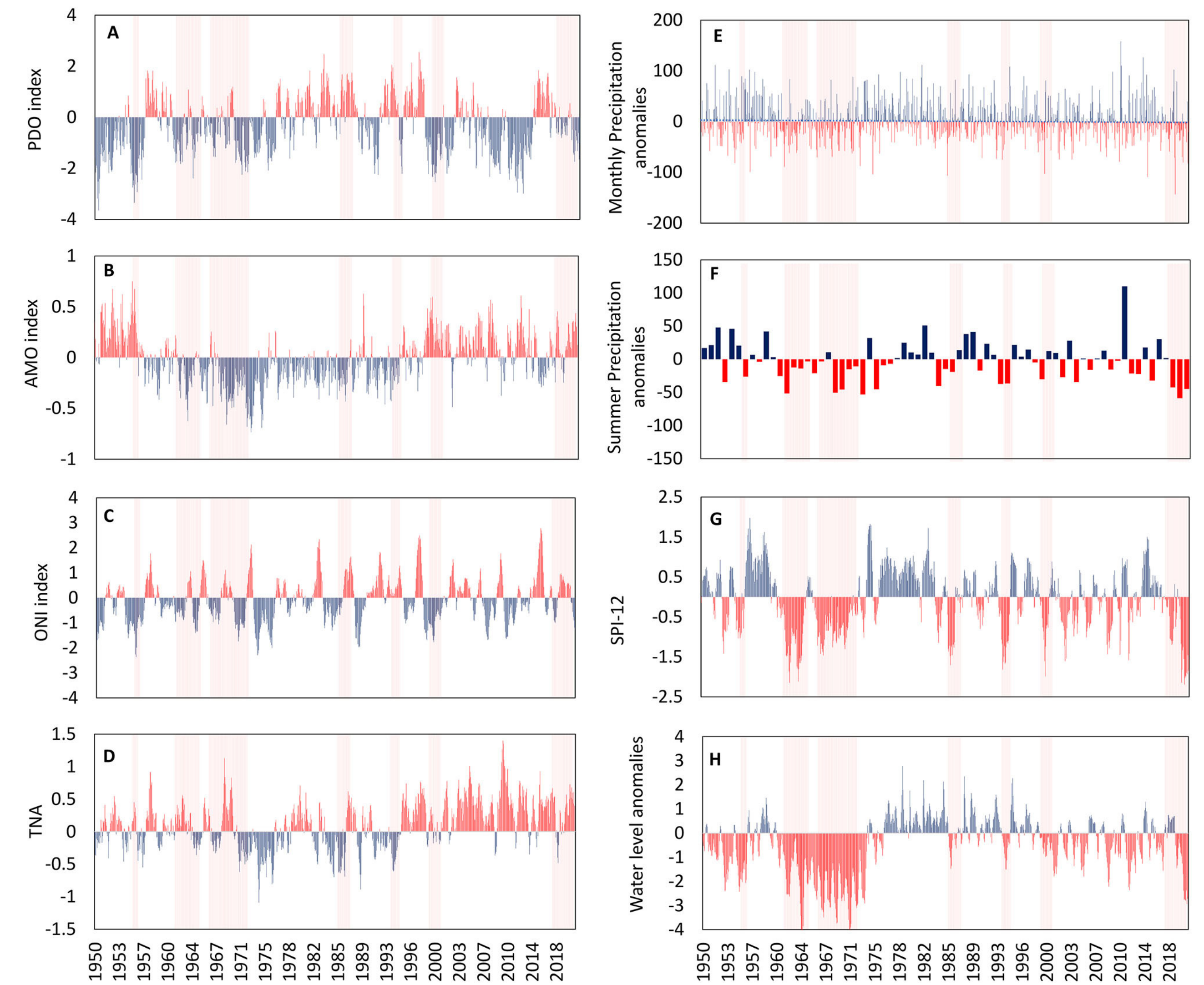

FIGURE 5 | Monthly variability of teleconnection indices at monthly level from 1960 to 2020 (September): **(A)** PDO, **(B)** AMO, **(C)** ONI, **(D)** TNA, **(E)** monthly precipitation anomalies, **(F)** summer (December-March) precipitation anomalies, **(G)** SPI-12, **(H)** water level anomalies at Ladário. Red bars represent years with drought as defined by SPI-12 < −1.00. Base period is 1981–2010 (Sources of data: NOAA, Brazilian Navy, CEMADEN).

baroclinicity further south from its average position (observing the anticyclonic anomalies over 30°S at high levels), and the strong anomalously anticyclonic circulation over the continent at low level explains the scarce precipitation observed. In particular, the greatest rainfall in that month occurred in the southern portion of the La Plata basin, that is, in the region of convergence of the surface flow. On the contrary, the region at the entrance to the northern flow, where divergence occurs, took place near the Pantanal.

Some resemblances can be verified when comparing the condition in the December 2019–February 2020 period and those in January 2019 (**Figures 6E,F**). The 500 and 200 hPa fields show anticyclonic anomalies over practically the entire continent. Although, in this case, there was no displacement of the baroclinicity to the south. On the contrary, there was an increase in the geopotential height gradient over the 30°S over the Atlantic Ocean. An anomalous trough, whose axis extended to the coast of the southeast region of Brazil, is also visible on the 850 hPa map. This trough was associated with the formation of a strong and long-lasting SACZ in January. The SACZ significant precipitation over the east of Brazil is detected approximately to the north of the 20°S. Thus, in a context of positive geopotential anomalies at medium levels, the Pantanal region was in the anticyclonic portion of the surface flow, south of the SACZ. This inhibited the occurrence of precipitation.

In general, moisture transport anomalies were reduced in both austral summers of 2019 and 2020, mainly resulting from low specific humidity values. Circulation in the lower levels is totally altered by the strong disturbances on a synoptic scale. There is no typical northern flow that transports moisture from the

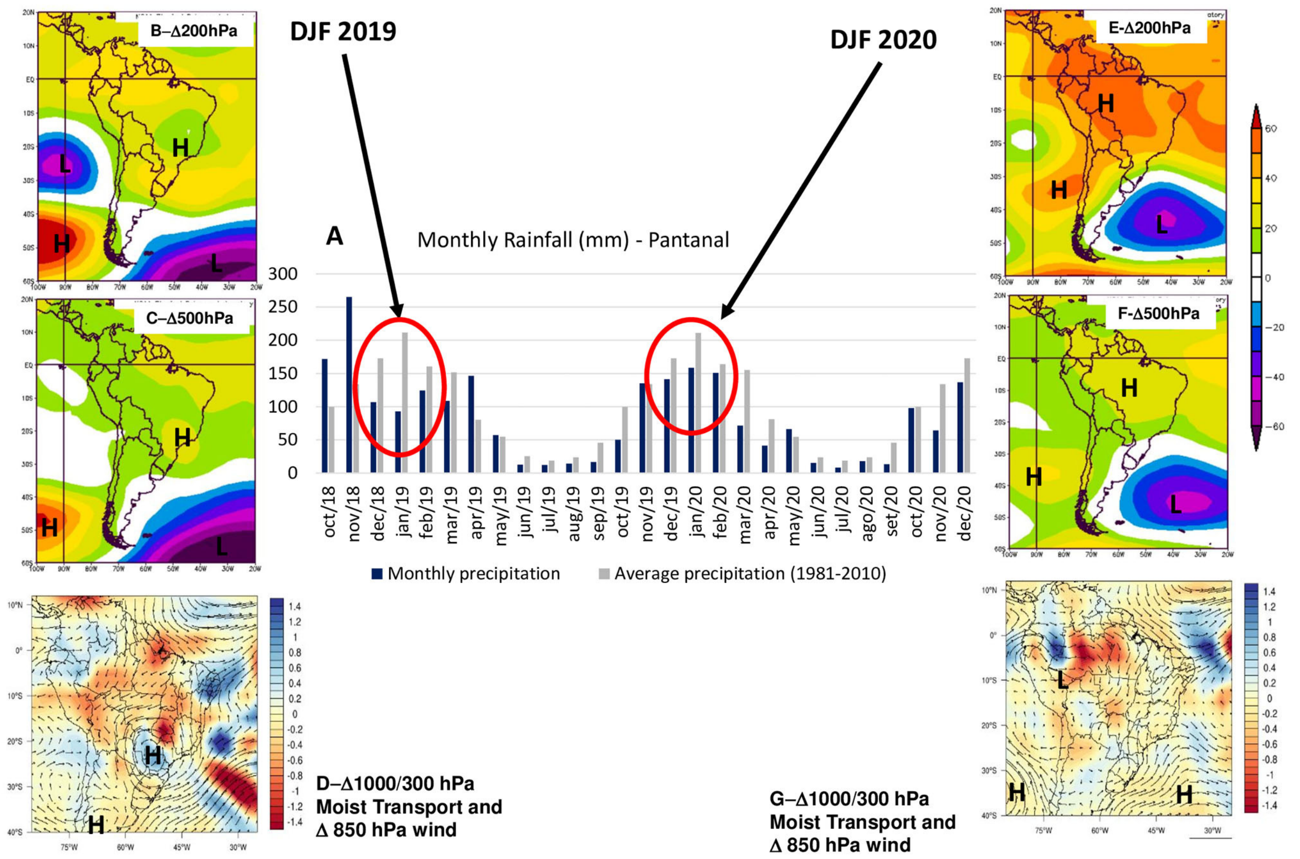

FIGURE 6 | (A) Mean monthly precipitation from October 2018 to September 2020 for the Brazilian Pantanal. Blue bars show observed precipitation and gray bars show 1981–2010 climatology. **(B,E)** show 200, **(C,F)** 500 geopotential height anomalies, **(D,G)** 1,000–300 hPa vertically integrated moisture transport (color) and 850 hPa winds (arrows) for December-February 2019 (left) and 2020 (right). Base period is 1981–2010.

Amazon along the Andes to the Pantanal. In December 2018–February 2019, the low-level flow is from the east since the ocean at this time is colder than the continent and, therefore, it contains less moisture, according to the Clausius-Clayperon equation. In December 2019–February 2020, this situation is even clearer, since the moisture transport comes from the south, associated with a post-frontal situation. This is probably linked to the successive passage of frontal systems during that month. In other words, instead of the transport of warm and humid summer air from Amazonia, characteristic of the monsoon circulation in the central region of South America, the predominance of air masses of higher latitudes, colder and drier, contributed to the scarcity of rain.

Rainfall

Rainfall anomalies in the Pantanal region are consistent with changes in the lower and upper-level circulation during the summers of 2019 and 2020 (**Figure 6**). Seasonal rainfall anomaly maps from **Figures 7A–H** show that summertime (December–February) rainfall of 2019 and 2020 was well below normal. For 2020, rainfall was reduced until November (**Figures 7E–H**). It rained 160 mm in January, and in March and November, it rained half of the expected value (**Figure 6**). Since August 2019, rainfall was below normal, and in October 2019, it rained 50 mm (half of the 100 mm average). This suggests a late onset of the rainy season of the hydrological year 2019–2020.

Figure 7 shows that in March-May 2019, rainfall was about normal, and from June-August 2019 to September-November 2020 rainfall was about 100–200 mm per month below normal. Rainfall in the hydrological year 2019–2020 was deficient from the rainy season in SON 2019 until September 2020. Furthermore, in 2019, the summer rain was well below normal, and this situation worsened in March-May, particularly over the Upper Paraguay River basin. According to CEMADEN (www.cemaden.gov.br) the volume of rainfall in the Pantanal Basin from October 2019 to March 2020 (rainy season) was 40% lower than the average of previous years. This situation was worsened because summer 2019 had already been a dry year in the Pantanal, and water stress had accumulated. Without enough rain to fill wetlands, the biome was more susceptible to fires. As seen in **Figure 7**, the seasonal mean in both December-February 2019 and 2020 is dominated by the large negatives in January alone, when rainfall was well below January climatology in both 2019 and 2020. Both GPCC and CHIRPS precipitation time series

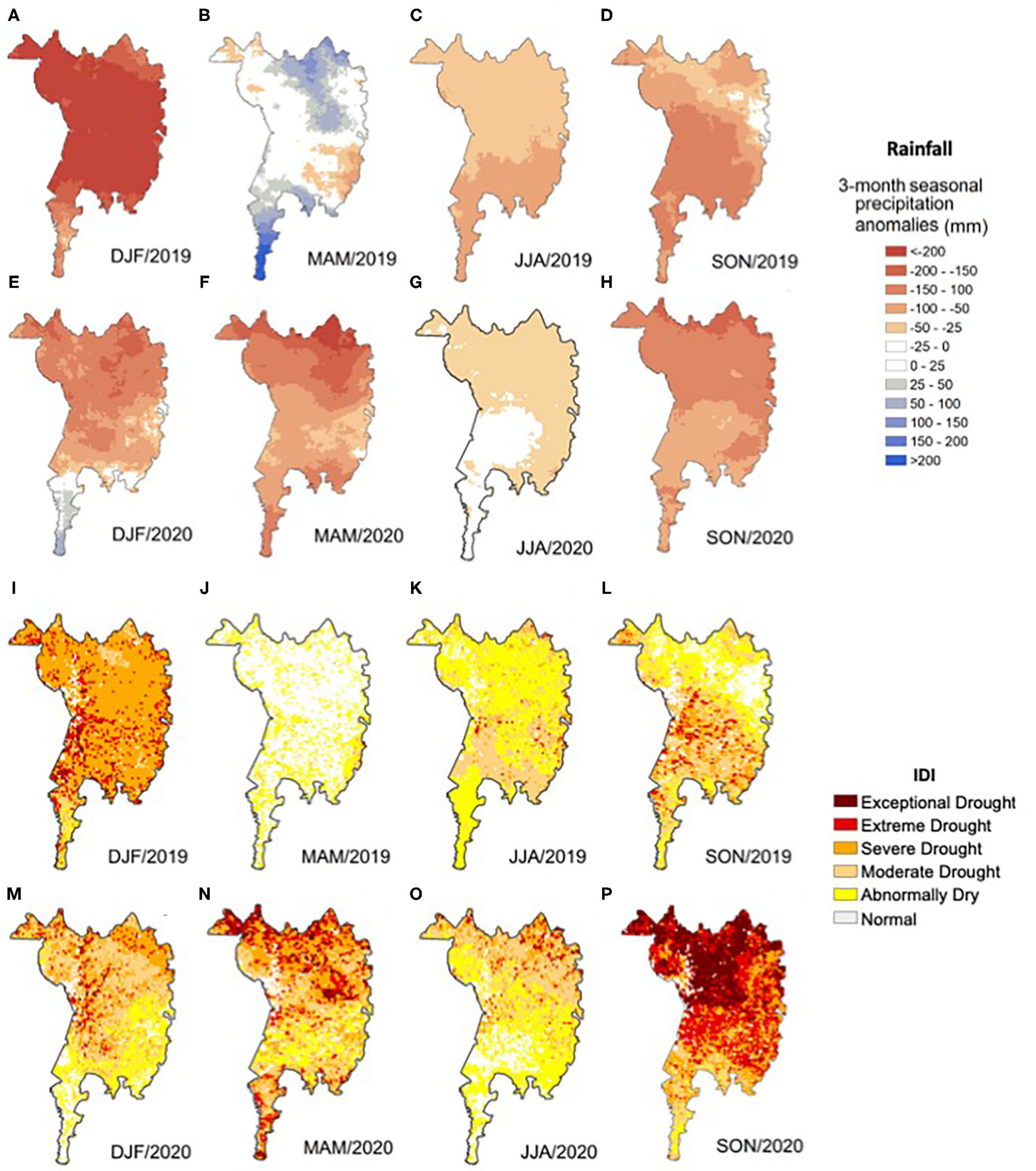

FIGURE 7 | (A–H) Seasonal rainfall anomalies for the Brazilian Pantanal from DJF 2019 to September-November 2020 in mm; **(I–P)**; seasonal IDI values for the Brazilian Pantanal from December-February 2019 to September-November 2020. Base period is 1981–2010.

indicate that the z-score reached lower values in 2020, −2.30 and −2.61, respectively (p-value = 0.021 and 0.0091, respectively). Considering 2019, precipitation z-scores were −1.88 (CHIRPS) and −1.81 (GPCC), with p-values of 0.06 and 0.07, respectively. These results indicate that since the beginning of the record the year 2020 was a year of historic drought.

River Levels

Figure 2B shows that the monthly levels of the Paraguay River at Ladário, showing about 240 cm below normal in June 2020. By the July-August 2020 season, the levels reached 300 cm below normal. **Figure 3** shows that in other periods in the past, the levels at Ladário were much lower than in 2020, such as from 1961 to 72, stabilize in the ending 1980s, and showing a negative tendency since 1978 and with lower values in recent years.

At the time this paper was written, no formal studies were available to quantify the variations of river levels at the Pantanal Basin, so we have to rely on information from web sites of Brazilian states and federal government as well as from local news that reported based on these official statistics. According to local media (G1, 2020) and the Brazilian Geological Survey CPRM site, the Ladário fluviometric station registered 174 cm in the Paraguay River on July 17th, 2020 (mean for July is 385 cm). This mark is 218 cm below the 392 cm recorded on the same day of previous year, 2019. At the Porto Murtinho fluviometric station, the difference in the same comparison is also over 200 cm. From 488 cm in July 2019, the Paraguay river level dropped to 280 cm in July 2020. At the Caceres fluviometric station, the levels of the Paraguay River reached 72 cm on August 17th 2020, compared to 122 cm on August 17th 2019. As shown in **Figure 3**, as of September 2020, there were no negative minimum levels, as in 1962 to 1973. On October 1st, the CPRM reported for the first time in 2020 a negative level (−3, 3 cm below hydrometric zero) at Ladário. A level 32 cm below hydrometric zero was reported on October 18th (https://www.cprm.gov.br/sace/boletins/Paraguai). By December 17th the level at Ladário was −4 cm, being the mean for that day 220 cm (www.cprm.gov.br/sace/boletins/Paraguai/20201217_17-20201217%20-%20175215.pdf).

The water level z-scores reached low values in several years. The lowest z-score were observed in 1971 (−2.26, *p*-value: 0.024) and in 1964 (-2.18, p-value: 0.029). In 2020, z-score reached −1.58 (*p*-value: 0.114). Although this value is not the lowest of the time series, it was the lowest in the past 49 years. Important to note that climatological annual cycles of precipitation and the average river levels present a time lag of 5 months (Araujo et al., 2018b), which reflects the existence of important geomorphological factors that influence strongly the slower river flow. Therefore, following the below-average rainfall trend observed at the end of 2020 (**Figure 2A**), probably the z-score will be lower in 2021.

Vegetation and Drought Mapping

In general, for the assessed period, the TCI values (**Figures 8A–H**) were lower in March-May 2019 (as a consequence of dry conditions in December-February 2019). The low TCI values continued from December-February 2020 to SON 2020, indicating that the vegetation in most of the region was under high water stress. From January to November 2020, the TCI values were below 30. Specifically, between March and May 2020, these values were subsequently below 10 (not shown), indicating increasing levels of vegetation stress in this period. The minimum VHI (**Figures 8I–P**) shows vegetation in stress, particularly in September-November 2019, in March-May 2020, and SO 2020.

As seen on VHI maps (**Figures 8I–P**), September-November 2019, March-May 2020, and September-November 2020 show widespread drought conditions in the region (VHI lower than 40). In this latter period, concomitantly low VHI values were the lowest due to VCI (not shown) and TCI values. This result is a response to the accumulated rainfall deficits since late 2019. Between December 2019 to April 2020, rainfall was below average (1981–2010) over the region (**Figure 6**), and especially in January, March, and April 2020, the accumulated rainfall was below the 25th percentile.

In wetlands such as the Pantanal, the differences between drought response from TCI and VCI can be related to the local soil conditions and plant types. This can favor water access during dry conditions. In this case, VCI (NDVI) would not be efficient in detecting short droughts. On the other hand, when the stomata close due to the increased evaporative demand of a dryer and warmer atmosphere, leaf temperature increases, and that is what the TCI captures (Andujar et al., 2017). The lower the TCI, the higher the thermal stress. The advantage of TCI is that in some regions the vegetation response to drought occurs, even when the vegetation is still green. The closing of the stomata minimizes water loss due to transpiration, reducing the latent heat flux.

The assessment of annual drought-affected areas, indicated by VHI z-score with $p < 0.05$, indicates that around 62,000 km^2 (∼32% of the Brazilian Pantanal biome) showed high water stress conditions in 2020. This value was the highest one since 1982 when the AVHRR dataset started to be produced.

The drought-affected areas can be also assessed by the Integrated Drought Index (IDI), which combines the lack of precipitation and the surface response to water stress. **Figures 7I–P** shows IDI calculated for the 3-month season from 2019 to 2020 over the Pantanal. Excluding March-May 2019, the drought intensities in most of the Pantanal biome ranged from moderate to exceptional. According to the IDI, in December-February 2019, March-May 2020, and September-November 2020, 23, 16, and 61% of the Pantanal experienced extreme and exceptional drought conditions, respectively.

An analysis of summer rainfall and the number of fires in the Pantanal is shown in **Figure 4A**. Annual rainfall shows a negative non-significant trend (Kendall's tau = −0.059 and *p*-value = 0.35, **Figure 4C**), and 2019 and 2020 showed the lowest values since 1982. Furthermore, 2020 shows the highest number of fires (22,116) since the beginning of the monitoring (1998). Before this, the year 2005 showed the highest number of fire (12,536), which coincided with the drought that affected southwestern Amazon in that year (Marengo et al., 2016). The highest number of fires in 2020 is consistent with the largest burned area (40,171 km^2, accounted for until November 2020). The lowest rainfall and river levels occur with the warmest air temperature at the Cuiaba station (**Figure 4B**) since 1980. The prolonged drought event started in late 2018 is ongoing in December 2020. Combined with the warmer conditions, this contributed to making the vegetation vulnerable to fires. This is consistent with low TCI values over most Pantanal

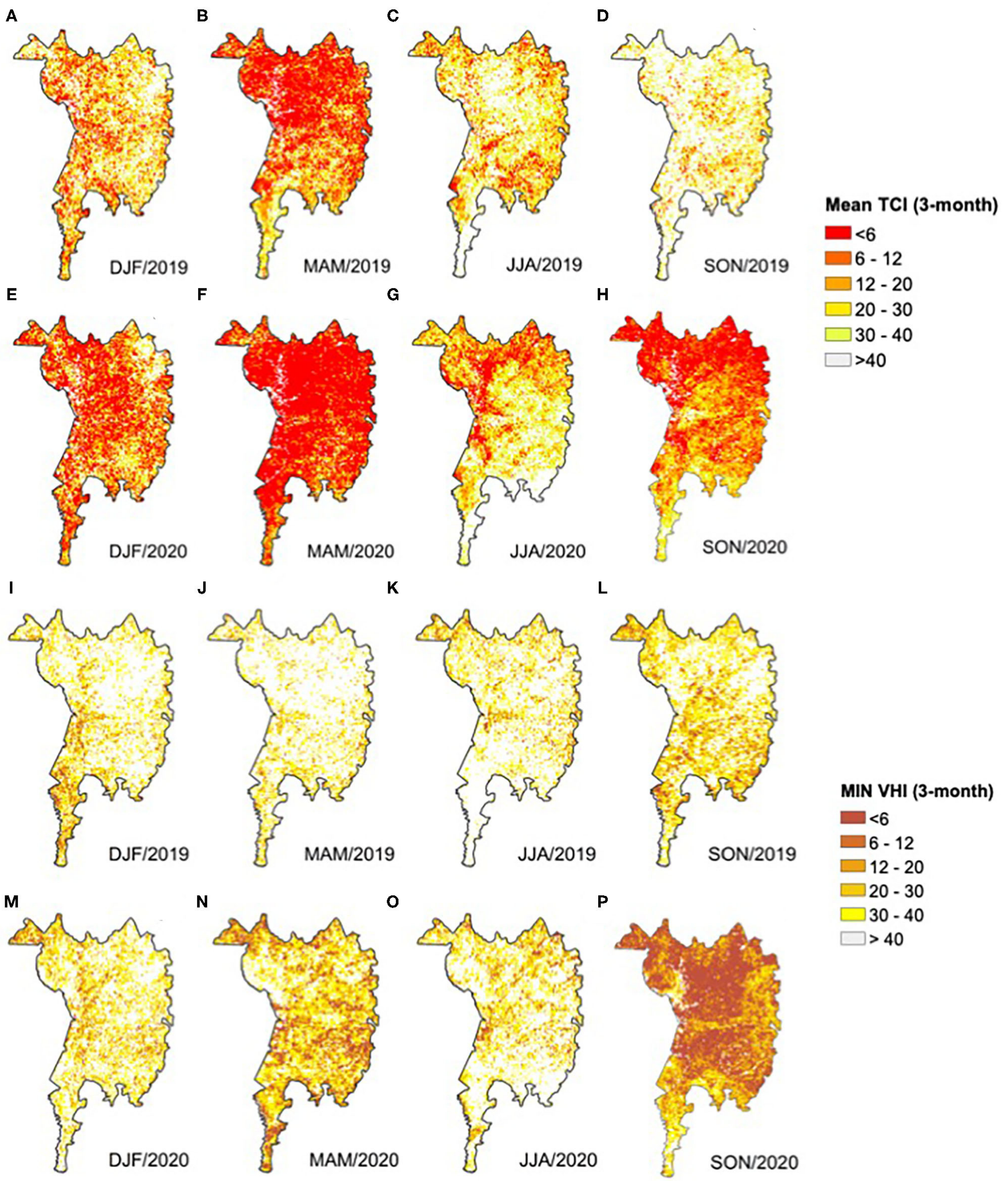

FIGURE 8 | (A–H) seasonal TCI-3-month values for the Brazilian Pantanal from December-February 2019 to September-November 2020; **(I–P)** seasonal minimum VHI-3 month for the Brazilian Pantanal from December-February 2019 to September-November 2020 in mm. Base period is 1981–2010.

areas, especially from December to December (**Figures 4A,B, 7E–H**). Previous studies have shown that severe drought events have a significant impact on wildfire risk. Heat stress and rainfall deficit reduce soil moisture, leading to easy ignition and wildfires spread (Littell et al., 2016; Bugalho et al., 2019).

Although a non-significant trend of increase in the number of fires has been observed (Kendall's tau = 0.03, p-value = 0.87), the TCI (**Figures 4A,B**) shows a significant reduction (Kendall's tau = −0,54, p-value < 0,0001), that is consistent with rainfall reduction (from **Figure 4C**) and a significant increasing trend in air temperature (Kendall's tau = 0.49, p-value < 0.0001). The lowest TCI and highest Cuiabá temperature values were in 2020.

This suggests a tendency of thermal stress and dryness in the Pantanal since 1982. These are indicators of conditions leading to water stress impacting natural and human systems. This combination of hot, dry conditions pushed flammability thresholds to their highest since 1980 (Libonati et al., 2020).

IMPACTS ON VULNERABLE SECTORS

At the time this study was prepared (December 2020), no formal studies have been published on the impacts of the drought on human activities or natural systems. So, we based this section on official statistics from Brazilian states and federal agencies (INPE, CPRM, EMBRAPA, CEMADEN, and ANA), NGOs and news reports. While INPE monitoring reported increases in the number of fires and burned area of the Pantanal, state and federal agencies as well as NGOs have reported variations in the levels of the Paraguay River almost daily in the news. The reports highlight the record drought and its impacts on fires over natural vegetation and agricultural land, transportation and even smoke moving into cities in southern Brazil, generating impacts on population. Upcoming paragraphs detail some of these observed impacts. At this stage, studies on impacts of the drought on human and natural systems are undergoing.

The main cause of increasing deforestation in the Pantanal is the growth of agribusiness in the region. For decades, the biome has coexisted with extensive cattle production. A survey of the SOS Pantanal Institute (2020) states that about 15% of the Pantanal area was converted into pasture for livestock. The use of the Pantanal area as pasture has become a big problem due to new methods used by local producers. In addition, soybean cultivation has been introduced in the Pantanal. Soybean production and cattle ranches, along with tourism, are the main economic engines in the region.

By December 2020, extreme drought in the Brazilian states of Mato Grosso (MT) and Mato Grosso do Sul (MS) affected 4.17 million people (76% of the population de MT and MS). A total of 218 municipalities (almost 100%) were affected by drought. **Table 1** shows the area affected by severe and exceptional drought in the Brazilian Pantanal. The area is estimated based on the IDI classification. The area affected by drought was larger in 2019, as compared to 2020, with the difference that the 2019 drought area was concentrated in the northern part of the basin, while in 2020 the affected area also included the southern part of the basin (**Figures 7**, **8**). The main crops in the Brazilian Pantanal are sugar cane and soybeans.

The low river level season is from October to December. By August 2020 river transportation had to be suspended due to anomalously low river levels. According to the State Secretary for the Environment, Economic Development, Production and Family Agriculture of Mato Grosso do Sul (SEMAGRO-www.semagro.ms.gov.br), the very low levels of the Paraguay River affected navigation and transportation along the river. The Brazilian Navy restricts navigation along the Paraguay River when levels drop to 150 cm at Ladário. This stopped the export of 40% of soybean crop by the *Hidrovia Paraná-Paraguai*- in 2020. By September 18th, the level at Ladário fell to 25 cm. The drought began to generate collapses in the export of grains and minerals in Mato Grosso do Sul, directly affecting the regional economy.

Due to low river levels, in Ladário, the port of Bulk Chemical operated with 60% of its capacity, and the Vale Mining terminal in Porto Esperança was forced to carry a thousand tons of minerals by highway. This *Hidrovia* is of extreme importance for exports from the state of Mato Grosso do Sul, and for its commercial relations with Paraguay and Bolivia, according to local newspapers (Jornal A Critica de Campo Grande, 2020). The SEMAGRO (2020) official web site reported that the low levels of the Paraguay River affected transport of exports and imports from Brazil, Bolivia, and Paraguay along the *Hidrovia*. This caused economic losses of about US$ 28 million to business in Bolivia and Paraguay. The *Hidrovia Parana-Paraguai*- reduces the cost of commercial shipping of soybeans and minerals to the Atlantic Ocean. Dredging the river for the passage of commercial boats can decrease the water retention time in the area (Lázaro et al., 2020).

According to INPE (queimadas.dgi.inpe.br//queimadas/portal), the number of fires in the Pantanal increased by 210% by August 2020, compared to August 2019. Between January and June 2020, the Pantanal had 2,534 fires, which represents an increase of 158% compared to the same period in 2019 (981 fires). From January 1 to September 16th 2020 the number of fires reached 15,756 compared to 4.660 in 2019. The previous record was in 2005, when the total number of fires was 12,536, according to the Prevfogo program of IBAMA (www.gov.br/ibama/pt-br/composicao/quem-e-quem/centros/prevfogo). CPRM shows that levels of the Paraguay River are the lowest in the last 50 years, and that situation aggravated fire impacts, with almost 3 million hectares burned in the Pantanal lowlands.

Silva Junior et al. (2020) quantify fire foci, burned areas, and carbon emissions in all Brazilian biomes. They show that the highest emissions occur and will persist in the Amazon and Cerrado biomes. The Atlantic Forest, Pantanal, Caatinga and Pampa biomes had low emissions compared to the Amazon and Cerrado. To reduce greenhouse gases (GHG) emissions and meet the goals of the Paris Agreement, Brazil will need to control deforestation induced by the expansion of the agricultural frontier in the Amazon, Cerrado and Pantanal biomes. This can only be achieved through significant political effort involving the government, civil society, and the agroindustry sector (Tomas et al., 2020).

In the future, meteorological droughts will likely increase in frequency and severity in large areas of the world, and key drivers here are a decrease in rainfall, or an increased evaporative demand due to increasing temperatures, or a combination of both (Spinoni et al., 2020). Climate modeling experiments suggests that the Pantanal could become hotter and

TABLE 1 | Areas of agriculture, natural vegetation and agriculture+pasture land (for livestock) affected by severe and exceptional drought.

Season	Natural vegetation area affected drought (km^2)	% Natural vegetation area affected drought	Agriculture land area affected by drought (km^2)	%Agricultural land area affected by drought	Agriculture+pasture land area affected by drought (km^2)	%Agriculture l+pasture land area affected by drought
DJFM/2019	32586.7	88	102.1	56	14,728.9	73
DJFM/2020	21399.5	57	79.4	29	9,629.4	48

Area was defined by the IDI during December-March 2019 and 2020 in the Brazilian Pantanal (Source: MapBiomas).

drierProjections within the Pantanal suggest a 5–7°C increase in temperature and a 30% reduction in rainfall under RCP8.5 by 2100 (Marengo et al., 2016). Recent projections by Vogel et al. (2020) using CMIP6 models show the risk of occurrence of "extreme droughts" strongly increases with higher global warming levels (above 2.0°C). The co-occurrence of warm and dry conditions substantially increases with global warming in some regions, showing increased occurrence of hot and dry clusters in various regions of the planet, including Northeast Brazil, the Amazon and the northern section of the Brazilian Pantanal and southern South America (Spinoni et al., 2020; Vogel et al., 2020). A better understanding of these projections requires an analysis of how these meteorological conditions translate into soil moisture and hydrological droughts and their relation with impacts on societies and the environment.

CONCLUSIONS AND RECOMMENDATIONS

Since 2019 the Pantanal has suffered a prolonged drought that has spelled disaster for the region. In the summers of 2019 and 2020 near surface atmospheric circulation changes are consistent with reduced moisture flow coming from the Amazon region. Subsequent fires engulfed hundreds of thousands of hectares across the biome. This caused a marked decrease in the hydrometric levels throughout the Paraguay River. The values have continued well below normal for the season. The level of the Paraguay River in Asunción on September 16th registered only 14 cm. This is very low compared to the minimum average historical for this month of the year, which is 100 cm. The annual mean river level at Ladário is 273 cm and during drought situations transportation in some sections of the Paraguay River had to be restricted. A major threat in the Pantanal is the economic pressure imposed by the agribusiness sector outside the region. The extreme low levels affected the mobility of people and the shipments of soybean and minerals to the Atlantic Ocean by the Hidrovia Paraná- Paraguai.

The drought situation in 2019–20 in the Pantanal and the Upper Paraguay River basin has been unusually harsh, with dry and warm conditions favoring propagation of fires. The increased number of fires affects human activities and biodiversity. Cross-border fires have not been restricted only to Brazil, Bolivia and Paraguay; they have also spread along the banks of Paraná River in northern Argentina in the spring. These fires and drought aggravated the situation of vulnerable fauna and flora.

Changes in the quality of rainy season can affect wetlands hydrology, and drought situations can seriously affect the living conditions of biological populations. The Pantanal has been affected by drought, due to weak rainy seasons in 2019 and 2020. The dryness, together with high temperatures increased the risk of fire. As the hot, dry days progress, the Brazilian Pantanal and the southern Amazon are under more pressure from fires. The fires in the Pantanal in 2020 are truly unprecedented. As of December, 31th 2020, 22,116 fires were recorded in the biome, according to data from INPE. Uncontrolled fires destroyed vast areas of vegetation and killed wildlife, putting one of the world's most diverse ecosystems in danger. International media showed charred jaguar carcasses littering the ground, along with burned caimans and fallen birds. Local ranchers struggle to survive (Canadian Broadcasting Corporation, 2020). The previous total record was from August 2005, with 5,993 hot spots. It occurred when a very intense drought affected these regions, as well as southwestern Amazonia.

As a consequence of higher temperatures and reduced rainfall, an increased water deficit would be expected, particularly in the central and eastern parts of the basin during spring and summer. This could affect the pulse of the Paraguay River (Marengo et al., 2016). The largest anomalies projected for the months of the dry season (June–August) are due to the relatively low precipitation rates during these months. However, Bravo et al. (2019) indicate that dispersion among model projections result is considerably larger during the low rainfall period as well as during the rainy period. In addition, more extreme floods and droughts are expected (Benitez and Domecq, 2014; Marengo et al., 2016).

We need to better understand current drought and flood dynamics in the Pantanal. To accomplish this, an adequate hydrometeorological monitoring network in the entire Pantanal basin is crucial. The study by Cristaldo et al. (2017) in the Upper Paraguay river basin shows that the current meteorological network is not satisfactory. The operating stations suffer a lack of maintenance, creating a need for additional stations. So, to improve our knowledge of the hydrological processes in the region it is still necessary to install additional ground-based stations. There is a need to study the feedback between aerosols from the Pantanal's biomass smoke and rainfall during the wet season.

All these facts suggest the need for a science network with collaborative capability to generate creative ideas and solutions to address the big challenges faced by the Pantanal wetland. With better knowledge of the causes and trends in droughts or floods, it would be possible to propose strategies to reduce the impacts on natural and human systems in the region. Conservation of natural resources and ecosystems services provided by the Pantanal wetland must consider actions in favor of water security.

The resilience of the biome will be greatly improved by reducing the risk of fires and the over exploitation of its natural resources. Increasing agriculture, cattle ranching, fishing and tourism must proceed in a sustainable way so the Pantanal can be preserved. If current climate and land-management trends persist, the Pantanal as we know it will cease to exist. This could be worsened if anti-environment politics are adopted. Lastly, the many effects of climate change are felt most strongly in vulnerable ecosystems and poorest communities of the world. To avoid devasting impacts, the world needs urgent action in the next decades, with radical shifts by 2050 following the Paris Agreement (IPCC, 2018).

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: CEMADEN.

AUTHOR CONTRIBUTIONS

JM and AC conceived this paper and wrote it. LC, KD, and EB performed the hydrological analysis. MS, NM, RS, EC, and EA conducted the meteorological analysis of the drought. CM, CD, and MK worked on the analysis of land use and land use changes. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2021.639204/full#supplementary-material

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