European Commission

The 2019-2021 extreme drought episode in La Plata Basin

A Joint Report from EC-JRC, CEMADEN, SISSA and WMO

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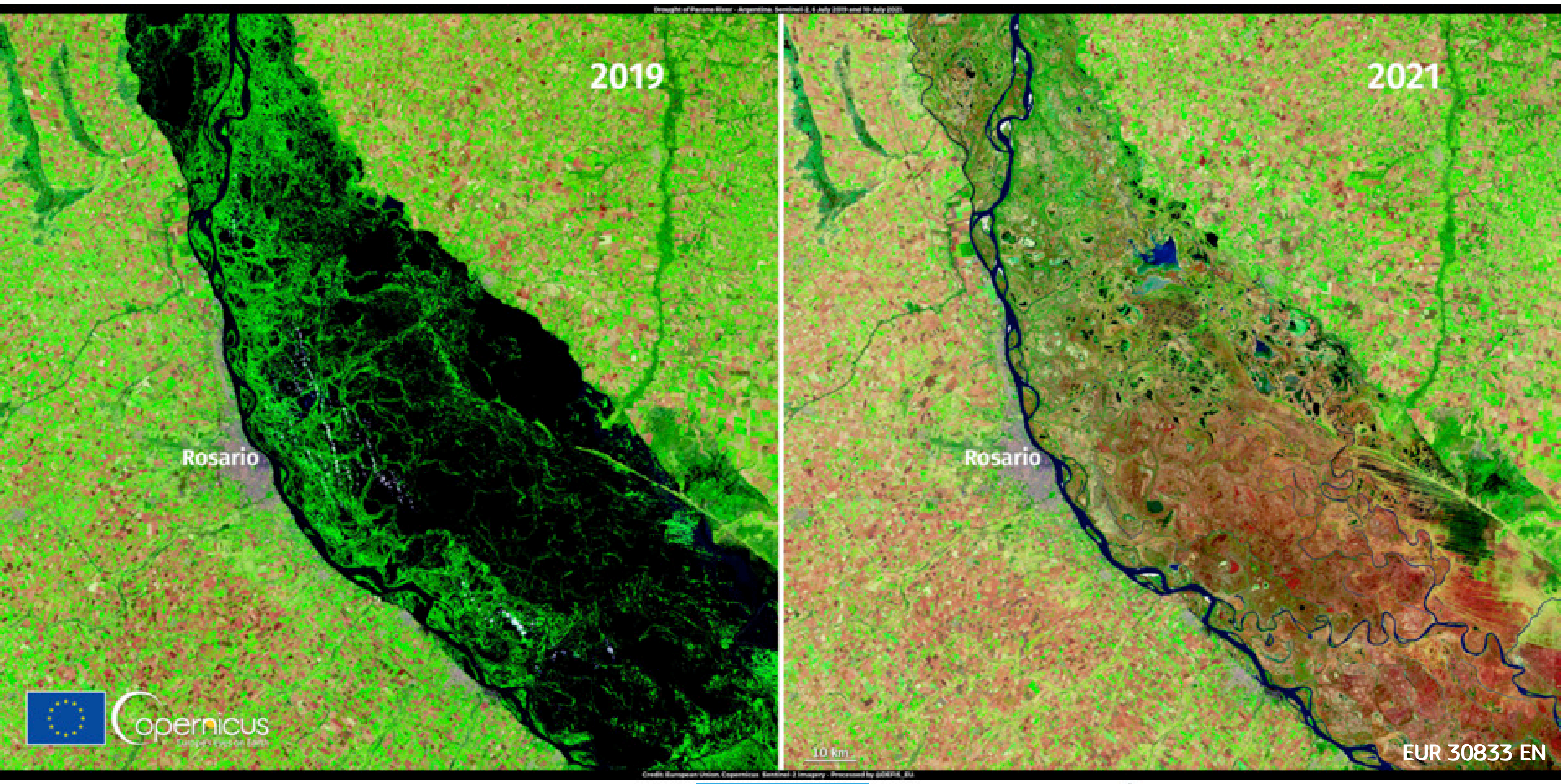

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 Cover page: Pair of images acquired by one of the Copernicus Sentinel-2 satellites on 6 July 2019 (left panel) and 10 July 2021 (right panel). The images provide evidence of the drought affecting the Paraná River in Argentina, near the port of Rosario. Exposed sandbars and dried wetlands are apparent in the left image. Credit: European Union, Copernicus Sentinel-2 imagery.

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Contents

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Abstract

A persistent and extreme drought started in 2019 is still ongoing and has been affecting the La Plata Basin, the second largest river basin in South America and the fifth in the world. Here we provide an overview of the event, its climatological background, its spatio-temporal evolution, its causes and characteristics, as well as its impacts on natural and human systems.

The 2019-2021 drought started with below normal precipitation in the upper part of the basin in mid-2019 and due to its persistence has spread through the hydrological cycle affecting soil moisture, flows, groundwater and vegetation. Severe, extreme, and exceptional drought conditions began to appear in the upper basins of the Paraguay and Paraná rivers in south-central Brazil. By the end of 2019 drought conditions were already affecting the Brazilian states of Mato Grosso, Goias, Sao Paulo and Paraná, and in Paraguay and central Argentina. This situation continued during 2020 and became most spatially extended by the end of 2020, when northern Argentina and the Pampas of central-eastern Argentina suffered widespread drought as well.

The ongoing 2019-2021 La Plata Basin dry event can be already ranked among the top five events in South-Eastern South America since the 1950s. Most of the parameters included in the present classification (severity, intensity, and peak) show that the ongoing drought falls behind the 1968-1971 event because of its shorter duration.

In most parts of the La Plata Basin, La Niña is often accompanied by drought, leading to particularly negative impacts in southern Brazil, north-eastern Argentina, Paraguay and Uruguay. Recent observations and seasonal forecasts suggest that La Niña conditions may be back again in October-November 2021 and lasting till 2022 spring, thus delaying the return to normal conditions in the La Plata Basin, including river flows. This is in line with most seasonal precipitation forecasts from global model ensembles, which indicate a precipitation deficit scenario in the middle and lower part of the La Plata Basin.

According to the impacts reported and attributed to this event, many sectors including agriculture, inland water navigation, energy production, water supply and several ecosystems have been suffering from the ongoing drought. However, total damage estimates and characterisation of all affected sectors can be performed only once the event will be over.

1 Introduction

The La Plata Basin (hereafter, LPB) encompasses southern Brazil, south-eastern Bolivia, Paraguay, most of Uruguay, and north-eastern Argentina. With an area of 3.1 million km², the LPB is the second largest river basin in South America and the fifth in the world, covering about 17% of the land surface of the South American continent. The region relies mostly on rainfall to sustain a large agricultural production, hydropower, transportation of goods along its rivers, and to satisfy household, industrial and environmental water needs. The LPB includes three major river systems: the Paraná, the Paraguay and the Uruguay rivers all of them converging into the Río de La Plata estuary that drains into the Atlantic. Each of these water basins has unique socio-economic characteristics that reflect its source water and the associated flow pattern variability (Figure 1). The Paraguay-Paraná river system, for instance, is a 3,500 km long, free flowing fluvial corridor that, due to the absence of dams and other major interventions, still preserves its hydrological and ecological functions (Baigún and Minotti, 2021).

Figure 1. Map of the La Plata Basin including the main hydroelectric dams. Dark green areas represent zones of irrigation development. Source: FAO, (2016).

The total population living in the LPB is about 100 million people, nearly half of the population of the basin-countries. Within the LPB, about 70% of the aggregate GDP of the basin-countries is produced (Barros et al., 2006). Currently the rivers of the LPB are exposed to factors that modify the quantity and the quality of their waters. These pressures are exacerbated by the extraordinary variability in the hydrological regime linked in part to climate variability and climate change, with recurrent droughts and/or floods. Additional important drivers are associated with changes in: land use, population growth, urbanisation, agricultural, industrial, and infrastructure development. Understanding the impacts of current and recent past climatic and environmental conditions, and assessing future scenarios (including, e.g., an increased frequency and intensity of drought events) is crucial to support governmental policies and decisions, as well as to foster progress towards low-carbon economies, high resilience and more equitable societies in this region (Coelho et al., 2016).

Since 2019, the LPB region has suffered from a long, exceptional and devastating event that has started as a meteorological drought[1] (precipitation deficits), but because of its persistence has spread through the hydrological cycle affecting the entire hydrology (soil moisture, rivers, superficial and groundwater storage) and ecosystems of the region. It is considered as "the most severe since 1944" (INA, 2021), and caused severe impacts on the regional societies, ecosystems and economy. Here, we provide an overview of the drought development and the associated impacts on ecosystems and key socio-economic sectors. The main features and the climate drivers are described in the following sections, together with an overview of the main drought-sensitive sectors.

[1] Droughts are a recurring feature of all climates and are generally defined with respect to the long-term average climate of a given region. The Intergovernmental Panel on Climate Change (IPCC) defines drought as "a period of abnormally dry weather long enough to cause a serious hydrological imbalance" (IPCC, 2021). It results from a shortfall of precipitation over a certain period, from the inadequate timing or the ineffectiveness of the precipitation, and/or from a negative water balance due to an increased atmospheric water demand following high temperatures or strong winds (UNDRR, 2021).

2 Evolution and status of the 2019-ongoing drought in the LPB

Several reports (GDO[2], CEMADEN[3], INA[4] and WMO[5,6]) have analysed the early stages of this drought that began approximately in mid-2019 in the north of the LPB and has recently spread spatially, affecting almost the entire basin. Recent observations[7] and monitoring by CEMADEN, hydrological agencies and meteorological services in the region have confirmed a worsening of precipitation and streamflow deficit.

Different drought stages require different indicators for their characterization (see box 1). Precipitation anomalies and the standardized precipitation index are often used for meteorological drought analysis. Soil moisture indicators such as the soil moisture-based drought severity index characterize drought impacts in terms of plant water stress (Vogt et al., 2018). Hydrological indicators, such as flow percentiles and deficits are used to quantify the volume of water deficit in rivers and reservoirs or to monitor whether a required ecological flow or a minimum flow regime is maintained. Remote-sensing-based indicators such as the fraction of absorbed photosynthetically active radiation are used to monitor drought stress on the vegetation canopy (UNDRR, 2021).

Box 1. Drought types

Depending on the effect in the hydrological cycle and the impacts on society and environment, different drought types are commonly distinguished:

- Meteorological drought is a period of months to years with a deficit in precipitation or climatological water balance (i.e. precipitation minus potential evapotranspiration) over a given region. The deficit is defined with respect to the long-term climatology. A meteorological drought is often accompanied by above-normal temperatures and precedes and causes other types of droughts. Meteorological drought is caused by persistent anomalies in large-scale atmospheric circulation patterns, which are often triggered by anomalous tropical sea surface temperatures or other remote conditions. Local feedbacks such as reduced evaporation and humidity associated with dry soils and high temperatures often enhance the atmospheric anomalies.

- Agricultural and ecological drought is a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general.

- Hydrological drought occurs when river stream flow and water storages in aquifers, lakes, or reservoirs fall below long-term mean levels. Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. Time-series of these variables are used to analyse the occurrence, duration and severity of hydrological droughts.

Source: adapted from Vogt et al. (2018); IPCC (2021)

2 GDO, 2021. GDO Analytical report. Drought in centre-south Brazil – June 2021. JRC Global Drought Observatory (GDO) of the Copernicus Emergency Management Service (CEMS). Available at: https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2050

3 CEMADEN, 2021. Monitoramento De Secas E Impactos No Brasil – Julho/2021. Available at: https://www.gov.br/mcti/pt-br/rede-mcti/cemaden/conteudo/monitoramento/monitoramento-de-seca-para-o-brasil/monitoramento-de-secas-e-impactos-no-brasil-2013-julho-2021

4 INA, 2021. Posibles escenarios hidrológicos en la cuenca del plata Durante el período septiembre-octubre-noviembre 2021. Available at: https://www.ina.gob.ar/alerta/index.php?seccion=6

5 WMO, 2021a: State of the Global Climate 2020, WMO-No. 1264

6 WMO, 2021b: State of the Climate in Latin America and the Caribbean 2020, WMO-No. 1272

7 https://www.ina.gob.ar/archivos/alerta/Tabprono_2021sep29.pdf

Here, we describe the evolution of the different meteorological, hydrological, and vegetation-related drought indicators. A detailed description of the drought indicators used in this section can be found in Annex 1.

2.1 Total precipitation and cumulative anomalies since September 2016

Figure 2 shows the temporal evolution of monthly precipitation and cumulative precipitation anomalies for the last 5 years (September 2016 – September 2021). The time series are shown for two locations: *(a)* one near Santa Fe do Sul in the state of São Paulo to describe conditions at the Cantareira water supply system providing water to the megacity of Sao Paulo (left panels) and *(b)* the Pantanal in the state of Mato Grosso, one of the largest wetlands in the world (right panels).

It is evident that during the last 5 years, precipitation has always been below the 1981-2010 average at both locations, therefore it has not contributed significantly to alleviating the antecedent drought conditions. The latest 12 months, nevertheless, stand out with very low values. Over the last 5-year period a strong precipitation deficit of more than 25% has been accumulated (with respect to 1981-2010). In the last the two years, total precipitation has been about 50% the average.

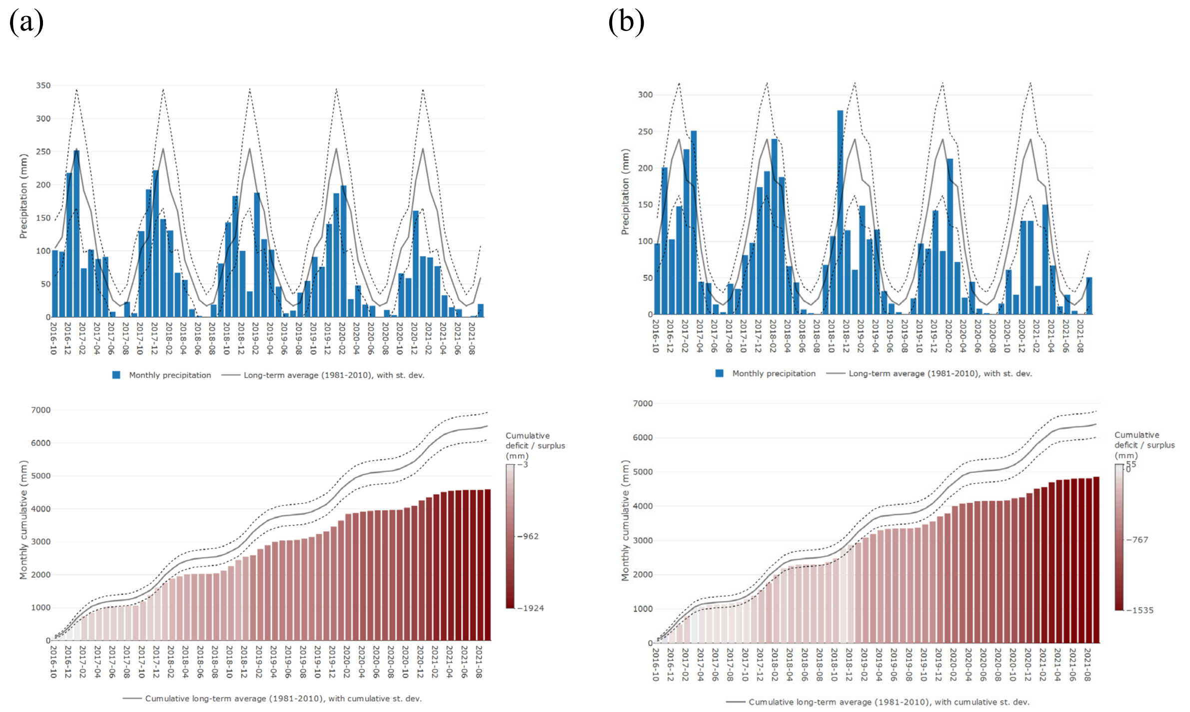


Figure 2. Time series of monthly total precipitation (blue bars) and cumulative precipitation anomalies (red bars) for the last 5 years (September 2016 – September 2021). Series are shown for: *(a)* a region near Santa Fe do Sul (20.3°S, 51°W) in the state of São Paulo to illustrate conditions near the Cantareira water supply system; *(b)* the Pantanal wetland in the states of Mato Grosso and Mato Grosso do Sul (16.7°S, 57.5°W). Both panels also show the 1981-2010 monthly average of total precipitation (solid lines) and the estimated range of variability given by the standard deviation (dashed lines). The lower panels show the 1981-2010 monthly average (solid lines) and the estimated range of variability given by the standard deviation (dashed lines) of cumulative precipitation anomalies over the last 5-year.

2.2 Standardised Precipitation Index (SPI)

This section focuses on the time series of the Standardised Precipitation Index (SPI, an indicator of meteorological drought, see Annex for details) for the two locations described in the previous section (the Cantareira water supply system and the Pantanal wetland)**.** SPI series are shown in Figure 3 and Figure 4 for three temporal scales: 3, 6 and 12 months.

The analysis of the SPI time series shows that since 1981 SPI-03 has reached very dry or extremely dry values between 20 and 30 times. Remarkably, however, 2/3 of these events have occurred in the last 4 years. In the last 6 months, SPI-12 shown negative values, suggesting a strong hydrological deficit. This information confirms that the current drought represents one of the driest and longest periods of below-normal rainfall in the upper LPB in the last 40 years.

The SPI time series of the long-term (12 months) accumulation period explains the impact of the lack of precipitation on the hydrology of the region. The severe SPI-12 deficit covers practically the entire northern part of the La Plata Basin (not shown). The severity of the long-term precipitation deficit is extremely strong over most of central and south Brazil, south-eastern Bolivia and north of Paraguay, north-eastern Argentina, and eastern Uruguay.

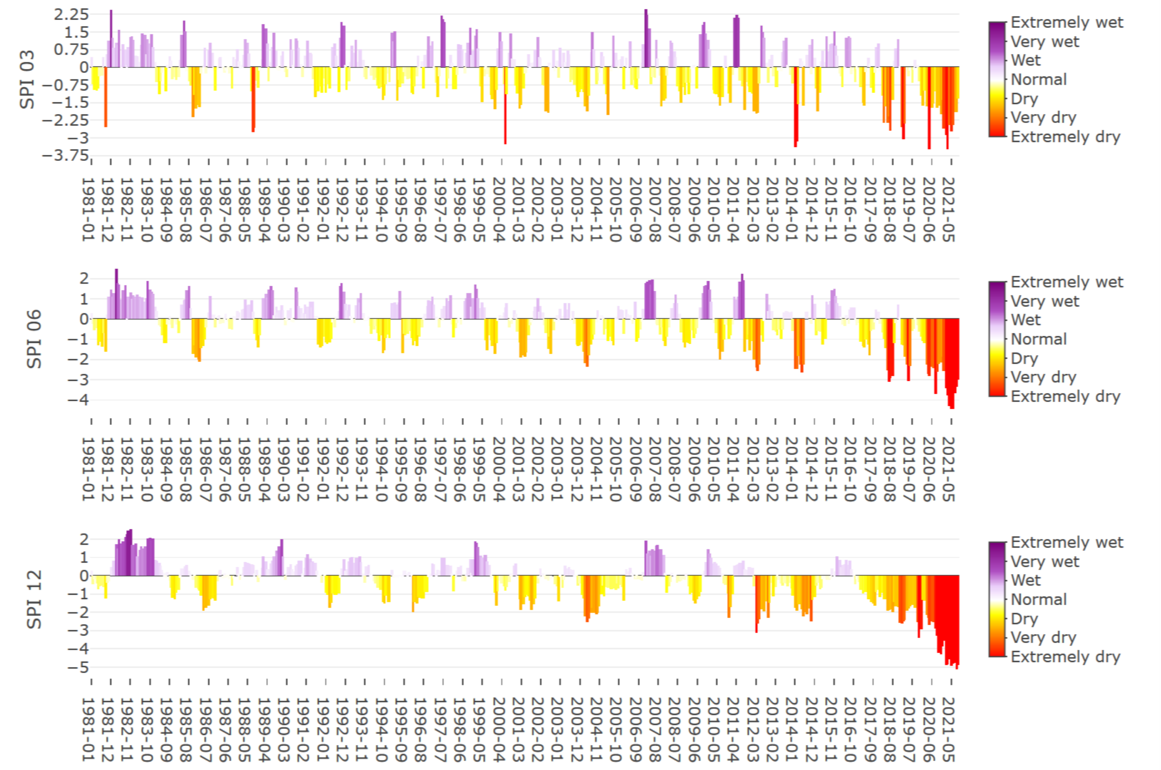


Figure 3. Time-series of SPI (January 1981 – September 2021) for three different temporal scales: 3, 6 and 12 months (from top to bottom) for a location near Santa Fe do Sul (20.3°S, 51°W) in the state of São Paulo to illustrate the conditions of the Cantareira water supply system.

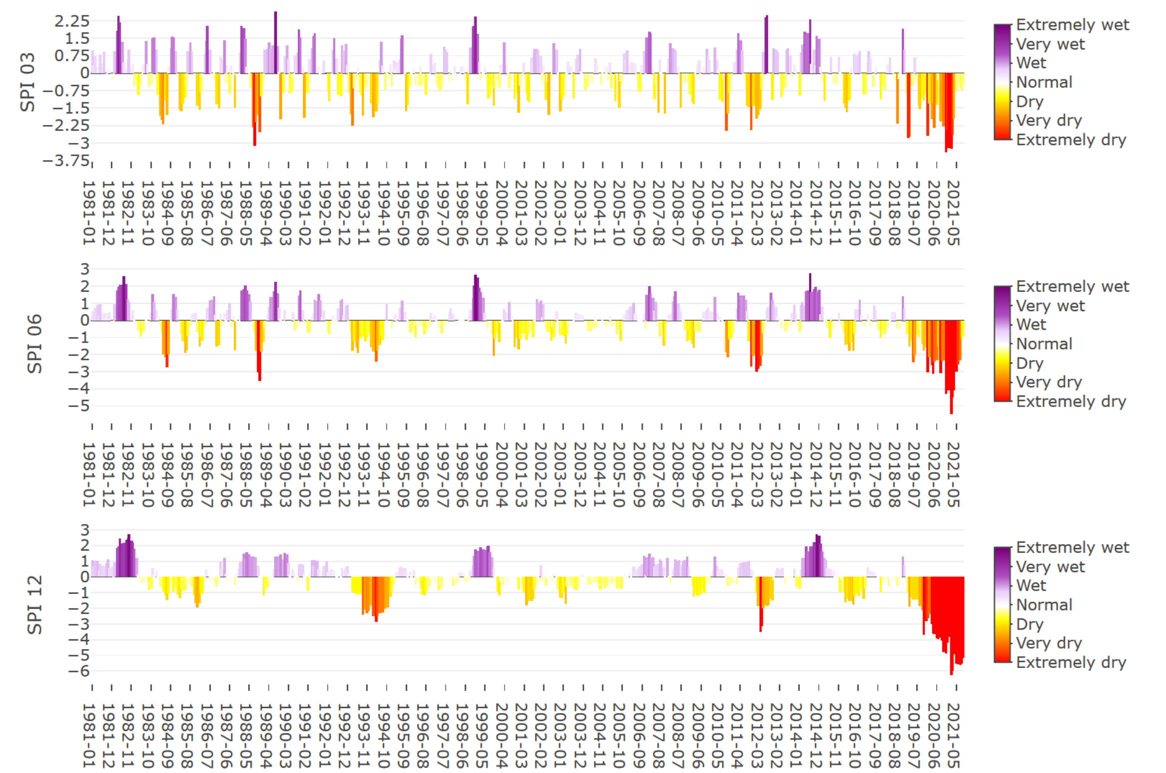


Figure 4. Time-series of SPI (January 1981 – September 2021) for three different temporal scales: 3, 6 and 12 months (from top to bottom) for a location in the Pantanal wetland in the states of Mato Grosso and Mato Grosso do Sul (16.7°S, 57.5°W).

2.3 Evolution of the area under different drought categories based on CHIRPS precipitation estimates

To monitor the temporal evolution of recent drought conditions in the Plata Basin we also use maps of drought categories calculated from CHIRPS (Climate Hazards InfraRed Precipitation with Station data) precipitation estimates (Funk et al., 2015). CHIRPS fields are derived from both satellite data and in situ observations; they are produced every pentad (periods of 5 days) and are available since 1981 on approximately a 5 x 5 km grid. The CHIRPS dataset has been validated worldwide, including some Brazilian regions and it was found to perform better than other precipitation datasets in central Brazil (Marengo et al., 2021b).

Here, CHIRPS precipitation estimates are aggregated over 6-month periods ending on the dates shown at the top-right corner of each map in Figure 5. For instance, the map in the upper left labelled "2019-03-15" includes values over the period between 16 September 2018 and 15 March 2019. A non-parametric approach (Kooperberg and Stone, 1991) is then used for each cell and end date/year to estimate the percentiles for each precipitation time series. These percentiles are used to assign each grid cell and end date/year combination to one of the six drought categories following the U.S. Drought Monitor system (Svoboda et al., 2002). The drought categories range from "no-dry conditions" (percentile values > 30) to "exceptional drought" (percentiles ≤ 2).

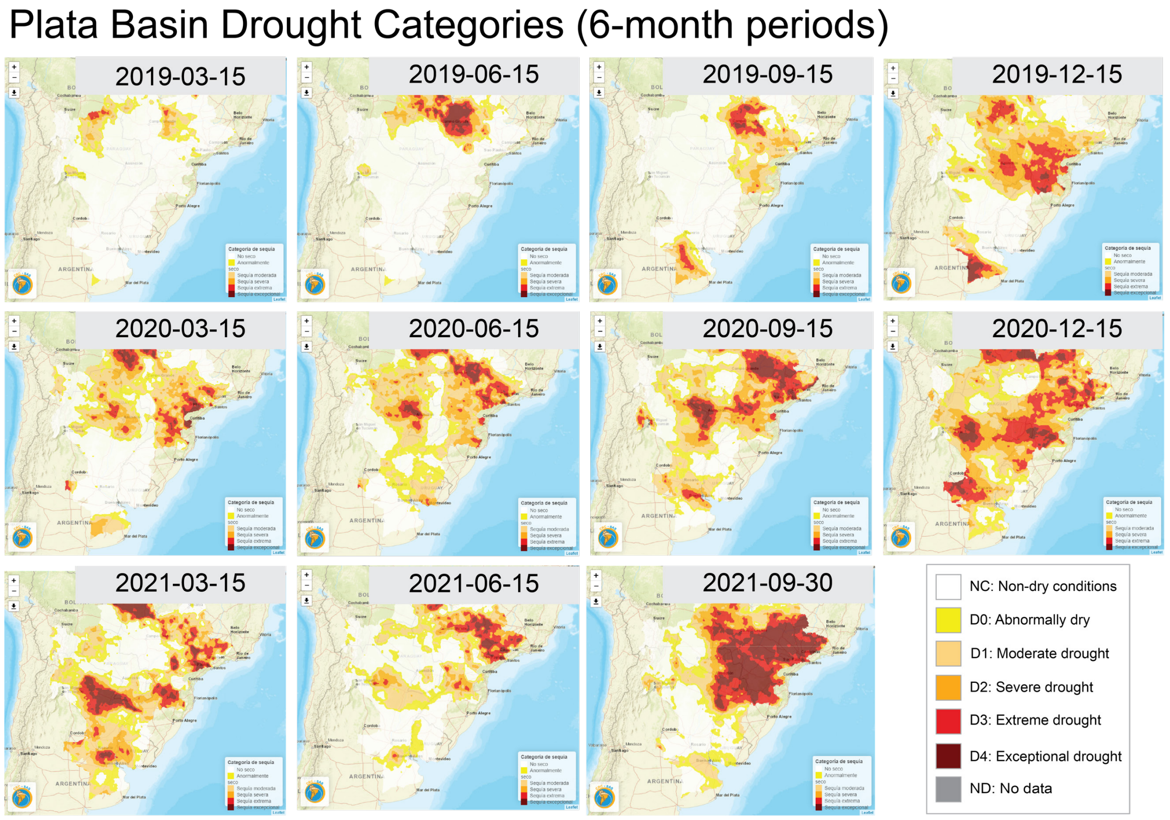


Figure 5. Drought categories for the Plata Basin derived from SPI-6 CHIRPS precipitation anomalies from 15 March 2019 to 30 September 2021. Source: SISSA

The spatio-temporal evolution of this drought, as given by the estimated percentile-based drought categories (approximately every three months – except for the bottom right panel that shows the most recently available data ending on 30 September 2021, i.e. three months after the previous map), is shown in Figure 5. As for the 6-month period ending in March 2019 (Fig. 5, upper left panel), most of the LPB was under no drought conditions. Severe, extreme, and exceptional drought conditions began to appear in the period ending on mid-June 2019 in the upper basins of the Paraguay and Paraná rivers in south-central Brazil. By the end of 2019 (Fig. 5, upper right panel), drought conditions were fairly extended in the Brazilian states of Mato Grosso, Goias, Sao Paulo and Paraná, and in Paraguay and central Argentina. As of autumn 2020, the drought persisted (Barbosa et al., 2021) and was aggravated by an intense heat wave that affected most of central South America between September and October (Marengo et al., 2021a). This situation continued and has reached its maximum extension at the end of 2020, when northern Argentina and the Pampas of central-eastern Argentina showed widespread drought.

Critical conditions were somewhat alleviated in Paraguay and southern central Brazil by March 2021, but severe-to-extreme drought continued to affect both the regions north and south of that *non-dry* area. This *non-dry* area expanded through mid-2021, except for southern central Brazil. Finally, by looking at the 6-month period ending on September 2021 (Fig. 5, bottom right panel), the area affected by severe-to-exceptional drought has expanded considerably, encompassing southern central Brazil, Paraguay, most of Uruguay, and northern and central Argentina.

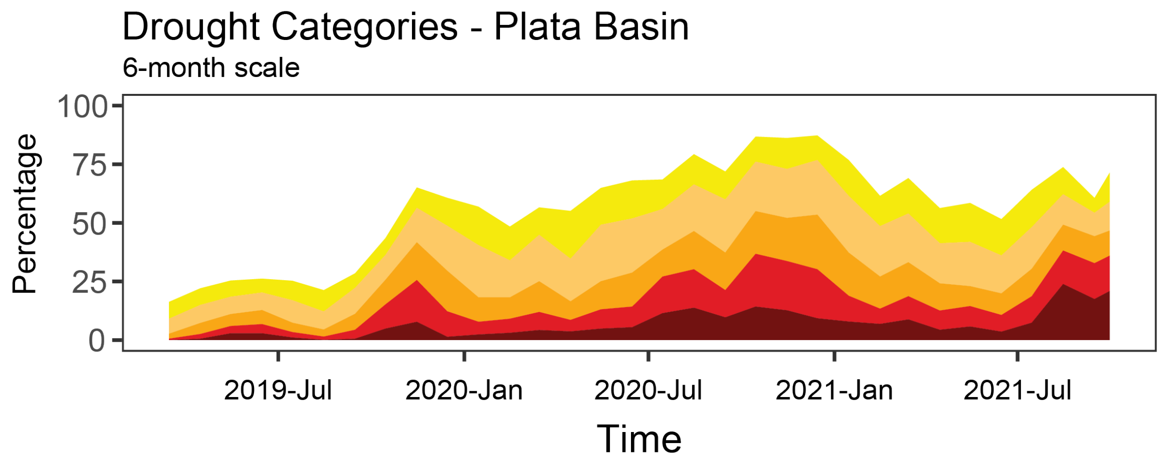


Figure 6. Percentage of area in the LPB under each of the five drought categories used in Fig. 5, according to the SPI-6 from March 2019 to September 2021. The areas were derived from CHIRPS precipitation anomalies. For scale and colours please see Fig. 5. Source: SISSA

The area affected by drought and consequently the population and the assets exposed has more than doubled since mid-2019. The time series of the proportion of area under each of the five drought categories (Fig. 5) for the LPB is shown in Figure 6. The figure shows that the La Plata Basin has had over half of its area under some drought category (from abnormally dry to exceptional drought) from October 2019 to September 2021. This means that the extended dry conditions have lasted for about two years. The largest spatial extent of dry conditions was reached during the last quarter of 2020, when about three quarters of the large La Plata Basin were under drought (Figure 6).

2.4 Hydrological variables

Precipitation in the LPB in both 2019 and 2020 was among the lowest on record. Precipitation shortage has had significant impacts on the hydrological cycle of the Basin, affecting, e.g., soil moisture and groundwater storage as well as river flows. As for the latter one, precipitation anomalies appear to be amplified: that is, the response to decrease in precipitation translates into a more than proportionally reduced surface and subsurface water flow.

The long-lasting precipitation deficit in the LPB directly translates into soil moisture and total water storage anomalies. The Global Drought Observatory (GDO) soil moisture indicator estimates the root zone water content, which is a direct measure of drought conditions, specifically regarding the difficulty for plants to extract water - which, in turn, limits their ability to produce biomass. The impact of the ongoing LPB drought on soil moisture has been intermittently mitigated by sporadic precipitation during 2020, but being not sufficient to restore the total (ground)water storage, causing the build-up of a clear and persistent negative total water storage anomaly.

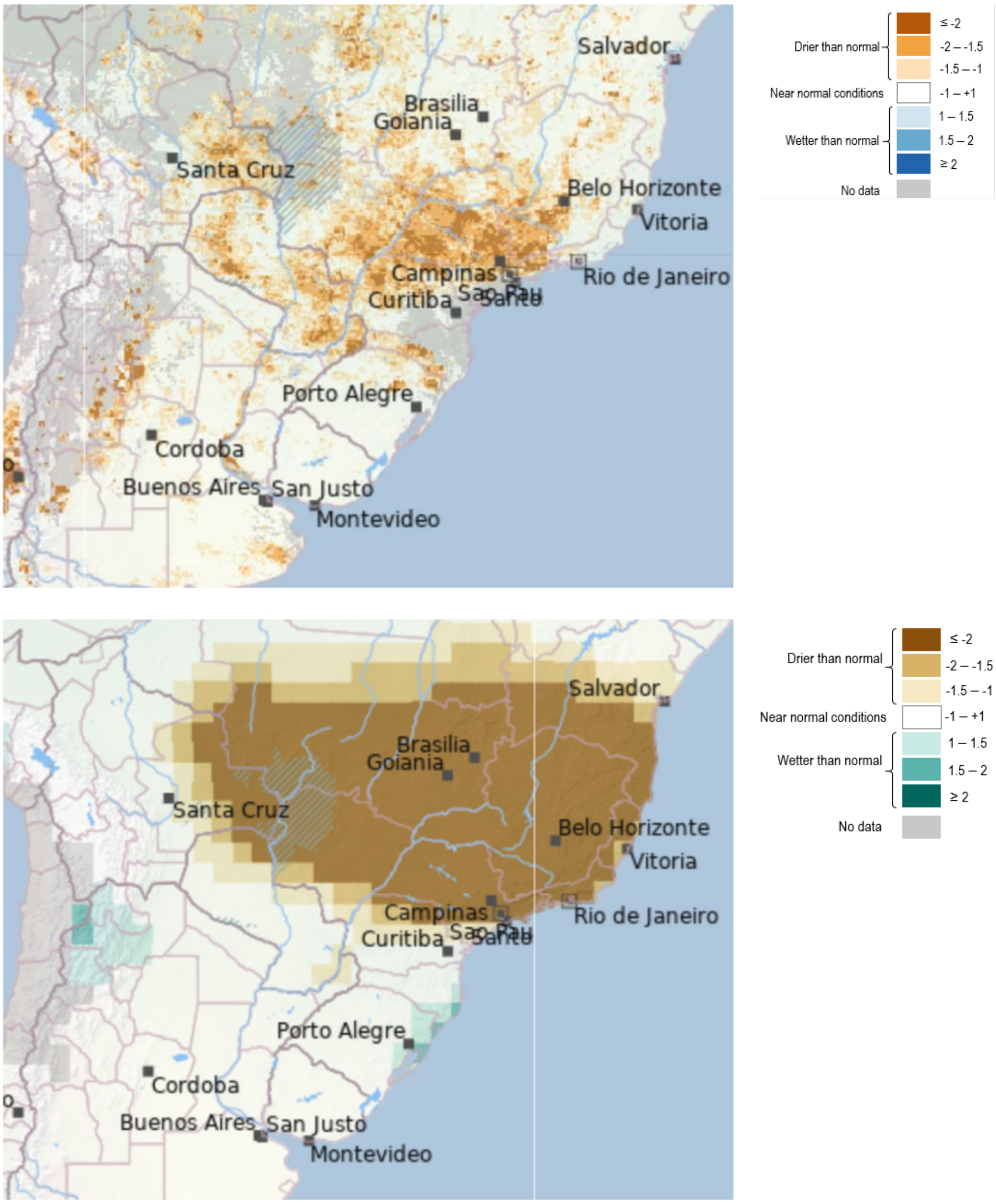


Figure 7. Soil Moisture Anomaly for the first ten-day period of September 2021 (upper panel) and Gravity Recovery and Climate Experiment (GRACE) Total Water Storage (TWS) Anomaly, July 2021 (lower panel).

Soil moisture anomalies at the end of the first 10-day of September 2021 reflect the drier conditions (Figure 7, top panel) in the northern part of the LPB (spreading over Paraguay and Southern Brazil), approximately in the same regions where SPI-6 reached the lowest values (Figure 5). This reinforces the assumption that the main trigger of this drought event is, to a large extent, a mild but persistent lack of precipitation over a prolonged period.

The Total Water Storage (TWS) Anomaly indicator (Figure 7, bottom panel) is used to detect the occurrence of long-term hydrological drought conditions; it is often used as a proxy of groundwater drought. The TWS Anomaly is computed in terms of anomalies of TWS estimated from data collected by the GRACE satellite mission (Landerer and Swenson, 2012). TWS is strongly correlated with the long-term SPI, i.e. 12, 24 and 48 months (Cammalleri et al., 2019). The TWS anomaly represents a reliable indicator of anomalies in groundwater availability and therefore is a useful proxy for anomalies in river flow levels. The TWS anomalies in July 2021 reflect the driest conditions in the northern part of the LPB, at roughly the same areas where the SPI-6 and soil moisture anomalies reached the lowest values.

The Low Flow Index (LFI) exploits the simulated daily river water discharge outputs of the LISFLOOD[8] hydrological model, in order to capture consecutive periods of unusually low streamflow, and compares the consequent water deficit during those periods with the historical climatological conditions, in order to derive the severity of the events. During the first 10 days of September 2021, the LFI is largely following the trend in soil moisture and groundwater conditions in the LPB, as expected (Figure 8). There are strong deficits in the upper eastern part of the basin, and close to the outlet[9] of the LPB. Areas where the low-flow index cannot be reliably computed (mainly in the central part of the LPB) due to inconsistencies between near-real time and historical data are masked in grey (Cammalleri et al., 2020).

Other local information sources, however, point to large deficit in the central part of the LPB. A report by Argentine "*Instituto Nacional del Agua*" (INA)[10] describes the conditions during the first week of September 2021. This report highlights that low streamflow values for the Paraná and Paraguay rivers confirm the drought condition affecting the northern and middle half of the LPB. In the Paraná-Paraguay confluence section, river levels remained in gradual decline during the first half of August 2021. The Paraná flow off Corrientes and Rosario in August 2021 was less than half the average value for that month calculated by using the last 25 years.

Figure 8. Low-Flow Index (LFI) for the first ten-day period of September 2021. A Low Flow Index of 0 corresponds to no drought and a value of 1 to the highest drought hazard.

Discharge of the Paraná River has been impacted, with values far below average. According to the Standardized Streamflow Index (SSFI) at time scales of 12- and 24-months, the Emborcação (Paranaíba River Basin) and Furnas (Grande River Basin) hydropower plants (HPP), located in the Northeast of the Parana River Basin (Figure 9) have been facing a hydrological drought since 2014,

8 https://publications.jrc.ec.europa.eu/repository/handle/JRC78917

9 A river mouth or outlet is the part of a river where the river debouches into a larger body of water, such as another river, a lake or reservoir, a sea, or an ocean

10 https://www.ina.gob.ar/archivos/alerta/Escenario2021_Septiembre.pdf

classified as severe (SSFI < -1.3) and exceptional (SSFI < -2.0). Since February 2019, the Jurumirim (Paranapanema River Basin) and Foz do Areia (Iguazu River Basin) HPPs have been under hydrological drought condition, classified between severe and exceptional. Currently, the HPP Jurumirim remains in the most critical conditions (SSFI-12 = -2.7 and SSFI-24=-3.1). The inflow at the Itaipu HPP has been facing a hydrological drought since April 2019 and has been in “exceptional” drought conditions since December 2020 (SSFI < -2.0). Overall, the current hydrological drought is the most severe since at least January 1981.

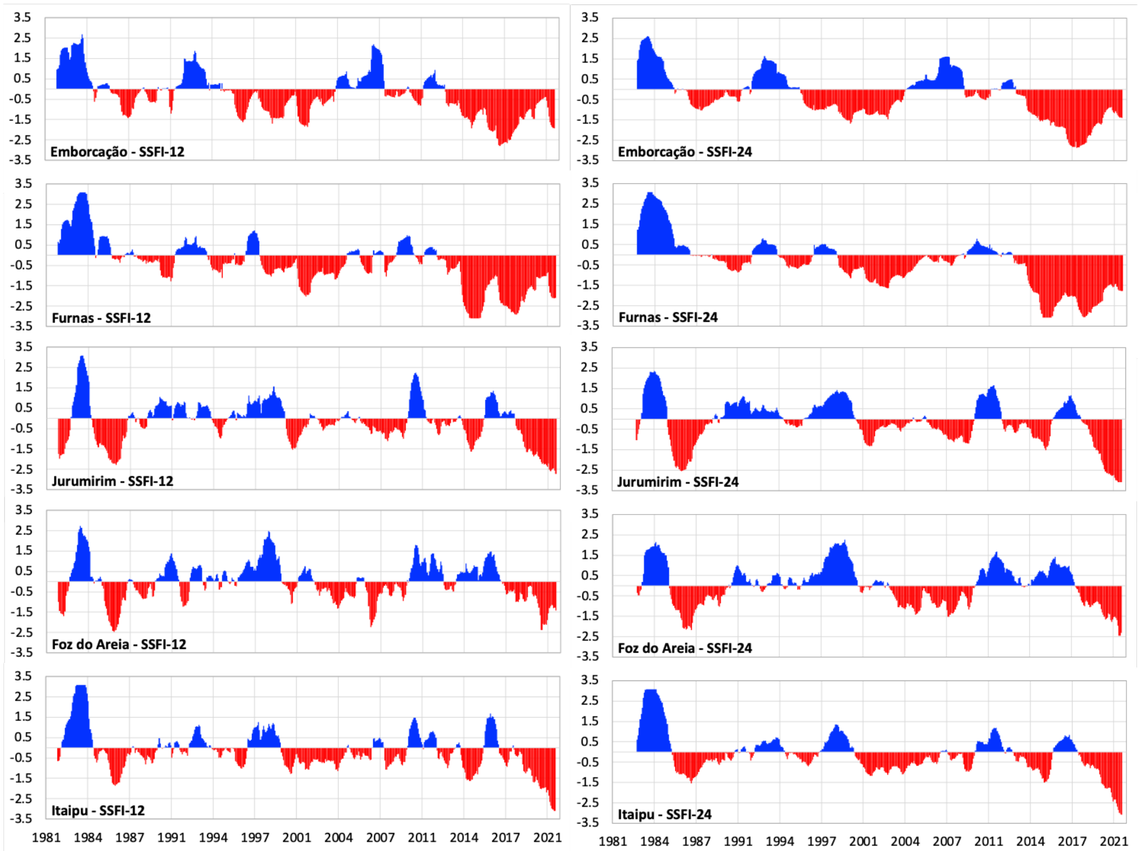


Figure 9. Standardized Streamflow Index (SSFI) at time scales of 12- (left panel) and 24-months (right panel), for the HPP sub-basins of Emborcação, Furnas, Jurumirim, Foz do Areia and Itaipu. (Source: CEMADEN).

In the Paraná river basin outlet section, the extreme value of the low flow index clearly illustrates the severe drought condition of the whole basin and gives the magnitude of the event[11]. The flow into the Paraná Delta (near its entry to the Río de la Plata Estuary) has recorded a downward trend throughout the whole month of August 2021. The flow observed in this section has been 7,000 m^3 s^{-1}, well below pre 2019 conditions. Given the low Paraná levels, the whole Delta is highly dependent on the oscillations coming from the estuary.

2.5 Vegetation response

The fraction of Absorbed Photosynthetically Active Radiation (fAPAR, a satellite-based GDO indicator) is an indicator of anomaly, used to detect and monitor the impacts on vegetation growth and

11 This index is officially provided and distribute at present only for Europe (European Drought Observatory https://edo.jrc.ec.europa.eu), but, in principle, it is based on the same algorithm and it is going to be implemented at a global scale.

productivity from environmental stress factors, especially plant water stress due to drought. This indicator represents the fraction of the solar energy absorbed by vegetation. fAPAR anomalies, specifically the negative deviations from the long-term average over the same period, are a good indicator of drought impact on vegetation. During the second 10 days of September 2021 and in accordance with the other drought indicators, a significant impact on vegetation photosynthetic activity is detected in the upper LPB (Figure 10).

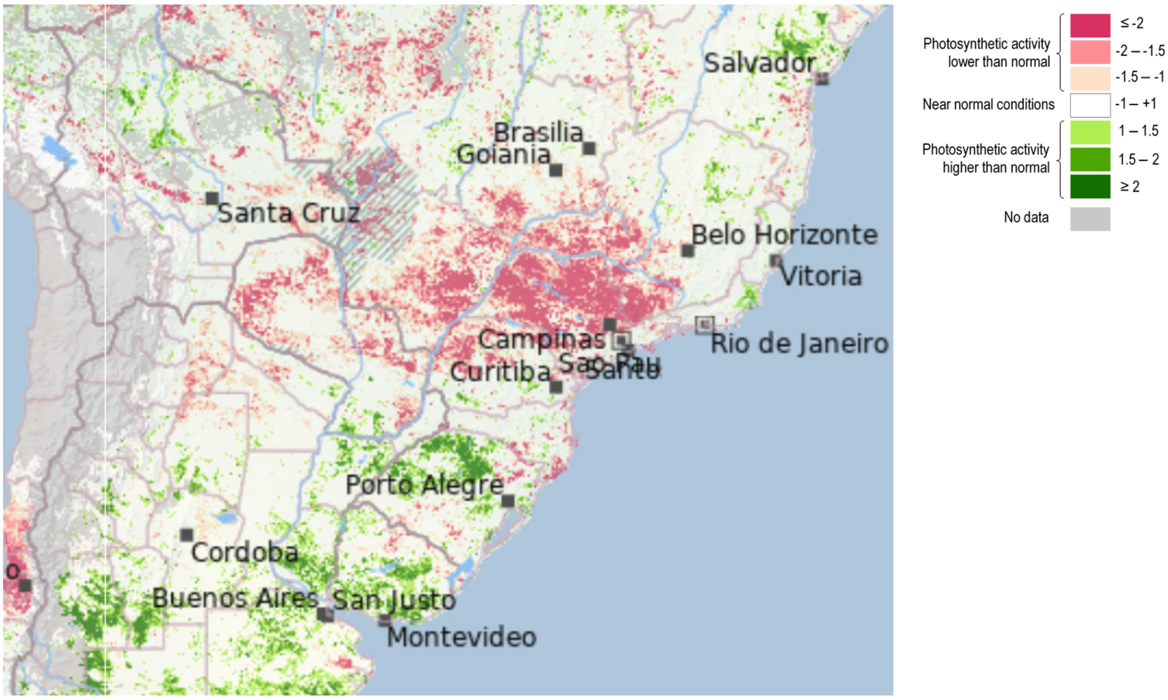


Figure 10. Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) anomalies for the second 10-day period of September 2021. fAPAR anomalies represent the impact on vegetation growth and productivity of environmental stress, especially plant water stress due to the ongoing drought.

3 Causes of the recent drought

3.1 El Niño-Southern Oscillation phenomenon (ENSO)

The El Niño-Southern Oscillation phenomenon (ENSO) is the major single source of interannual climate fluctuations in many parts of the world (Cai et al., 2020; Davey et al., 2014). The climate of most of South America is closely linked with El Niño/La Niña – the extreme phases of the ENSO phenomenon, which is historically described as anomalous sea surface temperatures in the equatorial Pacific (Cai et al., 2020). ENSO-related changes in the atmospheric circulation over South America influence transport of tropical moisture into the extra-tropics. This modulation of the low-level jet east of the Andes either favours or suppresses the occurrence of extreme precipitation events (Mo and Berbery, 2011). Consequently, there are clear links between ENSO and precipitation in the LPB during spring/summer (a critical period for rainfed summer crops). El Niño events generally are associated with higher median precipitation in the LPB, whereas La Niña events show markedly lower median rainfall and a narrower dispersion of anomalies (Cai et al., 2020; Davey et al., 2014; Prieto, 2007). ENSO also influences the frequency of extreme precipitation events that had dramatic socio-economic impacts in the past (Grimm and Tedeschi, 2009; Prieto, 2007). Other processes influencing the climate of the LPB include: humidity transport from the Amazon Forest towards the east, from the Atlantic Ocean; the displacement of the Inter-Tropical Convergence Zone (ITCZ); the South American Low-Level Jets; the strength and the variability of the subtropical Bolivian High; the Antarctic circulation variability.

Throughout South America, precipitation and temperature show a substantial, but regionally diverse, association with the ENSO. In the upper LPB, the ENSO signal in the interannual variability is not as well defined as in the lower basin, as this region lies in the transition band between opposing impacts of ENSO (Coelho et al., 2002). Nevertheless, a recent study of the Paraná Basin by (Santos et al., 2021) found that most events considered as extremely dry in the upper portion of the basin were associated with La Niña events. In most parts of the LPB, La Niña is often accompanied by drought, leading to particularly negative impacts in southern Brazil, north-eastern Argentina, Paraguay and Uruguay. The close association between La Niña events and dry conditions throughout the LPB is of high concern, as recent observations and seasonal forecasts suggest that La Niña conditions may be back again in October-November and lasting till the southern hemisphere autumn of 2022, thus potentially delaying the return to normal conditions, including river flows, in the LPB (Figure 11 and Box 2).

Due to its spatial extent, especially towards the south, the LPB has different climatic regimes. The upper-basin region, located in tropical latitudes in central Brazil, has a monsoon climate with a marked rainy season that spans from November to March and a dry season that occurs from May to September. In general, this region has been experiencing a gradual decrease in rainfall during recent decades (Cunha et al., 2019). Such decrease has affected the level of reservoirs in the region, especially in the last decade.

In addition to the interannual signal, the LPB also has shown marked decadal climate variability (Boulanger et al., 2016; Cavalcanti et al., 2015; Seager et al., 2010). Precipitation trends in this region have been among the largest observed in the 20th century (Cavalcanti et al., 2015). An increase in annual precipitation (particularly in spring-summer) has been observed since the 1970s over most of central-eastern Argentina (Haylock et al., 2006; Jacques-Coper and Garreaud, 2015). However, in this area there is evidence of reversals in trends in the drought-affected area around the 1990s, from decreasing trends during the early period to increasing trends during the recent years (Rivera and Penalba, 2014). A comprehensive analysis of the variability at decadal scale. encompassing multiple rainfall regimes of the LPB (Grimm, 2011) and over the entire year is needed, especially in the light of the forthcoming climate services focusing on multi-annual climate predictions.

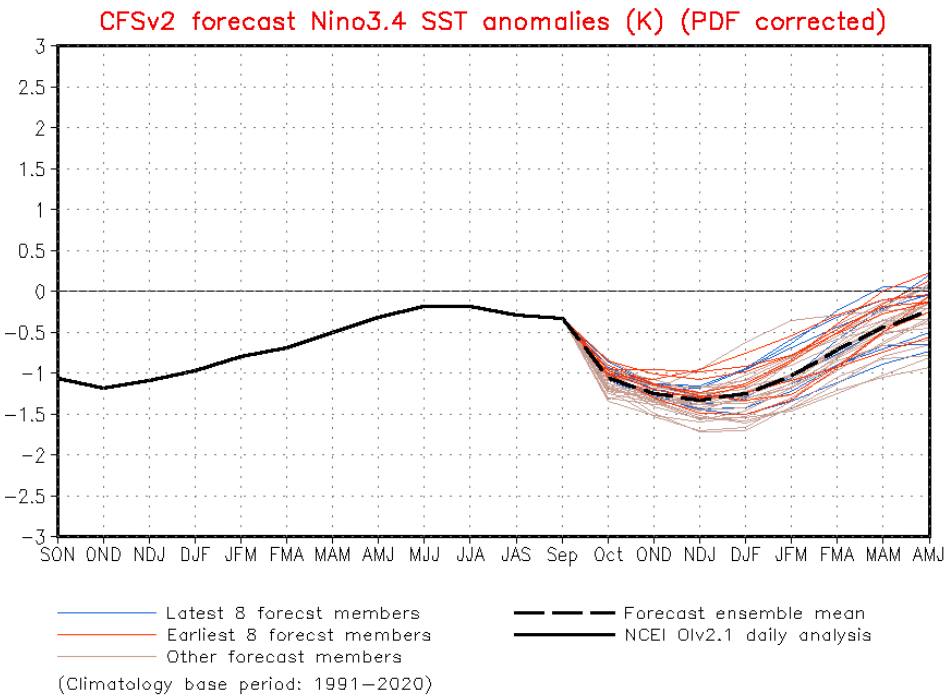


Figure 11. Sea surface temperature (SST) anomaly plume issued on 6 October 2021. The black solid line shows the recent observed anomalies, and the red and blue lines show the GFS.V2 ensemble model-predicted SST anomalies in the regions of the NIÑO3.4 region (5N-5S, 170W-120W). The dashed black line shows the ensemble mean. The anomalies are shown with respect to the 1991-2020 climate. Source: NOAA.

The influence of the Southern Meridional Mode (SAM) in the drought events affecting the Parana River in Argentina has been observed with the severe events during the '40s, '60s, late '80s and the recent ones in 2011 and 2013 (Díaz et al., 2018). The SAM also known as the Antarctic Oscillation (AAO) describes the north-south movement of the westerly wind belt that circles Antarctica, dominating the middle to higher latitudes of the southern hemisphere. The influence of La Niña has been observed in drought events during the '50s and '60s (severe due to their long duration), and during 1988-1989, 1993-1995, 2002-2004 and 2011-2013. The influence of the sea surface temperatures over the Tropical South Atlantic has been noted during drought events occurring in 1962-1971 and precede the 1988-1990 and 2005-2010 droughts. Since 1950, these droughts were the longest identified to date (Díaz et al., 2018).

3.2 Land use change and deforestation

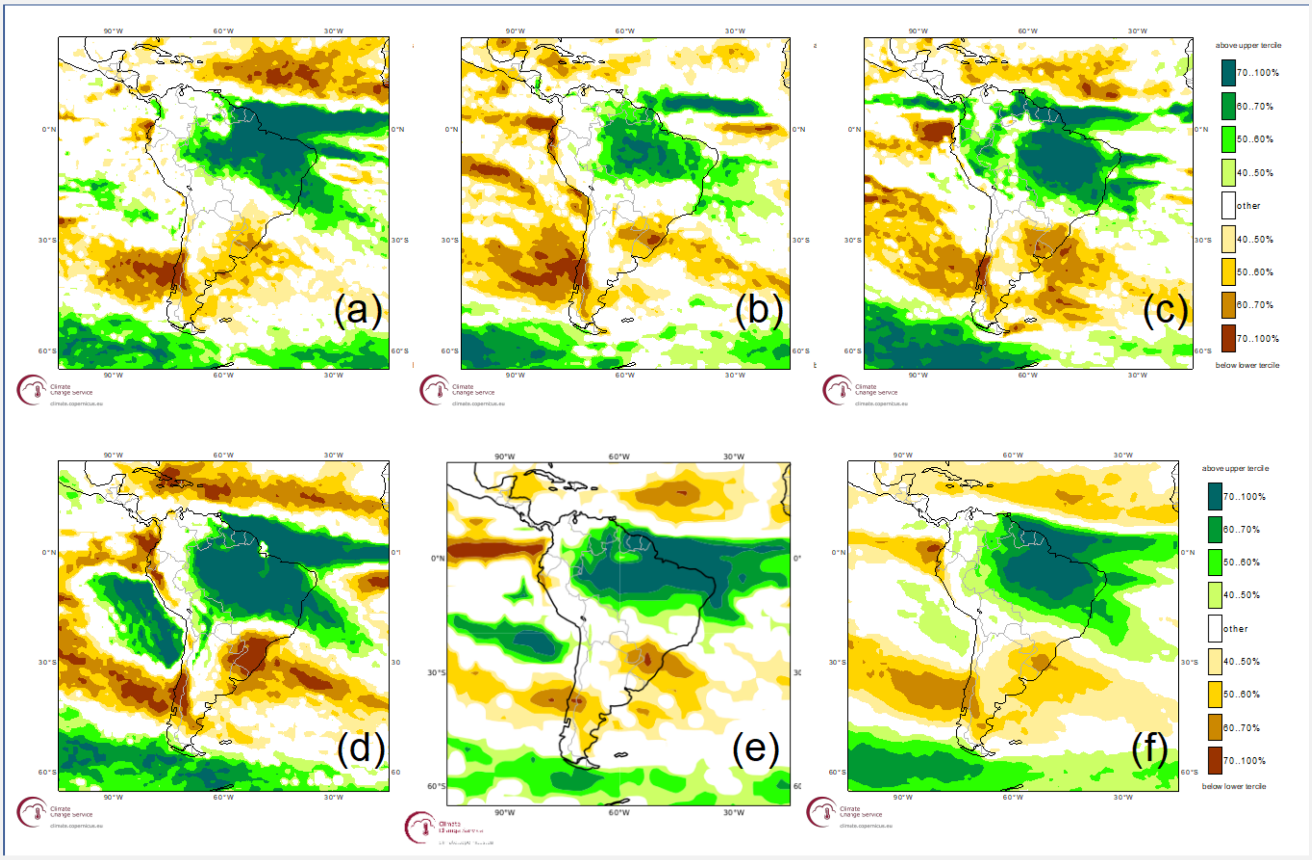
Earlier rainfall-runoff studies in LPB found that climate has a more dominant effect on streamflow that land use (Collischonn et al., 2001; Tucci, 2003). At the sub-basin scales climate is also the main driver of streamflow variations, however also, land use has effects on the hydrological response of the basins (Saurral et al., 2008). Studies conducted in the Upper Grande River Basin, Minas Gerais State, Brazil, showed that conversion of forest into pasture led to an increase in total runoff and peak flow and a decrease in the base flow and evapotranspiration (Oliveira et al., 2018).

Box 2. Precipitation Outlook

On average, the rainy cycle in the LPB starts gradually, with precipitation first being observed in the second half of September. Nevertheless, the transition to the rainy season occurs in mid-October. At present, it is difficult to forecast the onset and intensity of the rainy season. The behaviour of convection in north-western South America does not present a clear signal and it is not possible to predict with high certainty the onset of the seasonal precipitation beyond climatological information. However, it should be noted that there is no clear association between the start date of the rainy season and the total rainfall recorded during the wettest months.

At present, most seasonal precipitation forecasts from global model ensembles and the WMO regional CRC-SAS consensus outlook indicate a scenario of deficit rainfall in the middle and lower portion of the LPB (Figure below).

In summary, in the headwater areas of the Paraná River basin, under normal conditions the most abundant rainfall should only occur after mid-October. However, due to the low soil moisture resulting from the dry season and lower than average rainfall during the rainy season in recent years, rainfall will take a while to make significant contribution to river flow and reservoir storage. Furthermore, the likelihood of a La Niña event developing during the last months of 2021, may affect rainfall in the middle and lower portions of the LPB. As a result, the most likely scenario for the next three months is the continuation of the drought situation, both from a rainfall and hydrological points of view.



Climate forecasts for October-December 2021 precipitation in South America from various sources. (a) ECMWF, (b) NCEP, (c) Met Office, (d) DWD, (e) JMA and (f) C3S Multisystem seasonal forecast. In all panels brown/yellow (green) areas correspond to below (above) normal precipitation. Probabilities are estimated by comparing the forecast probability density function (PDF) with the corresponding model climate PDF, estimated from the hindcast set. The probabilities are stratified according to: the median, the lower/upper/middle third, and lowest/highest 20% of the model climate distribution. As an overview to the seasonal forecast, a summary plot is presented for tercile categories, which shows in a single figure the areas which have an increased probability (exceeding 40%) of being either below the lower tercile or above the upper tercile.

Sources: C3S, https://climate.copernicus.eu/charts/c3s_seasonal/ and CRC-SAS https://www.crc-sas.org/en/perspectivas_climaticas.php.

Effects of land use on streamflow however are well known at global level, increasing peak flows and decreasing base flows. The role of vegetation cover, floodplains and wetlands is to store and retard runoff, an effect that, to a certain extent, counteracts the consequences of droughts. Therefore, the effect of the current drought is exacerbated with land use changes, such as deforestation and intensive agriculture, which are most likely happening in LPB.

These land use changes have characterised the three major sub-basins of the LPB: Paraguay, Paraná and Uruguay in the last decades. Agricultural expansion from 1960 onwards, particularly in Brazil, has left some areas with only 5% of its original forest cover (FAO, 2016). In the Brazilian state of São Paulo, the area of primary forest has decreased from 58% to 8% at the end of the 20th century. Similarly, in eastern Paraguay the forest area has fallen from 55% in 1945 to only 15% in 1990 (FAO, 2016).

The effects of dams in the river system are also visible in the LPB. In the Upper Paraguay River basin, the number of dams upstream of the Pantanal have more than doubled over the last twenty years, significantly affecting the frequency and duration of high and low pulses (Ely et al., 2020). At a larger scale, data acquired before and after construction of Porto Primavera Dam in the upper Parana River showed changes in water discharge, bank erosion, flood pulse and other variables (Stevaux et al., 2009).

4 Historical drought events in the LPB

Since the 1960s, seven droughts (1977, 1984, 1990, 1992, 2001, 2012 and 2014) have reduced reservoir storage supplies for São Paulo state in Brazil (Coelho et al., 2016). In some parts of the LPB, such as the Upper Paraná River Basin, severe-to-exceptional hydrological drought conditions have been present since 2014. Nevertheless, in the last two years this situation has worsened.

As shown by the Standardized Precipitation Index (SPI) at both 12- and 24-month scales (Figure 12), precipitation in the Paraná River basin has been below average in recent years. The SPI time series show several dry and rainy cycles over since the early 1900s, with the most severe drought recorded from December 1968 to September 1971, peaking in March 1969. However, it is important to note that, at that time the water demand throughout the Paraná River basin was much lower than at present. By looking at the SPI-24 in the last 22 years, below-average conditions have predominated, with short exceptions in 2010 and 2015. Since the end of 2019, drought conditions have intensified, ranging from severe (SPI < -1.3) to exceptional (SPI < -2.0).

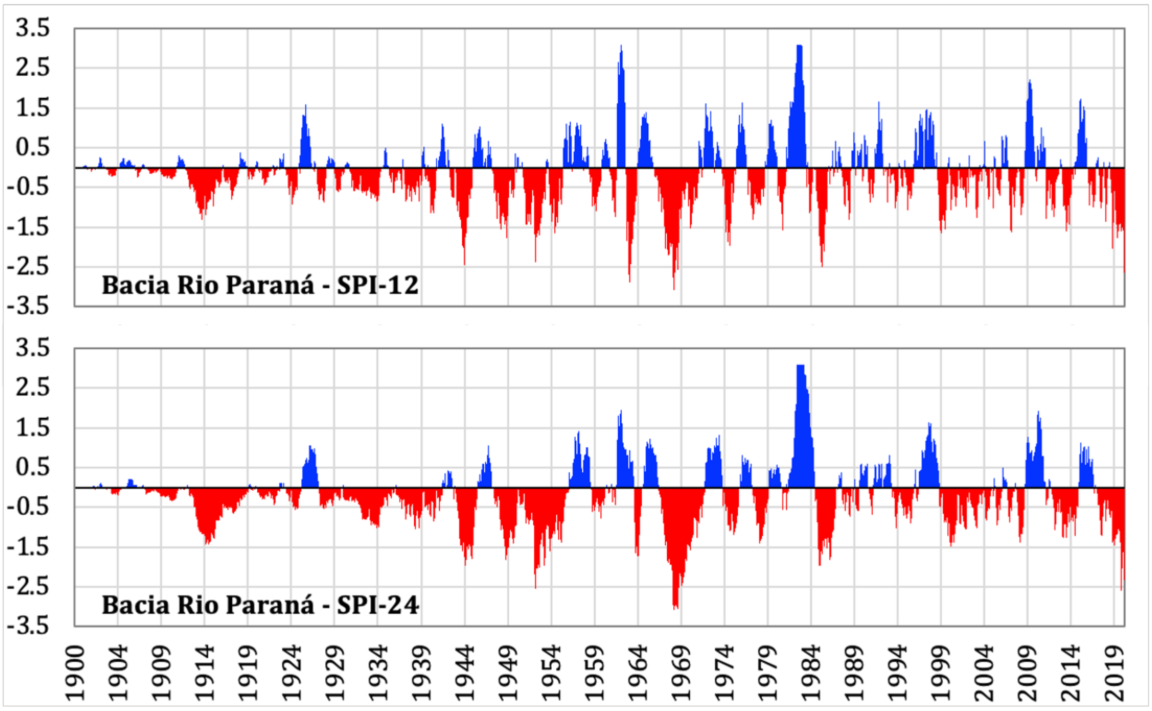


Figure 12. Time series of SPI-12 and SPI-24 calculated using rainfall estimated by the Global Precipitation Climatology Center for the Paraná River basin from 1900 to 2021. (Source: CEMADEN)

The long-term SPI analysis outlines a severe worsening of the dry conditions in the last two-three years which confirms that this drought event has been slowly building up since at least 2019 and its long duration is the main reason of its severity (Cunha et al., 2019; Leal Filho et al., 2021; Libonati et al., 2020).

Figure 13 shows the hydrometric level of the Paraná River off Corrientes for some selected years during the 20th century, upstream of the important Greater Rosario grain processing and shipping cluster. The temporal evolution of the daily Paraná hydrometric level update until August 2021 (dashed black line) and for the five years having the lowest historical levels (solid lines) is shown in Figure 13. The severity of the current low-level event is evident, and its evolution is comparable to the one experienced during the two most severe low-level events in recorded history, i.e. 1934 and 1944. Furthermore, the previous patterns show that the minimum levels off Corrientes historically have occurred between September and November, therefore a few weeks remain from the time of writing (early October 2021) until Paraná levels may start recovering.

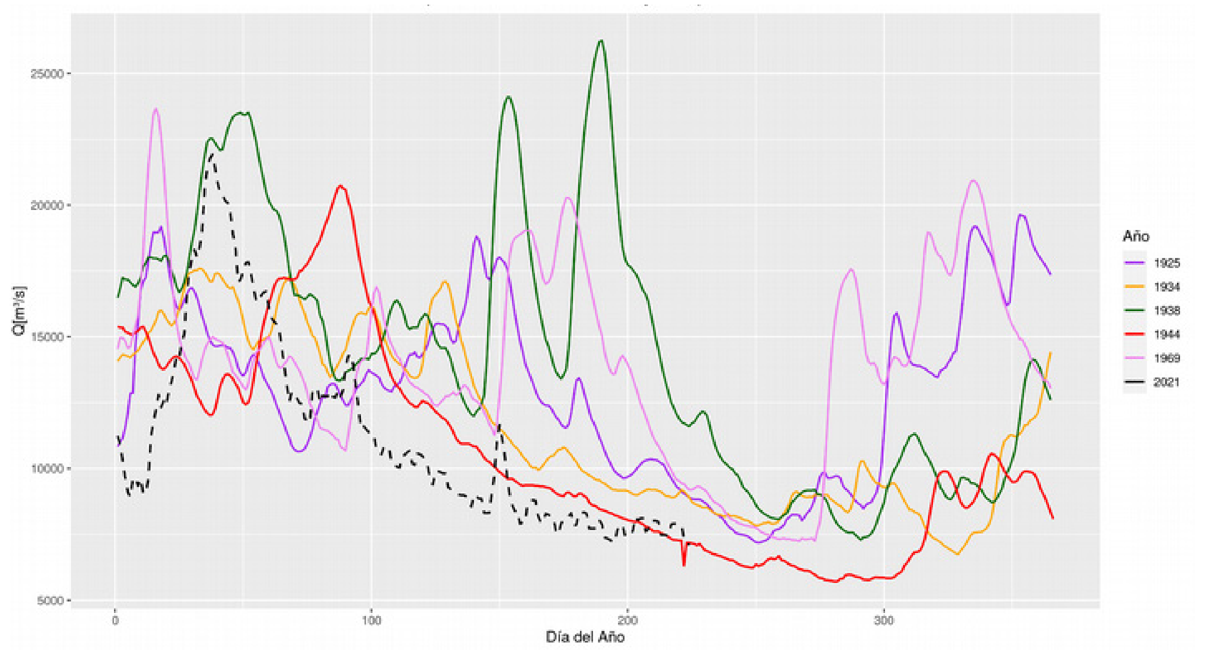


Figure 13. Comparative annual evolution of the daily hydrometric levels of the Parana river off Corrientes, Argentina. Time series are shown for 2021 (dashed black line) and for the five most intense low-flow events in the recorded history. Source: INA (2021), published 13 August 2021.

A drought in the southern part of the LPB was identified by Abelen et al., (2015) and Lovino et al., (2018) during the strong La Niña event of 2008/2009. This drought has been considered as the worst over the past century in Argentina, as it hit the most agriculturally productive region causing a sharp reduction in grain and meat output. According to the Argentine agricultural research institute (INTA), the 2008/09 drought caused a major drop in wheat production, from 16 million tons in the preceding harvest to around eight million after the dry event.

A much stronger La Niña event occurred in 1999/2000 that was associated with a major drought in the LPB. However, the magnitude of this event (at least in the lower LPB) appears to be less significant than the ongoing drought as suggested by precipitation data. This indicates that other factors (besides La Niña) played an important role (Chen et al., 2010). The severe drought in 2011–2012 caused economic losses of USD 2.5 billion in the production of soybean and corn in Argentina (Naumann et al., 2019).

Another major drought occurred in late 2017-early 2018 in the Pampas of central-eastern Argentina, the southern portion of the LPB. This drought was linked to a weak La Niña event, as well as to other intraseasonal modes of atmospheric variability (Bert et al., 2021). Several locations in the Pampas showed historical minimum precipitation values during this event. Lack of rainfall was compounded by high temperatures and heat waves during early 2018. This drought had large impacts on production of summer crops such as maize and soybean. When propagated throughout Argentine economy, crop losses (about 1550 M USD) had an overall impact three times higher (about 4600 M USD). Conservative estimates suggest that Argentine GNP decreased at least 0.8% due to this drought (Bert et al., 2021).

To compare the ongoing drought with previous events occurring in the same region, historical time series of two well-known drought indicators, i.e., the SPI and the SPEI (which also makes indirectly use of temperature and thus includes the effects of warming) were examined. Both indicators were computed at 3-month and 12-month accumulation scales. We used the same approach described in Spinoni et al., (2019) which resulted in the creation of the global meteorological database of drought events hosted by the European Commission's Global Drought Observatory[12]. This database had been updated through 2016 and it classifies drought events which can be considered to have finished from a meteorological point of view. We have performed new analyses that now extend the database to 2021 and adapted the classification system in order to fit events that have not concluded yet. Regarding the extension of the approach, we used both GPCC and ERA5 data[13].

The Paraná River Basin encompasses more than one country but, according to the new macro-regions officially included in the latest IPCC-AR6 report (IPCC, 2021; Iturbide et al., 2020), we selected the South-Eastern South America as the target of our retrospective analyses. As mentioned before, one historical drought event stands out when considering both precipitation (SPI) and temperature (SPEI) as indicators, namely the event that began in the late 1960s (1967 or 1968) and lasted until 1971 (or 1972 in some areas). This was the only event in the region that can be classified as "exceptional" from 1950 until 2016. By refining the classification score – now ranging of 1 to 100 instead from 1 to 25 as in the published version of the historical database – the 1967-1972 event shows a value of 60, therefore it can be considered among the twenty most severe events at global scale since 1950.

The ongoing 2019-2021 LPB drought has not yet reached the status of exceptional (score above 58), but it is very close (score: 55) to that status and can be already ranked among the top five dry events in South-Eastern South America since the 1950s. Most of the parameters included in the classification (severity, intensity, peak) show that the ongoing drought falls behind the 1968-1971 event because of its shorter duration. Nevertheless, the ongoing event is likely to evolve from "very severe" to "exceptional" if the precipitation stays below the normal values for another three to six months and if the temperature does increase above normal during that period.

Over Paraguay, three historical meteorological drought events stand out the one in 1968-1971 and two later events, namely one in 1978-1979 and one in 2008-2010. The latter peaking in 2009, when an extreme drought also hit Argentina and southern Brazil. Looking at the ongoing drought event, the country-based score for Paraguay is now around 50 (very severe), in the same range of the 2009 event (score: 49) and behind the 1968-1971 (score: 53). Furthermore, high scores are also found in Uruguay, thus confirming that the event in the Paraná River basin discussed in this report can be taken already as one of the most severe in the last seventy years also at country scale.

12 https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2020
13 https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

5 Reported impacts of the ongoing drought

Prolonged drought events can affect large areas and population, with wide-ranging impacts on society, economic activities, and the environment. These impacts can be direct and indirect in nature and are often difficult to quantify in economic terms. The ongoing drought in the LPB has already had considerable impacts on the structure and functioning of natural ecosystems and has compromised the well-being of important sectors of society. This section presents a collection of the impacts reported and attributed to this event to date. Most of the reports come from recognised media outlets, governmental reports and scientific publications. Since the event is still in progress at the time of writing, total damage estimates and characterisation of all affected sectors can be performed only once the event will be over.

5.1 Drought emergency declaration

Argentina[14], Brazil[15] and Paraguay[16] have declared formal drought emergencies during 2021. On 24 July 2021, the Argentine Government declared a state of water emergency valid for 180 days and encompassing seven provinces with coastlines on the Paraná, Paraguay and Iguazu Rivers. On 8 July 2021, the Government of Paraguay declared a state of emergency for navigation on the Paraná, Paraguay and Apa rivers.

5.2 Ecosystems – Wetlands

As the availability of water in wetlands is reduced during droughts, wet corridors that connect sections of open waters decrease in area and dry, resulting in loss of habitat, soil structure and erosion, organic soil oxidation and carbon release into the atmosphere (Dollar et al., 2013). The extension of wetlands ecosystems in LPB is considerable, covering a continuous area from the Pantanal in the north, to the La Plata Estuary in the south.

The very wide regions of Great Chaco, Pantanal and Paraná basin (northern Argentina, Bolivia, Paraguay, Mato Grosso and Mato Grosso do Sul in Brazil) had intense dryness since austral summer of 2018 (Marengo et al., 2021b), with wide ranging impacts on natural ecosystems, agriculture, transportation and power generation. Since 2019, the Pantanal is suffering a prolonged drought that has spelled disaster for the region, and subsequent fires have engulfed hundreds of thousands of hectares (Marengo et al., 2021b). By December 2020, extreme drought in the Brazilian states of Mato Grosso and Mato Grosso do Sul had affected 4.17 million people (76% of the population of both states). A total of 218 municipalities in this area (almost 100%) were affected by drought..

Further north, the drought has also affected the Pantanal Matogrossense National Park (Mato Grosso, Mato Grosso do Sul, 135,000 ha wide), that is part of the largest, permanent freshwater wetland in the Western Hemisphere. It is situated in a large depression functioning as an inland delta and is probably the most important wetland in South America.

In Argentina, environmental organizations have warned about significant changes in the ecosystems associated with Paraná River shores, with places where the aquatic or marsh vegetation is no longer present. Exposed sandbars and dried wetlands off Rosario emerge from satellite imagery (Figure 14). By May 2021, Argentine authorities announced measures to safeguard river's biodiversity and protect

14 https://www.boletinoficial.gob.ar/detalleAviso/primera/247302/20210726
15 https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/eventos-criticos/salas-deacompanhamento/Paraná/ResolucaoANA771junho2021.pdf
16 https://www.bacn.gov.py/archivos/9613/LEY%206767.pdf

fish species and fauna[17]. In the city of Paraná, the capital of Entre Ríos province, the president of the Paraná Canoeing School has stressed the visual impact on the landscape: the typical postcard of green ravines where people enjoy and exercise with a view of the Paraná River is now a sandy area that allows crossing the river on foot[18]. Important collapses have been reported in islands near the bridge that connects Rosario and Victoria. In different towns of Entre Ríos, vessels have been stranded in dry mud, numerous sandbars came into view, old anchors were exposed, and large fish were stuck in sandbanks. Moreover, municipalities had to work hard to ensure the supply of drinking water. The existing instrumentation was not capable of providing accurate measurements of the extreme situation: The Argentine Coast Guard could not measure the Paraná levels off Victoria and Diamante between April and June 2020, as instruments could not record river heights below one meter[19].

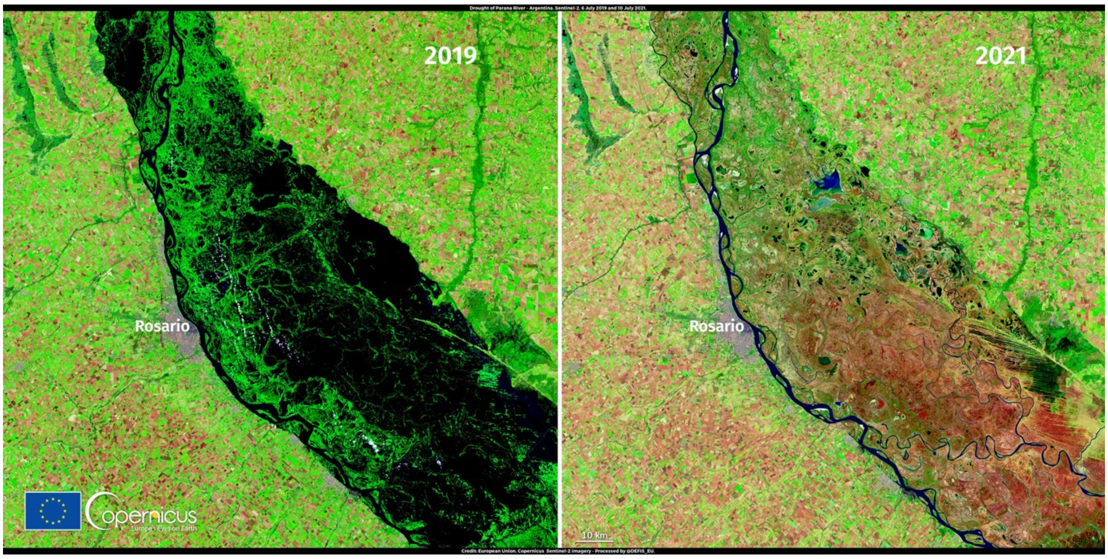


Figure 14. Pair of images acquired by one of the Copernicus Sentinel-2 satellites on 6 July 2019 (left panel) and 10 July 2021 (right panel). The images provide clear evidence of the drought affecting the Paraná River in Argentina, near the port of Rosario. Exposed sandbars and dried wetlands are apparent in the left image. Credit: European Union, Copernicus Sentinel-2 imagery.

The low Paraná waters have also affected the livelihood of artisanal fishing communities that operate along the Paraná River off the Argentine provinces of Santa Fe and Entre Ríos. About 4100 households rely on freshwater fish species such as *sábalo, bagre, boga* and *dorado* for self-consumption, proximity markets or even for export. Export quotas for freshwater fish were reduced to one third of 18,000 tons allowed in 2019[20]. Few fish market stalls have remained open in the district of Bajada Grande. Consequently, the economic impact on households of canoe fishermen has been very high. As the lagoons where the fish reproduce have dried up, the provincial government decreed a ban that does not allow fishing on weekends to protect the nearly 200 species in the river[21,22,23]. Moreover, fishing off Santa Fe was limited to three days a week to protect fish stocks. In addition to the lower

17 https://www.cronica.com.ar/sociedad/Preocupa-la-situacion-del-Parana-el-rio-continua-bajando-en-Entre-Rios-y-se-acerca-a-niveles-historicos-20210804-0099.html
18 https://www.pagina12.com.ar/364519-bajo-el-rio-y-dejo-las-heridas-expuestas
19 https://www.telam.com.ar/notas/202106/557869-bajante-del-parana-ciudades-entrerrianas.html
20 https://www.chacodiapordia.com/2021/08/23/bajante-del-parana-barcos-sin-granos-y-pescadores-sin-peces-mientras-esperan-niveles-mas-bajos/
21 https://ar.radiocut.fm/audiocut/parana-seco-drama-familias-pescador-s-del-litoral-roxana-russo/
22 https://www.pagina12.com.ar/364519-bajo-el-rio-y-dejo-las-heridas-expuestas
23 https://elmercurio.com.mx/internacional/rio-parana-el-segundo-de-america-registra-su-peor-baja-desde-1940

availability of fish, shallow waters in small streams and lagoons result in tangled nets and loss of gear[24].

5.3 Fires

Because of the great amount of dry biomass in the soil and the use of burning as a practice associated with human activities, fires have flourished along the extensive corridor of Paraná River wetlands. The fires have had a marked impact on certain areas of the Paraná Basin, especially its two extremes: the Pantanal **(Figure 15)** and the Paraná Delta.

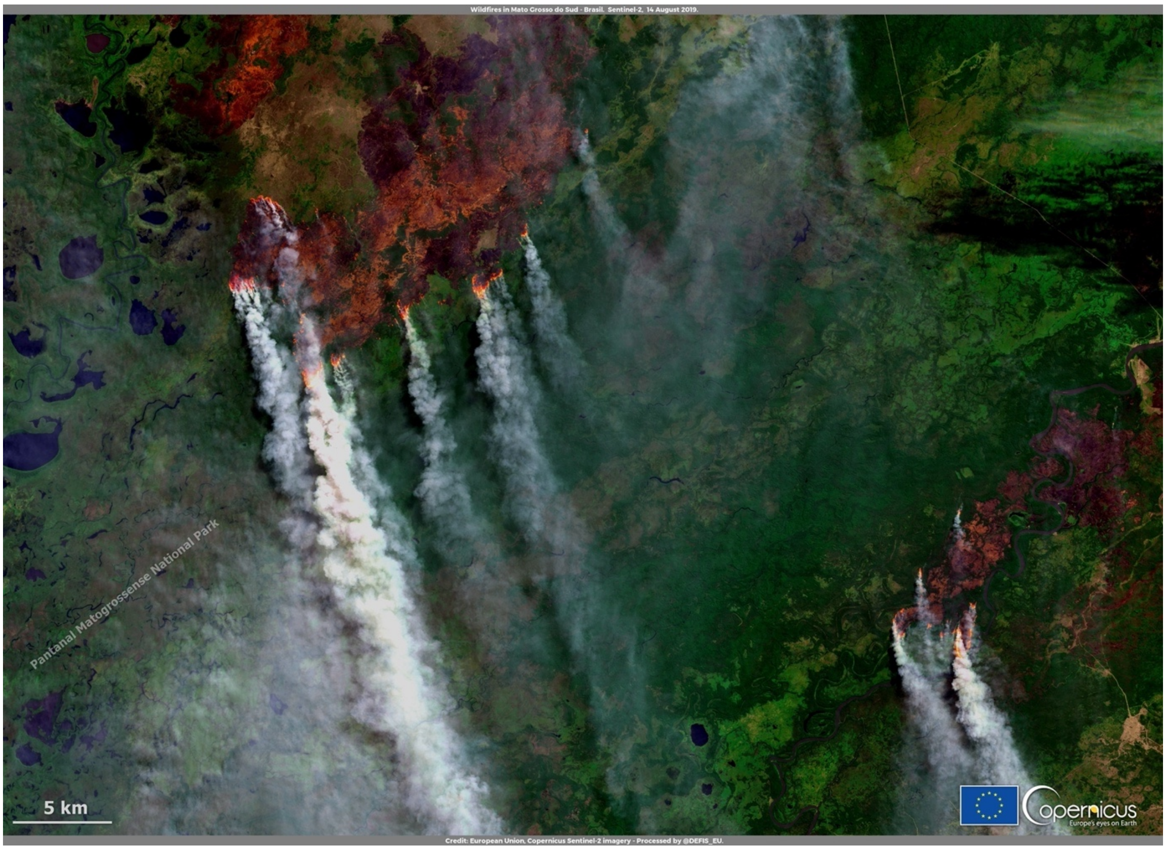


Figure 15. This image, acquired by one of the Copernicus Sentinel-2 satellites on 14 August 2020, shows wildfires in the Pantanal *Matogrossense* National Park (Mato Grosso state). Credit: European Union, Copernicus Sentinel-2 imagery.

In the Pantanal, the Instituto Nacional de Pesquisas Espaciais (INPE – Brazil's Space Research Centre) reported that the overall number of fires increased by 233% during 2020 compared to the previous year. It is not yet possible to estimate the numbers of animals killed by fire, but the loss of wildlife is known to have been significant (Libonati et al., 2020; Li et al., 2020). Fire Brigades have reported on dead tuiuiús, armadillos, sucuris and anteaters, many of them charred. Moreover, there have been reports of animals running over on highways trying to escape the fire, such as quatis, anteaters, alligators and snakes. Couto Garcia et al., (2021) showed that the burnt areas in the Brazilian Pantanal increased by 376% in 2020 compared to the average of 2003-2019; 43 % of the area affected in 2020 had not been previously burnt in 2003-2019. At the beginning of October 2021, the fire hazard

24 https://intainforma.inta.gob.ar/bajante-del-parana-como-afecta-a-la-pesca-artesanal/

still remains as moderate to high in most of the upper LPB (Figure 16), including the Pantanal area in the upper Paraguay basin.

During 2020, Paraguay experienced the simultaneous impacts of the strongest drought in recent years, massive forest fires and the COVID-19 pandemic. Together, these events led to the end of seven consecutive years of economic growth in this country. Indigenous populations in Paraguay (about half of which are concentrated in the north-eastern portion of the country, in the departments of Alto Paraguay, Boquerón and Canindeyú) were disproportionately affected by drought and forest fires[25].

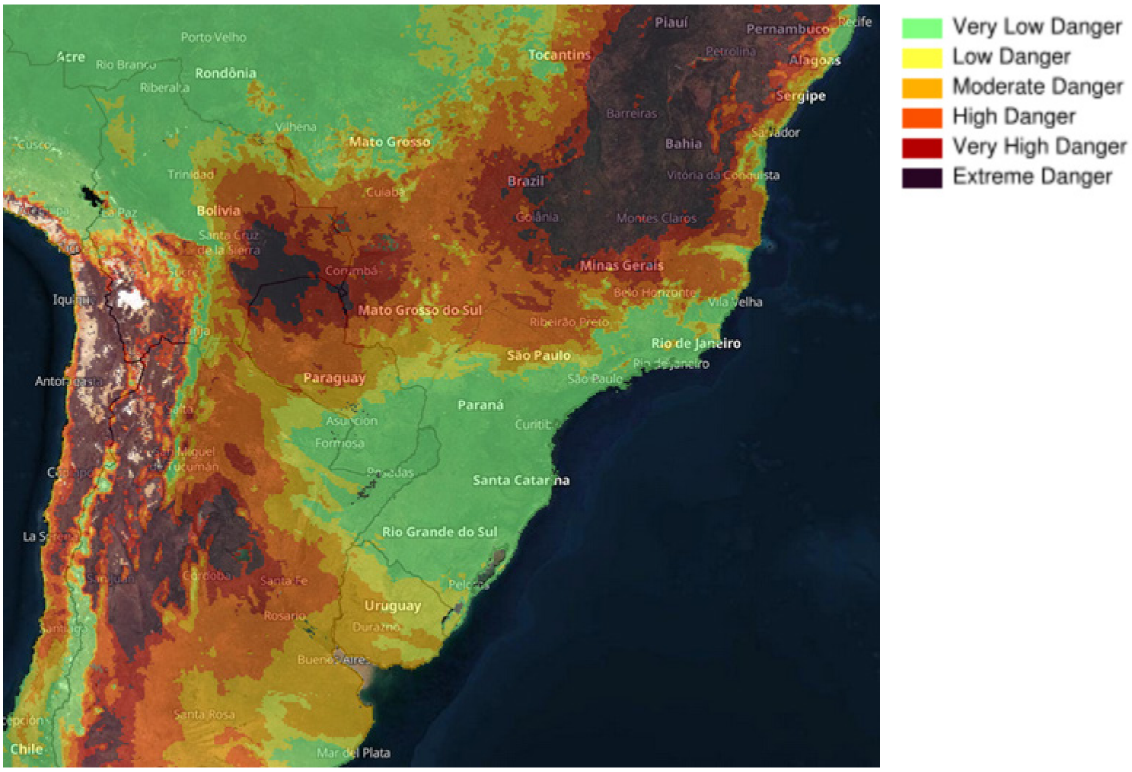


Figure 16. Global Wildfire Information System, GWIS. Fire danger forecast for 6th of October 2021 expressed by the Fire Weather Index issued on the same day. Source: JRC Global Wildfire Information System https://gwis.jrc.ec.europa.eu/apps/gwis_current_situation/**.**

In Argentina the number of fire spots between January and May 2021 included 273 spots detected by the MODIS sensor and 1118 spots for the VIIRS sensor (Suomi-NPP). The month with the highest number of foci was January 2021, with a total of 101 foci detected by MODIS and 444 detected by the VIIRS sensor. A similar number of hot spots were reported in May 2021, with 109 and 376 foci detected by each sensor, respectively. February 2021 had 35 foci identified by MODIS and 192 by VIIRS. Fewer number of fires were registered in the months of March (16 MODIS and 81 VIIRS foci) and April (12 MODIS and 25 VIIRS foci). According to the Regional Museum of Natural Sciences of San Nicolás, Province of Buenos Aires, Argentina, from 2020 to August 2021 more than 700,000 hectares of wetlands have been burned in the Paraná Delta, encompassing about 30 % of this region. River houses and corrals were burned; cities like Villa Constitución were invaded by smoke and ashes. Experts of the Environmental Observatory of the National University of Rosario (UNR) estimated that

25 https://reliefweb.int/updates?search=sequia%20Paraguay

7000 hectares were affected off San Nicolás, another 20,000 between San Pedro and Zárate, adding up to almost 30,000 hectares burnt by the end of August 2021[26].

5.4 Crops, Livestock and Economy

Agricultural production from the LPB plays an important role in supporting global food availability through the export of agricultural commodities. The LPB is not only exporting food, but also "virtual water" embedded in agricultural commodities (Hoekstra and Mekonnen, 2012). In the region, food production comes mostly from rainfed agriculture, where crop yields, and thus food production, depend almost exclusively on sufficient rainfall.

The Risk of Drought Impacts for Agriculture indicator (RDrI-Agri) is implemented in the Global Drought Observatory (GDO) of the Copernicus Emergency Management Service. This indicator is used for determining the area more likely to be affected by drought. The RDrI-Agri is computed as the combination of dynamic layers of drought hazard, exposure and vulnerability. For areas with higher values of this indicator, it is more likely that impacts associated with drought will occur. Therefore, the maps of RDrI-Agri can be used as a precursor of negative impacts caused by 2019-2021 drought. However, due to the complexity of drought propagation throughout the hydrological cycle and different socio-economic sectors, these impacts can develop and be clearly detected with a considerable temporal delay.

The map of RDrI-Agri at the end of the second 10-day period of September 2021 (Figure 17) suggests that the upper portion of the LPB is the main affected area. The RDrI-Agri map shows a large area with moderate risks of impact in the upper LPB, including the Brazilian states of Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais, São Paulo, and Paraná. In the same regions, some areas in the Pantanal and south-western Paraguay has reached a high-risk value.

Paraguay is the fourth world exporter of soybeans and this crop contributes greatly to the country GDP. The drought events of 2009 and 2012 affected also soybean production, contracting the economy and reducing GDP by 4% and 1.2%, respectively[27]. Predictions of soybean production in Paraguay for 2020/21 were reduced from 10 million tons to about 8 million tons. This was due to the lack of rainfall associated with La Niña. Rainfall in Canindeyú and Itapúa departments during September-October of 2020 was about 30% the normal[28]. The lack of rainfall affected the yields of short-cycle soybean, sown at the beginning of 2021. In the department of Alto Paraná, short-cycle soybean was expected to be almost completely lost. A similar decrease in the sown area and yields of short-cycle soybean had been observed during the previous cropping cycle (2019/20)[29].

The Grain Exchange (*Bolsa de Cereales*) of Buenos Aires (Argentina) stated that the production of soybean in the 2020-21 cropping cycle was about 43.5 million tons, about 3 million tons below forecasts. The decrease in production – 11% lower than in 2019/20 – was tied to low rainfall during February and March 2021, critical periods for yield definition of this crop. Nationally averaged soybean yields for Argentina were about 10% lower than the 2019-2020 cycle[30]. The Rosario Stock Exchange (Bolsa de Comercio) estimated that the historic low level of the Paraná could cost the country's grain exporting sector a loss of about 315 million USD in six months (March to August 2021)[31]. Finally, the Argentine agricultural research institute (INTA) has reported that low levels of

26 http://observatorioambiental.org/informe-sobre-el-monitoreo-diario-de-focos-de-incendio-en-el-humedal-correspondiente-al-delta-del-rio-parana-en-los-primeros-5-meses-del-ano-2021/
27 https://reliefweb.int/updates?search=sequia%20Paraguay
28 https://www.hoy.com.py/comercio-e-industrias/dejaran-de-cosechar-al-menos-2-millones-de-toneladas-de-soja-causa-de-la-sequia
29 https://www.lanacion.com.py/negocios/2021/04/21/sequia-afecto-cultivos-de-soja-y-maiz-zafrina-en-varios-departamentos-del-pais/
30 Informe Cierre de Campaña Soja 2020/21/, Instituto de Estudios Económicos, Bolsa de Cereales de Buenos Aires.
31 https://www.ambito.com/informacion-general/rio-parana/piden-poblacion-limitar-consumo-agua-historica-bajante-del-n5227686 1/4 7/26/2021

the Paraná near its junction with the Río de la Plata (at the so-called Delta) has resulted in disruptions in the transportation of cattle raised in small islands and wetlands[32].

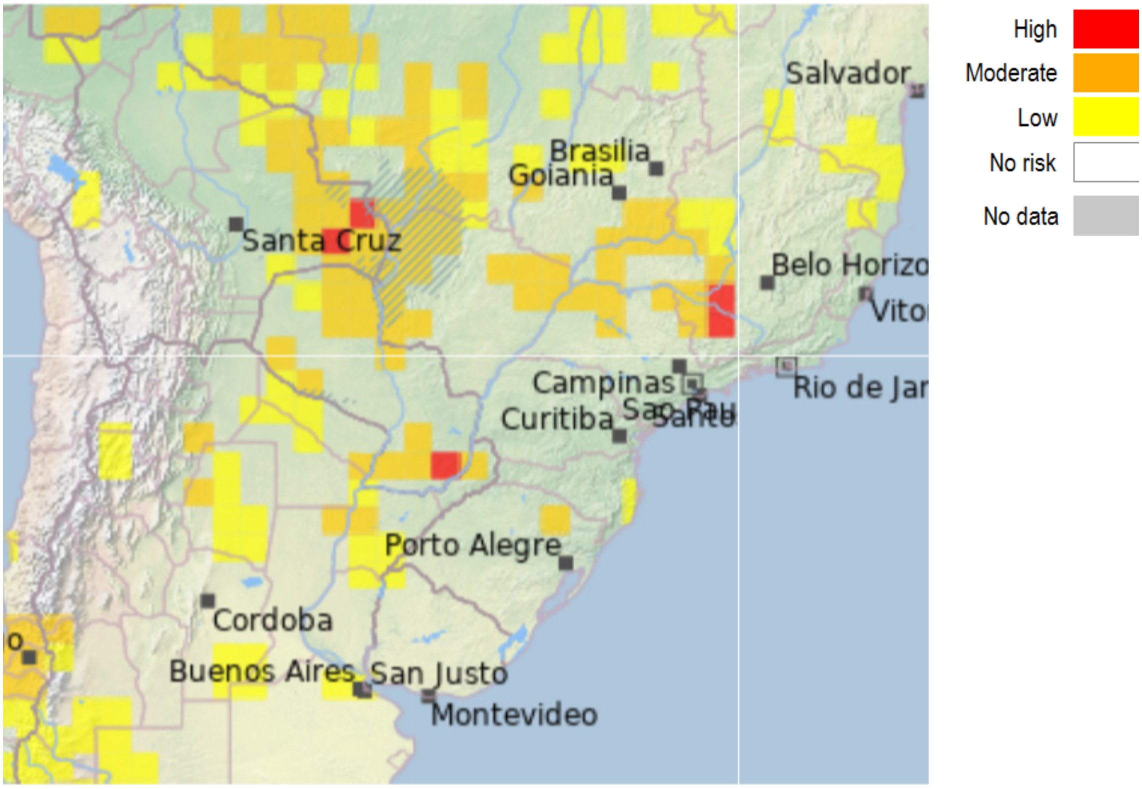


Figure 17. Risk of Drought Impact for Agriculture (RDrI-Agri) for the second 10-day period of September 2021. The RDrI-Agri indicator is computed as the combination of the dynamic layers of drought hazard, exposure and vulnerability. Higher risk means that the areas affected will be the most likely to report impacts due to droughts.

It should be noted, however, that agriculture in LPB is the primarily responsible for the land use changes reported in section 3.2. As mentioned in that section, land use changes brought about by agriculture may be decreasing the soil's moisture storage capacity in LPB, increasing runoff and decreasing base flow.

5.5 Waterway Transportation

Drought has important impacts on waterway transportation of goods in the LPB. The Paraguay-Paraná Waterway (PPW, or “Hidrovía Paraná-Paraguay”) is a major geopolitical component of transportation systems in the LPB, as it provides ocean access to river land-locked Paraguay and Bolivia. The 3400 km PPW joins southern Brazil to the Río de la Plata and the Atlantic Ocean. As many as 4500 barges, tugs and container ships sail up and down the PPW each year, carrying about 102 million tons of freight. The navigability of the PPW, however, is closely tied to the depth (and streamflow) of the Paraná and Paraguay rivers. Large seafaring ships (Panamax class, 36 ft draft) can only reach the Greater Rosario area in Santa Fe, Argentina (km 420 of the waterway). Smaller

32 https://intainforma.inta.gob.ar/bajante-del-parana-como-afecta-a-la-pesca-artesanal/

ships (“handy max”, 28 ft draft) can get further north to the port of Santa Fe (km 590). North of Santa Fe, only inland barge traffic (10 ft draft) is possible.

Decreased levels in the Paraguay River has considerably affected barge traffic. The Center of Fluvial and Maritime Shipowners (*Centro de Armadores Fluviales y Marítimos*) of Paraguay has reported that, due to reduced river levels, barges have had to carry lower loads, thus generating cost overruns. An increase in the number of stranded barges was reported. Despite continuing navigation problems, as of May 2021 3,309,619 tons of soybeans could be exported by Paraguay, about 5% more (or about 165,190 tons) than at the same time in the previous year. An agreement reached among the governments of Argentina, Brazil and Paraguay allowed the Yacyretá Binational Entity (operator of the Yacyretá hydropower plant) to schedule the “Operation Water Window” (*Operativo Ventana de Agua*) that raised the Paraná River to a level of about 1 m during 21-31 May 2021, thus allowing several convoys of barges stranded further north to pass through the power plant’s navigation locks[33]. This agreement allowed grain shipments from high production areas in Paraguay (Alto Paraná, Itapúa) to move south towards ports in the Greater Rosario area.

The so-called “Greater Rosario” or “Up-River” area is a 70-km stretch on the Paraná near the city of Rosario, Province of Santa Fe, Argentina, that encompasses the main soybean processing and export hub in the world, surpassing similar clusters in New Orleans (United States) and Santos (Brazil). The Greater Rosario cluster includes about 20 oilseed processing plants that account for about 80% of the Argentine crushing capacity; 12 of these plants have their own port terminal. In addition to Argentine soybeans, beans from Paraguay, Brazil and Bolivia are routinely transported to the greater Rosario cluster by barge. There, oilseeds can be processed into flour and oil or directly transferred to ocean-going vessels to be exported as beans.

To assess the likely impacts of Paraná River levels on the shipping activity near the Greater Rosario cluster, the temporal evolution of Paraná hydrometric levels near Rosario is shown from December 2019 to August 2021 (Figure 18). The depth of the PPW off the Greater Rosario area decreased rapidly between March and May 2020; a minimum level of 0.08 m was reached on 22 May 2020 (See Figure 18). River levels oscillated between 0.5 and 1.5 m between June 2020 and February 2021, when the level went up to a maximum of 2.88 m on 22 February 2021. Since that time, river levels had decreased continuously, reaching levels below the 0.0 m reference after July 2021. A minimum level of 33 cm below the zero reference was reached on 20 August 2021; the historical average level for this month is about 2.90 m. Unfortunately, at present no increase in PPW levels is expected until at least October 2021 and possibly – because of the predicted La Niña conditions – through the end of the year[34, 35].

The low PPW depth forces ocean freighters leaving greater Rosario to decrease their normal loads. The lost freight capacity, in turn, implies higher costs per load. Normally, a “handy max” ship carries 35,000-40,000 tons; each foot of draft lost by low PPW levels reduces that capacity by 1500-1800 tons. The largest ships that can reach Rosario ports (Panamax-sized, about 235 m long) can carry 60,000 to 75,000 tons of grains. One foot less in the draft of a Panamax freighter means that 2000-2500 tons of grain cannot be loaded. In mid-May 2020, PPW depth off greater Rosario was about 5 feet below its normal value, reducing the load of a Panamax by about 11,000 tons, or the load of about 370 trucks carrying 30 tons each. In addition to reducing ship loads, shallow waterway depths also raise navigational hazards, often restrict operations to daylight hours and increase the frequency of groundings. Furthermore, PPW low flows and depths also create problems on the land side of operations: slower navigation operations disrupt the overall flow of oilseeds and cereals.

33 “Ventana de agua”; operativo en Itaupu para elevar los niveles del Paraná (elabcrural.com). https://elabcrural.com/operativo-ventana-de-agua-en-itaupu-para-elevar-los-niveles-en-el-parana/
34 https://www.telam.com.ar/notas/202108/564834-rio-parana-bajante-grave.html
35 https://www.eldiariocba.com.ar/suplementos-especiales/2021/8/14/crisis-en-el-transporte-de-granos-por-la-bajante-del-rio-parana-52199.html

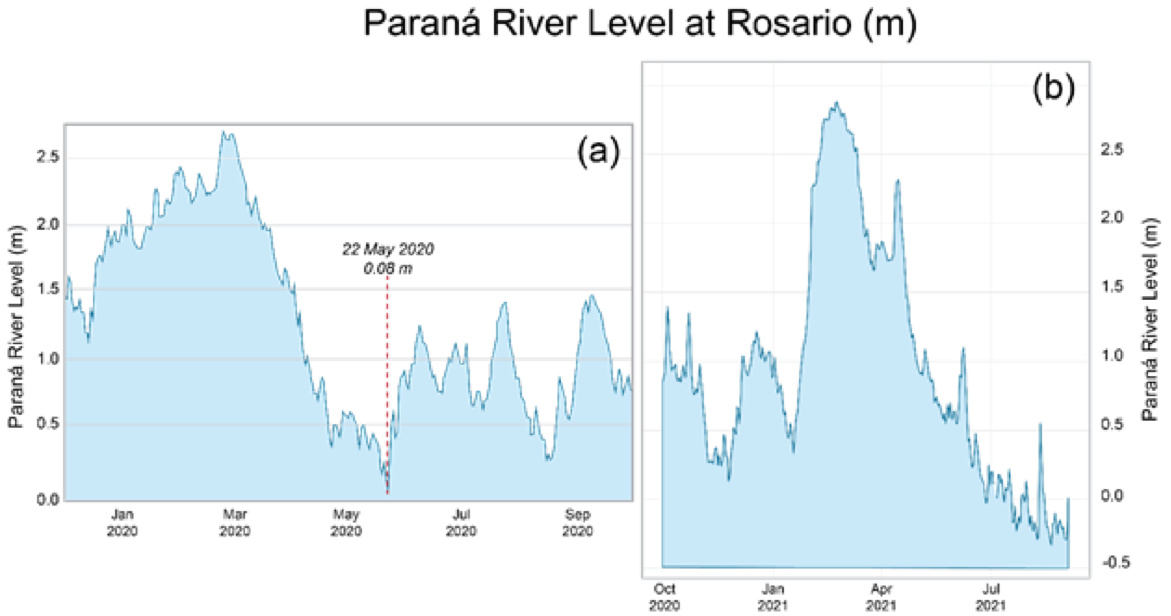


Figure 18. Temporal evolution of Paraná River hydrometric levels near Rosario from December 2019 to August 2021. (a) Adapted from the JRC's 2020 annual report (Barbosa et al., 2021) and (b) produced by using data from Oct 2020-Aug 2021 provided by the Universidad Nacional del Litoral in Santa Fe, Argentina[1]. Note: the scales may not match exactly between both panels.

Despite continuous dredging of the PPW between Rosario and the Plata estuary, Panamax ships loaded with maize typically leave Rosario carrying only about 70-80% of their maximum load and top off their holds at deeper ocean ports in southern Argentina (Quequén or Bahía Blanca) or Brazil. At present, however, ocean freighters can only load 40-50% of their capacity and must fill their holds elsewhere, creating additional costs. For instance, because Quequén or Bahía Blanca are further from core Argentine production regions for soybean and maize, an additional cost of about 30-40 USD per ton of grain is incurred to ship grains there by land. Because of the logistical difficulties in the PPW and the low production of short-cycle maize in Brazil, FOB prices for maize are considerably lower in the Up-River than in Brazilian ports (e.g., the port of Paranaguá): in June 2021 this price differential reached a historical maximum of 48 USD per ton of maize[36]. In 2020, the Rosario Bolsa de Comercio (Board of Trade or BCR for its Spanish acronym) estimated that the aggregate value of all impacts related to low flows and depths of the PPW at about 244 million USD for the first four months of that year. Because the PPW levels were lower during 2021, the BCR estimated cost overruns of about 315 million USD for exports of agricultural commodities for the period March-August 2021, an amount roughly equivalent to 1% of the total value of Argentine agricultural exports[37] [38] [39].

In addition to the economic benefits that the river system provides in terms of transportation, the environmental and hydro-ecological services it provides should be emphasized. This river system is one of the largest free flowing rivers in the world; it represents a unique system of wetlands from the Pantanal in the north of LPB to the Rio de la Plata Estuary in the south. The absence of fragmentation along the main channel and floodplains have preserved longitudinal and lateral connectivity, which provides ecosystem services and associated livelihood (Baigún and Minotti, 2021). As a one of the measures to mitigate the impacts of drought in shipping, many institutions have

36 https://www.bcr.com.ar/es/mercados/investigacion-y-desarrollo/informativo-semanal/noticias-informativo-semanal/la-bajante-4
37 https://www.chacodiapordia.com/2021/08/23/bajante-del-parana-barcos-sin-granos-y-pescadores-sin-peces-mientras-esperan-niveles-mas-bajos/
38 https://bichosdecampo.com/por-suerte-ahora-lo-va-a-dragar-el-estado-la-bajante-historica-del-parana-ya-costo-312-millones-de-dolares-en-mayores-costos/
39 https://www.bcr.com.ar/es/mercados/investigacion-y-desarrollo/informativo-semanal/noticias-informativo-semanal/la-bajante-3.

proposed important modifications to the river system, like dredging and channelization. Some of the characteristic features of the river, like its depth and meanders require the disassembly of tug and barge convoys, which increase shipping cost. This measure however, will have important hydrological and ecological impacts.

5.6 Hydroelectricity generation and other energy impacts

Hydropower is the main source of renewable energy in South America, followed by biofuels. The LPB is one of the largest producers of hydroelectric power (HEP) in the world (Rudnick et al., 2008): this region is endowed with 28% of the world's water resources that, along with its topographical characteristics, contribute to the LPB's high current and potential production of hydropower (Popescu et al., 2012). Many dams and HEP plants within the LPB provide about 55% of the energy demand of countries in the basin; the high importance of HEP, however, makes LPB countries highly dependent on water resource availability (Popescu et al., 2014).

Drought can have important direct impacts on energy production in the LPB. The Upper Paraná basin is home to over 63 reservoirs and hydropower plants with a total installed generating capacity of about 61,000 MW. The Argentine National Water Institute (INA, for its Spanish acronym) and Brazilian National Operator of the Electric System (ONS[40]) reported a critical status of storage in the larger capacity reservoirs in the Upper Paraná Basin, particularly on the Grande and the Paranaíba rivers, due to extremely low inflows since 2014 (Figure 9). Since February 2019, the Jurumirim (Paranapanema River Basin) and Foz do Areia (Iguazu River Basin) HEP plants have been facing hydrological severe-to-exceptional drought conditions. At the time of writing, the Jurumirim plant remains in the most critical situation (SSFI-12 = -2.7 and SSFI-24 = -3.1). Inflow at the Itaipú HEP plant has been facing a hydrological drought since April 2019 and has been in an "exceptional" drought situation since December 2020 (SSFI < -2.0).

Because of HEP shortages, the ONS has asked electricity generators to delay maintenance work as long as possible to avoid worsening the energy crisis stemming from the country's worst drought in almost a century. Hydro dams have reported the lowest water inflows in more than 90 years, pushing up electricity prices and boosting inflation rates. The Brazilian National Electric Energy Agency (Aneel) announced an average increase of 6.78% in the country's electricity bills since September 2021 because of the drought[41]. On August 30, 2021, the Brazilian President Jair Bolsonaro warned that the water crisis put the country "at the limit of the limit" and encouraged the population to save energy[42].

The Yacyretá power plant is shared by Paraguay and Argentina and is the southernmost HEP plant on the Paraná. Inflow into Yacyretá has been decreasing since 2017, but this plant was particularly affected by the ongoing event. According to plant operators, average inflow for June 2021 was 6,200 $m^3 s^{-1}$, a value like the one recorded during the 1934 low river flow event, and the second lowest since 1901[43]. By mid-July 2021[44], inflow into the Yacyretá reservoir was about 5,700 $m^3 s^{-1}$, while the average for this time of year is around 13,000 $m^3 s^{-1}$. As a result of the low inflows, Yacyretá power generation has decreased significantly. By the beginning of July 2021, a 45% decrease in the hydroelectric production of Yacyretá was reported in relation to January 2021 levels[45] (Figure 19).

40 http://www.ons.org.br/paginas/energia-agora/reservatorios
41 https://www.milenio.com/internacional/latinoamerica/brasil-vuelve-subir-precio-electricidad-causa-sequia
42 https://www.lanacion.com.ar/el-mundo/brasil-al-limite-por-su-peor-sequia-en-decadas-temen-apagones-y-jair-bolsonaro-ya-toma-medidas-nid26082021/
43 https://www.telam.com.ar/notas/202108/564834-rio-parana-bajante-grave.html.
44 https://econojournal.com.ar/2021/07/sequia-historica-del-parana-yacyreta-al-50-problemas-en-usinas-termicas-y-contingencia-en-atucha-para-garantizar-la-toma-de-agua-de-centrales-nucleares/
45 https://www.eldiariocba.com.ar/suplementos-especiales/2021/8/14/crisis-en-el-transporte-de-granos-por-la-bajante-del-rio-parana-52199.html

The economic losses for the Yacyretá plant by mid-2021 have been estimated at about 30 million USD per month[46].

Other energy-related impacts have been experienced downstream of Yacyretá, particularly affecting intakes of cooling water for power plants, such as the Vuelta de Obligado and San Martín thermal plants in Santa Fe, Argentina. Further south, two nuclear plants, Atucha I and Atucha II, have hired a dredge to ensure water availability[47].

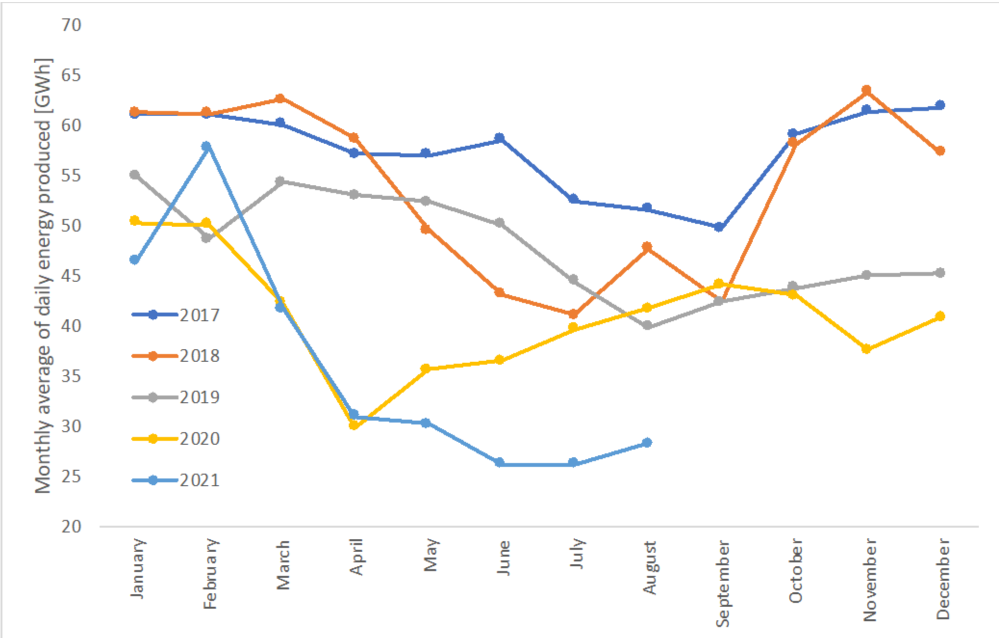


Figure 19. Monthly average of daily energy produced during the 2017-2021 period in the Yacyretá hydroelectric power station. Source: *Ente Binacional Yacyretá.*

5.7 Water supply for human consumption

In late May 2021, Brazilian President Jair Bolsonaro issued a water emergency declaration. Nevertheless, this declaration stopped short of imposing water restrictions to consumers [48]. The Government of Argentina issued a statement asking the population of seven provinces along the Paraná, Paraguay and Iguazú rivers to limit daily water consumption, rely on rainwater for irrigation and to suspend burning of grasslands [49]. Important cities such as Rosario, Santa Fe and Paraná rely on water from the Paraná River for their drinking water supply. On July 27, 2021, the Argentine Government allocated 1000 million pesos (about 10 million US dollars) to an emergency fund intended, among other purposes, to support cities in upgrading their water intake infrastructure[50].

46 https://www.bcr.com.ar/es/mercados/investigacion-y-desarrollo/informativo-semanal/noticias-informativo-semanal/la-bajante-4.
47 https://econojournal.com.ar/2021/07/sequia-historica-del-parana-yacyreta-al-50-problemas-en-usinas-termicas-y-contingencia-en-atucha-para-garantizar-la-toma-de-agua-de-centrales-nucleares/
48 https://elpais.com/clima-y-medio-ambiente/2021-07-25/brasil-sufre-la-peor-sequia-en-casi-un-siglo.html
49 https://www.infobae.com/sociedad/2021/07/20/historica-bajante-del-rio-parana-piden-limitar-el-consumo-de-agua-en-7-provincias/
50 https://www.perfil.com/noticias/politica/gobierno-crea-fondo-emergencia-hidrica-1000-millones-pesos-zonas-afectadas-bajante-rio-parana.phtml

5.8 Human health

The population potentially exposed to different levels of drought risk represents the number of people who may be directly affected by drought. This number is calculated as the overlap between the drought risk index (RDrI-Agri, Figure 17) and the population layers, and the reported figures refer to the total population of each country. During the second 10-days of September 2021 more than 11 million inhabitants in Argentina, 2 million in Bolivia, 41 million in Brazil and more than 2 million in Paraguay live in areas with some level being adversely affected by droughts (Table 1). Remarkably, during this period around 1.2 million people were located in areas at high risk of drought.

Table 1. Number of people potentially exposed to low, medium, and high drought risk (RDrI-Agri) during the second 10-days of September 2021 in each country. The numbers of population exposed to each risk category are expressed as thousands of people and, in parentheses, the percentage of the total population exposed in each country.

	Low	Medium	High	Total
Argentina	8,947 (22%)	2,293 (6%)	5,6 (0%)	11,246 (28%)
Bolivia	869 (9%)	1,220 (12%)	198 (2%)	2,288 (23%)
Brazil	22,575(12%)	17,778 (9%)	842 (1%)	41,196 (22%)
Paraguay	349 (5%)	2,073 (32%)	172 (3%)	2,594 (40%)

Although generally underestimated, drought can cause physical harm and even death to older people and vulnerable populations by direct impacts associated with the lack of water and heat waves (UNDRR, 2021). Impacts may also be felt indirectly through crop failure or changing patterns of disease vectors, which can lead to malnutrition or disease outbreaks (IPCC, 2014). The most vulnerable populations may also be at even greater risk due to socio-economic factors such as poverty, which may force people to live on land with low soil fertility or in ecosystems that are already prone to drought (Van Lanen et al., 2017).

According to the World Health Organization, (2012), the broad health impacts of drought can be categorised into five main classes: malnutrition; waterborne diseases; vector-borne diseases; airborne diseases and mental health, including distress and other emotional consequences. During this multiannual drought there have been some reports that highlight the testimonies from directly affected locals expressing uncertainty, fear and anxiety about the situation[51].

51 https://ar.radiocut.fm/audiocut/parana-seco-drama-familias-pescador-s-del-litoral-roxana-russo/

6 Conclusions

A multi-annual drought has been affecting the Plata Basin since mid-2019. The lack of rainfall, mainly in the upper part of the basin, has led to a considerable decrease in the flow of the Paraguay and Parana rivers.

Due to its prolonged duration and severity, this drought has already manifested many impacts on several different socio-economic sectors and has also severely affected ecosystems. These include water supply disruptions, forest fires, reduced agricultural yields, decreased river transport on the Paraguay and Parana rivers, and a considerable reduction in hydroelectric energy production. Severe are the regional effects on ecosystems and biodiversity, particularly acute in the Pantanal, one of the largest wetlands in the Americas.

Regarding the precipitation outlook, most global prediction systems forecast a precipitation deficit scenario for the October-December 2021 period in the middle and lower part of the Paraná basin, comprising southern Brazil, Uruguay, north-eastern Argentina and eastern Paraguay in the upstream areas of the Paraná River basin. Due to the extremely low soil moisture (resulting from the current dry season and below-average precipitation during the rainy season of recent years), it will take time for rainfall to make significant contributions to river flow and reservoir storage. In addition, it is very likely that the La Niña phenomenon, during the last months of 2021, will affect negatively precipitation in the middle and lower reaches of the Paraná. The most probable scenario for October-December 2021 is therefore a continuation of the drought situation, both from a rainfall and hydrological point of view.

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List of abbreviations and definitions

CEMADEN	Centro Nacional de Monitoramento e Alertas de Desastres Naturais
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
EBY	Yacyretá Binational Entity
ENSO	El Niño-Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FOB	Free on Board
GRACE	Gravity Recovery and Climate Experiment
GPCC	Global Precipitation Climatology Center
GWIS	Global Wildfire Information System
HPP	Hydro Power Plant
INA	Instituto Nacional del Agua
INTA	Instituto Nacional de Tecnología Agropecuaria
IRI	International Research Institute for Climate and Society – Columbia Climate School
JRC	Joint Research Centre of the European Commission
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
ONS	Operador Nacional do Sistema Elétrico - Brazil
SISSA	Drought Information System for Southern South America (Sistema de Información Sobre Sequias para el Sur de Sudamérica)
SMN	Servicio Meteorologico Nacional – Argentina
SPI	Standardised Precipitation Index
SPEI	Standardised Precipitation-Evaporation Index
SSFI	Standardized Streamflow Index
Suomi NPP	Suomi National Polar-orbiting Partnership
TWS	Total Water Storage
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIIRS	Visible Infrared Imaging Radiometer Suite
WMO	World Meteorological Organization

List of figures

List of tables

Annexes

Annex 1. Description of drought indicators used in this report

This annex contains a non-exhaustive list with a brief description of the main drought indicators used in this report. The monitoring of droughts is based on the analysis of a series of indicators, representing different components of the hydrological cycle (e.g., precipitation, soil moisture, reservoir levels, river flow, groundwater levels) or specific impacts (e.g., vegetation water stress) that are associated with a particular type of drought.

For further information please refer to the factsheets section of the European and Global Drought Observatory[52,53]. The Global drought observatory (GDO) is a service run by the European Commission's Joint Research Centre. The GDO portal contains drought information, graphs and time-series at Global level. All drought indicators can now be accessed for public download from the dedicated page on the GDO[54] .

Standardised Precipitation Index (SPI)

The ongoing drought episode over La Plata Basin is characterised and described starting with the analysis of precipitation patterns focusing on Standardized Precipitation Index (SPI). SPI is one of the most used and common indicators for drought analysis and evaluation and it measures precipitation anomalies comparing the observed total precipitation of a defined accumulation period with long-term historical data for the same period. The SPI is a statistical index comparing the total precipitation received at a particular location during a period of n months with the long-term precipitation distribution for the same period of time at that location (reference period is 1981-2010). Monthly accumulation periods (n) are 1, 3, 6, 9, 12, 24 or 48 months. The corresponding SPIs are denoted in this report as SPI-1, SPI-3, SPI-6 and SPI-12.

Each accumulation period describes a different aspect of the drought and its potential impacts. SPIs for short accumulation periods (e.g., SPI-1 to SPI-3) are indicators for immediate impacts such as reduced soil moisture, snowpack, and flow in smaller creeks. SPIs for medium accumulation periods (e.g., SPI-3 to SPI-12) are indicators for reduced stream flow and reservoir storage. SPIs for long accumulation periods (SPI-12 to SPI-48) are indicators for reduced reservoir and groundwater recharge, for example. The exact relationship between accumulation period and impact depends on the natural environment (e.g., geology, soils) and the human interference (e.g., existence of irrigation schemes). More details in *McKee, T.B., Doesken, N.J. and Kleist, J., 1993, January. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183).*

Soil Moisture Anomalies

Soil moisture anomalies are computed on a 30-day moving window at a spatial resolution of 0.1 decimal degrees and updated every 10 days. The index is computed as a weighted average of three standardized variables: 1) LISFLOOD root zone soil moisture, 2) MODIS Land Surface Temperature, and 3) ESA CCI remote sensing skin soil moisture. All three variables are standardized on the same baseline period 2001-2016 and the weighting factors are computed as described in *Cammalleri, C.,*

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52 https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1101
53 https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2101
54 https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2112

Vogt, J. V., Bisselink, B., & de Roo, A. (2017). Comparing soil moisture anomalies from multiple independent sources over different regions across the globe. Hydrology and Earth System Sciences, 21(12), 6329. The full ensemble of the three models is provided up to the second-to-last 10-days period, whereas the last 10-days period is a 'first-guess' estimate based only on LISFLOOD and MODIS LST data.

GRACE Total Water Storage anomaly

The Total Water Storage (TWS) anomaly is computed as standardized deviation of the GRACE satellite Liquid Water Equivalent (JPL TELLUS, Level 3 release 6.0, https://grace.jpl.nasa.gov/) from the baseline 2002-2017. The dataset is monthly at 1-degree resolution. Details on the relationship between this indicator and classic meteorological drought indices (e.g., SPI) can be found in *Cammalleri, C.; Barbosa, P.; Vogt, J.V. (2019). Analysing the Relationship between Multiple-Timescale SPI and GRACE Terrestrial Water Storage in the Framework of Drought Monitoring. Water 2019, 11, 1672.*

Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)

The FAPAR Anomaly indicator that is implemented in the Copernicus Global Drought Observatory (GDO) is used to detect and monitor the impacts on vegetation growth and productivity of environmental stress factors, especially plant water stress due to drought. The FAPAR Anomaly indicator is computed as deviations of the satellite-measured biophysical variable Fraction of Absorbed Photosynthetically Active Radiation (FAPAR, sometimes written as fAPAR or FPAR), composited for 10-day intervals, from its long-term mean values. FAPAR is one of the 50 so-called "Essential Climate Variables" (ECVs) that have been defined by the Global Climate Observing System as being both feasible for global climate observation, and important to support the work of the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change. (Of the 50 ECVs, 26 are listed as being significantly dependent on satellite observations). FAPAR values and their anomalies have been shown to be good indicators for detecting and assessing drought impacts on plant canopies, such as agricultural crops and natural vegetation, and thus provide information that is potentially useful for water and agricultural management purposes. More details can be found in *Gobron N., B. Pinty, F. Mélin, M. Taberner, M.M. Verstraete, A. Belward, T. Lavergne, and J.-L. Widlowski. 2005. The state of vegetation in Europe following the 2003 drought. International Journal of Remote Sensing, 26 (9): 2013-2020.*

Low Flow Index

The Low-Flow Index (LFI) indicator, is used for the operational, near real-time monitoring of hydrological (i.e. streamflow) drought in Europe. At global level the LFI is an experimental product. The LFI indicator exploits the simulated daily river water discharge outputs of the LISFLOOD hydrological model, in order to capture unbroken consecutive periods of unusually low streamflow, and compares the consequent water deficit during those periods with the historical climatological conditions, in order to derive the severity of the events. A key advantage of the LFI indicator, compared for instance with the widely used Standardized Runoff Index (SRI), is that the LFI indicator directly exploits daily streamflow values, allowing a near real-time update of the index at regular time steps. More information can be found in *Cammalleri, C., Vogt, J. and Salamon, P., (2017): Development of an operational low-flow index for hydrological drought monitoring over Europe. Hydrological Sciences Journal, 62(3), pp.346-358 and Cammalleri, C., P., Barbosa, J.V., Vogt (2020). Evaluating simulated* *daily discharge for operational hydrological drought monitoring in the Global Drought Observatory (GDO) Hydrological Sciences Journal 65 (8), 1316-1325.*

Risk of Drought Impacts for Agriculture (RDrI-Agri)

The Risk of Drought Impacts for Agriculture (RDrI-Agri) indicator that is implemented in the Global Drought Observatory is used for determining the area more likely to be affected by droughts. The RDrI-Agri indicator is computed as the combination of the dynamic layers of drought hazard, exposure and vulnerability. Higher risk means that the areas affected will be the most likely to report impacts due to droughts.

Maps of RDrI-Agri provide information on the spatial distribution of the risk of drought impacts globally, and their evolution over time. The maps of the RDrI-Agri indicator can be used as a proxy for the presence of potential impacts due to ongoing droughts. Due to the complexity of drought propagation through the hydrological cycle and different socio-economic sectors, as well as cascading effects, these impacts may well be observed much later. More information can be found in *Carrão, H., Naumann, G. and Barbosa, P., 2016. Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. Global Environmental Change, 39, pp.108-12*

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