MONITORING AND PREDICTING HYDROLOGICAL EXTREMES THROUGH REMOTE SENSING AND MACHINE LEARNING

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Abstract

The La Plata River Basin (LPRB) experienced a significant drought event from 2019 to 2021. This drought affected all aspects of life for over 100 million people who inhabit this area. In this study, we utilized satellite and model datasets to examine spatial and temporal variability of hydrological anomalies throughout the basin before and during the drought event. These variable anomalies, such as precipitation and groundwater, are derived from the Global Land Data Assimilation System (GLDAS). Additionally, the Soil Moisture Active Passive (SMAP) observations were used in the spatial and temporal analysis of the drought. The water loss was calculated using the Mann-Kendall test to assess the changes in anomalies for the terrestrial water storage (TWS) throughout the basin and subbasins. The main insight from this study is the agreement of the GLDAS anomalies with the SMAP data throughout the drought. The variable anomalies all decreased and showed alignment with the downscaled 1km SMAP that was validated with in-situ observations. It was also found that the Upper Parana subbasin lost the most water over the drought period. These products improve understanding of the spatial variability within the entire basin and facilitate understanding of droughts and resources to assist in the future management of water resources.

Introduction

Droughts have extensive economic and social impacts globally, including water scarcity and food insecurity. They cause over 25% of the world's population to face food insecurity (Kogan, 2019). Also, they diminish water resources, harm ecosystems, curtail hydropower production, and impede vital economic sectors such as agriculture, hydrological, and recreation. Various types of droughts – meteorological, agricultural, hydrological, and socioeconomic- can simultaneously afflict regions as they each pose distinct challenges to water availability and livelihoods (IPCC, 2012; Trenberth 1988; Vogt et al, 2018; Naumann et al, 2021).

Various research has explored the multifaceted aspects of droughts, utilizing diverse methods such as satellite data and climate modeling (Sordo-Ward et al., 2017; Cavalcanti et al., 2015). Satellite datasets, such as Gravity Recovery and Climate Experiment (GRACE), SMAP, and GLDAS (DEFINEEE) have been instrumental in understanding historical drought events and predicting future occurrences, as they help facilitate improved drought management strategies (Nikraftar et al., 2021; Fang et al., 2021a; Zhou et al., 2021; Baeza and Paruelo, 2020). Studies have also focused on validating satellite-derived data against ground observations to enhance the accuracy of drought monitoring and prediction (Chen at al., 2010; Forootan et al., 2019).

The causes of droughts have been explored extensively with research linking them to phenomena such as the suppression of rainfall zones and teleconnections from Él Niño Southern Oscillation (ENSO) (Forootan et al., 2019; Ceron et al., 2021; Meis et al., 2021) Recent drought events in South America, exacerbated by ENSO-related dry conditions, have underscored the urgent need for comprehensive drought analysis and mitigation efforts (Erfanian et al., 2017; Getirana, 2016; Naumann et al., 2021). These studies highlight the significant socio-economic and eco-hydrological impacts of droughts in vulnerable regions.

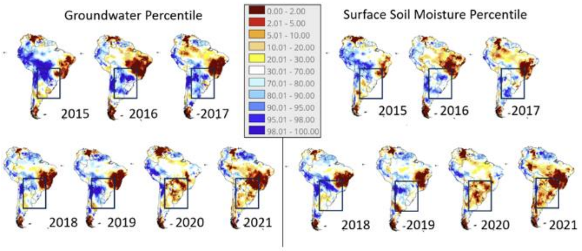


FIGURE 1: *Groundwater and Surface Soil Moisture Percentile across South America from NASA GRACE*

The La Plata River Basin (LPRB), encompassing five countries, plays a crucial role in sustaining livelihoods and ecosystems. Recent meteorological droughts in the region have underscored the importance of monitoring water resources at the basin-wide, subbasin-wide, and catchment levels (AghaKouchak et al. 2015; Naumann et al., 2021).

This research provides a basin wide as well as subbasin wide analysis for the following processes. To accomplish this, GLDAS derived variables have assisted in the understanding of physical processes that determine changes in soil moisture. One of the unique aspects of this work is the comparison between SMAP derived soil moistures and GLDAS hydrological variables, specifically groundwater and total water storage. This need for satellite soil moisture is amplified due to the lack of in-situ observations and in this study, we utilized both SMAP and GLDAS to combat this. By investigating anomalies of several hydrological variables, this work showcases the trends before, during, and after the drought of 2019-2021 in the La Plata River Basin for integrated water cycle variability. Additionally, the research on the subbasins with these datasets shows a unique and high spatial resolution variability of the current drought both with GLDAS and SMAP, which is innovative and novel in its application.

Data and Methods

Data

In order to model the drought in the LPRB, both the SMAP and the GLDAS data sets were used (Chan et al., 2018; Fang and Lakshmi, 2014). The specifics of the datasets used are shown in Table 1.

TABLE 1: *Summary of data used in study*

Source	Spatial Resolution	Temporal Resolution	Version	Data Source	Reference	Full name
GLDAS	~ 27 km (0.25x0.25 degrees)	1 day	2.2	https://disc.gsfc.nasa.gov/datasets/GLDAS_CLSM025_DA1_D_2.2/summary?keywords=GLDAS	(Li et al., 2020, Li et al., 2019)	GLDAS Catchment Land Surface Model L4 daily 0.25 x 0.25 degree GRACE-DA1 V2.2
SMAP	1 km	1 month	n/a	https://cmr.earthdata.nasa.gov/search/concepts/C2623698025-NSIDC_ECS.html	(Fang et al. 2018, Fang et al., 2021)	SMAP 1km
SMAP	9 km	1 month	n/a	https://cmr.earthdata.nasa.gov/search/concepts/C2136471727-NSIDC_ECS.html	https://doi.org/10.5067/4DQ54OUIJ9DL	SMAP Enhanced L3 Radiometer Global and Polar Grid Daily 9 km EASE-Grid Soil Moisture V005

Soil Moisture Active Passive

SMAP is a satellite mission that focuses on soil moisture, operating with an 8-day repeating track and a spatial resolution of 9km. SMAP has been downscaled to a higher spatial resolution (1km) by Advanced Microwave Scanning Radiometer (AMSR-E) (Fang et al., 2013, 2018a), AMSR2 (2018b) aircraft sensors (2019), SMAP for CONUS (2020) and global (2022), and to 400m using the Visible Infrared Imaging Radiometer Suite (2021b).

Global Land Data Assimilation System

GLDAS combines land-based observational data with satellite data to give near real time land surface states and fluxes (Rodell et al., 2004).

The specific GLDAS data set used in this research was the GLDAS Catchment Land Surface Model L4 daily 0.25 x 0.25 degrees GLDAS-DA1 V2.2 (GLDAS_CLSM025_DA V2.2) (Li et al., 2019; Li et al. 2020). This simulation assimilated GRACE observations into the Catchment land surface model within the Land Information System to obtain improved water storage and fluxes (Kumar et al., 2016; Li et al., 2019; Getirana et al., 2020). The main benefit to using this GLDAS model output with GRACE data assimilation is the addition of groundwater and soil moisture data to the normal hydrological variables from GLDAS.

Methods

The study extracted monthly 9km and 1km soil moisture data from SMAP and various hydrological variables from GLDAS, covering the period from January 2015 to December 2021 across the LPRB. GLDAS provided daily data for precipitation, evapotranspiration, runoff, groundwater, surface soil moisture, rootzone soil moisture, and profile soil moisture. Monthly hydrological anomalies were calculated to assess deviations from climatological averages, offering insights into temporal variations across the basin and its subbasins. Trend tests like the Mann-Kendall and Sen's Slope were applied to analyze the significance of trends in total water storage anomalies, providing valuable information on water storage dynamics over two periods, 2002-2021 and 2019-2021, the second being the drought period.

In addition to GLDAS, SMAP was used to show the spatial dispersion of soil moisture intensity over the entire basin. SMAP spatial plots were created to further analyze the drought and to show the focal points of the drought. Subbasin spatial plots were also created from 2019-2021 to show the intensity of the drought in these smaller areas monthly. By comparing these, this research validates the ability of 1km SMAP to show drought progression. This dataset is vital to understanding the specific soil moisture patterns in the smaller subbasins where the 9km spatial resolution of soil moisture is too coarse.

Study Area

The LPRB is the 2nd largest river basin in South America and spans over 3.1 million km^2, covering 17 % of the landmass of the continent (Chen et al., 2010; Krepper et al., 2009). The basin expands over five different countries: Argentina, Bolivia, Brazil, Paraguay, and Uruguay. The main industries suffering from the 2019-2021 drought are the energy sector, with the production of hydropower, and the agriculture sector. There are seven different subbasins which make up the LPRB: Upper Parana, Lower Parana, Upper Paraguay, Lower Paraguay, Upper Uruguay, Lower Uruguay, and Rio de la Plata. The areas of these subbasins can be found in Figure 2. The areas of these subbasins were calculated with spatial tools in ArcGIS and can be seen in Table 2.

The Upper Parana subbasin is 899,628 km^2, which is 29% of the LPRB. This subbasin is the largest and one of the most important subbasins, as it contains the Itaipu dam, one of the largest hydropower dams in the world. Additionally, Brasilia, the capital of Brazil, is in this subbasin.

TABLE 2: *The subbasin name, area, percentage of the entire LPRB, water loss per month from 2019 to 2021, and total water loss from 2019 to 2021*

Basin	Area (km^2)	Percentage of LPRB	Water loss (cm/month)	Total water loss (km^3)
Upper Parana	899,628	29%	- 0.491	158.98
Lower Parana	610,885	19%	-0.448	98.537
Upper Paraguay	600,085	19%	-0.384	82.892
Lower Paraguay	520,068	17%	-0.413	77.36
Upper Uruguay	116,470	4%	-0.300	12.57
Lower Uruguay	236,980	8%	-0.553	47.164
Rio de la Plata	159,787	5%	-0.185	10.64

FIGURE 2: *La Plata River Basin Boundaries and subbasin boundaries*

Results

Understanding of the drought through GLDAS

The monthly hydrological anomalies for the entire LPRB and its subbasins from January 2015 to December 2021 are examined in Figure 3. According to Figure 3, most variables for the entire basin, including precipitation, groundwater, and terrestrial water storage (TWS), decreased beginning in March and April 2019 until November 2020 when they became constant, then slowly increased towards the latter half of 2021. This shows the beginning stages of recovery from the drought. These three hydrological variables are important in determining when the drought occurred. These findings show the drought progressing from 2019 to 2021 through precipitation, evapotranspiration, runoff, and groundwater anomalies. The soil moisture anomalies for the entire basin all began to decrease in April 2019 and continued decreasing until the beginning of 2021 where they became constant and started to slightly increase soon after, as seen in Figures 3f, 3g, and 3h. These patterns reveal that the soil moisture and groundwater have dried up and decreased during this drought and are beginning to increase, showing the start of recovery from the drought.

In addition to the analysis of the entire basin, an analysis over each subbasin reveals similar patterns to the entire basin, however, there were some outliers as seen throughout Figure 3. Both the groundwater and total water storage show significant decreases starting in March/ April 2019 and continuing through the end of 2020 when these values plateaued, and some started to slightly increase. The Upper Parana subbasin had the lowest value at the end of 2021 for both the groundwater and total water storage anomalies, at -120mm and -17cm respectively, but also started out below the other subbasins in 2015. Following the other subbasins, the Upper Parana subbasin fell below and stayed below the other basins in 2018. The Upper Paraguay subbasin stays slightly above the Upper Parana subbasin starting in early 2019 through the decrease and plateau in 2019 and 2020 respectively, and levels around -100mm and -10cm for groundwater and TWS, respectively, in 2021.The anomalies derived using GLDAS model output show the progression, movement, and variation of the drought throughout the basin and its subbasins.

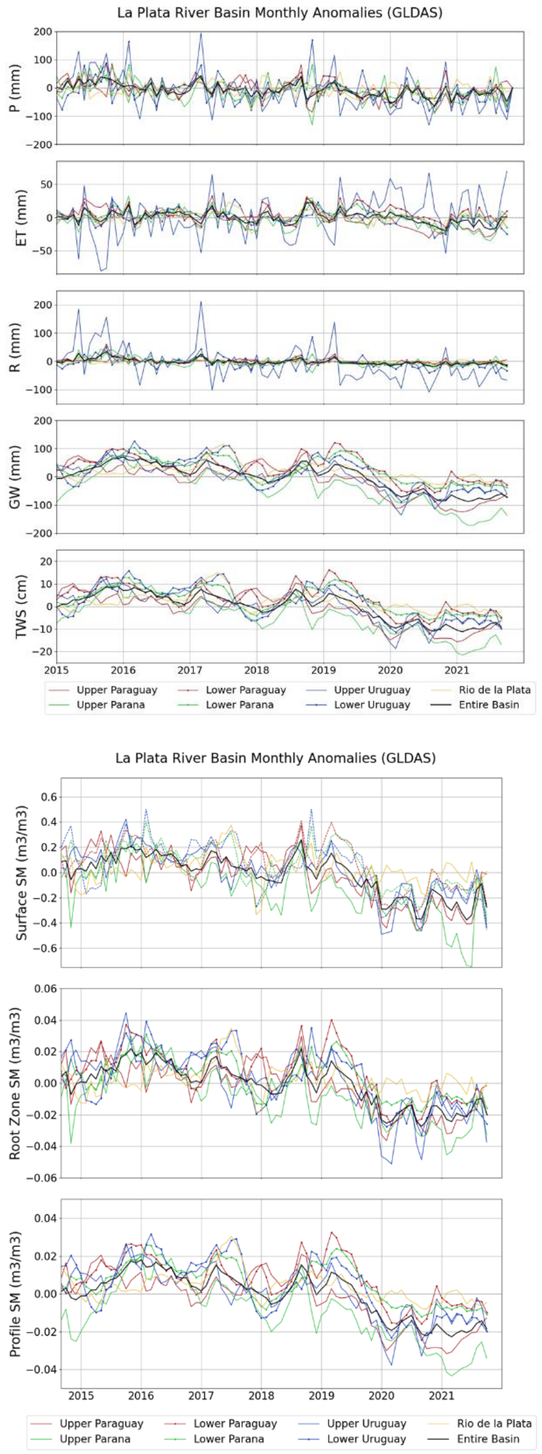


FIGURE 3: *These anomalies are plotted as an average over the entire LPRB (thick black line) and as monthly averages of each subbasin. The following variables are presented: a) precipitation, b) evapotranspiration, c) runoff, d) groundwater, e) total water storage, f) surface soil moisture, g) root zone soil moisture, and h) profile soil moisture.*

TWS trend analysis

The GLDAS anomaly plot in Figure 3e shows the TWS anomalies. From 2019-2021, the entire basin and all subbasins show a decreasing trend. When the Mann-Kendall and Sen's Slope trend tests were run for this time span, all the basins had $p<0.001$ thus showing significance. The alpha value for these and the Sen's slope tests was 0.05. Contrastingly, the trends analyzed from 2002-2021 overall generally showed no trend, but the Lower Paraguay and Lower Parana subbasins showed an increasing trend, while the Upper Parana showed a decreasing trend for the 20-year span which was depicted in both the Mann-Kendall test and Sen's Slope analysis. The subbasin that experiences the most water loss would display the most negative effects from this drought. In this scenario, the Mann-Kendall test was used to identify significant trends and the Sen's slope trend was used to quantitatively analyze the TWS.

As depicted in Table 2, during the 2019-2021 study interval, the subbasin with the fastest decrease in the TWS anomaly was the Lower Uruguay subbasin with a slope of -0.55 meaning that the overall total water storage anomaly decreased 0.55 cm per month. The total water loss for this time span over the entire subbasin was 47.2 km3. While the Lower Uruguay decreased the fastest, the Upper Parana subbasin lost the most water over this time due to the size of the subbasin and the second fastest rate of decrease. The Upper Parana lost 159 km3 with an average decrease of 0.49 cm per month. Overall, the entire basin decreased at 0.43 cm per month from 2019 to 2021, resulting in about 1,230 km3 of water being lost over this period. All these trends support the presence of a drought from TWS anomalies by showing there were decreases in all subbasins as seen in Table 2.

Progression of the drought across the entire basin and upper Parana River subbasin

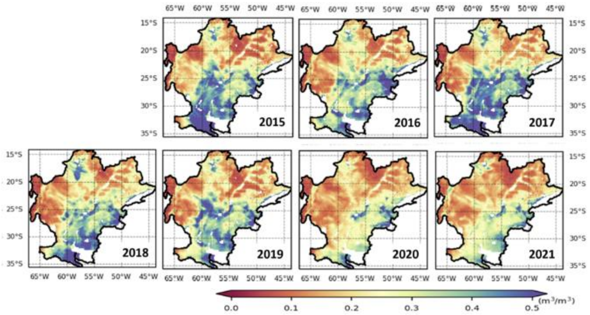


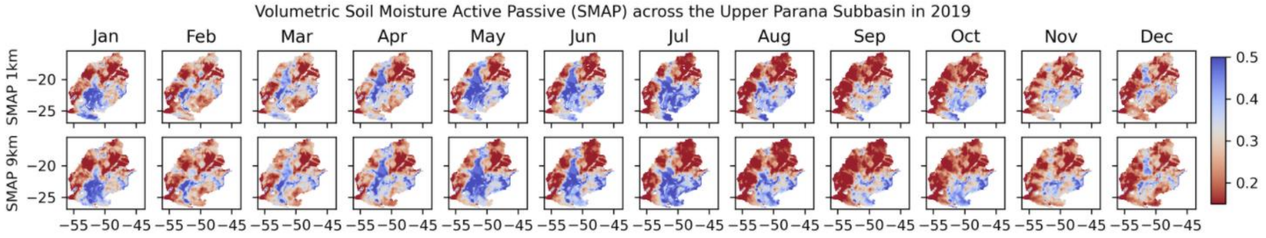
FIGURE 4: *SMAP progression from across the entire basin*

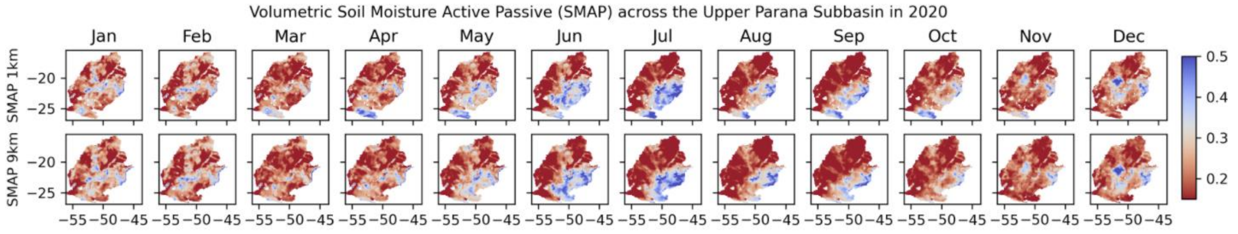
SMAP data was used to characterize and analyze the drought throughout the basin. Through these spatial plots, the dry down of the soil is evident, especially in the southeastern and central parts of the basin where the soil moisture went from 0.4-0.5m3/m3 in August 2015 to 0.2-0.3 m3/m3 in August 2020. Additionally, throughout the basin, the area covered with 0.4-0.5m3/m3 decreased significantly from 2015 to 2021 with the biggest changes occurring between August 2019 and 2020, coinciding with the onset of the drought.

The two SMAP datasets show a dip in the middle of 2019 after the drought began. After a steep decrease, the soil moisture increases a little bit towards the last few months of 2019, then plateaus around 0.2 m3/m3 for the duration of 2020, followed by a slight recovery into 2021 and throughout the rest of that year. Figure 5b shows a bias between the 1km and the 9km data.

One of the objectives of this study is to utilize SMAP data to characterize the drought throughout the basin and the subbasins. By doing this, the spatial and temporal progression of the drought can be understood. In addition to the entire basin, the subbasins we are looking into are the Upper Parana, Upper Paraguay, Lower Paraguay, Upper Uruguay, Lower Uruguay, Lower Parana, and Rio de la Plata. Including a three-year span (2019-2021) allows for a further examination of the drought trends throughout the normal dry and wet seasons and allows for proper analysis.

The Upper Parana Subbasin dries down substantially in the western part of the basin as seen in S1a. One interesting aspect of this subbasin is that in July 2020, the soil moisture in the western side of the basin is 0.1 m3/m3, whereas on the eastern side of the basin, it is 0.4-0.5 m3/m3, showing the variability of the drought in a small subbasin. Overall, the driest month for this subbasin is October 2020, followed by December 2021, and the wettest months are May-July 2019. The seasonal trends of wet and dry seasons remain apparent in this basin.


Volumetric Soil Moisture Active Passive (SMAP) across the Upper Parana Subbasin in 2019


Volumetric Soil Moisture Active Passive (SMAP) across the Upper Parana Subbasin in 2020

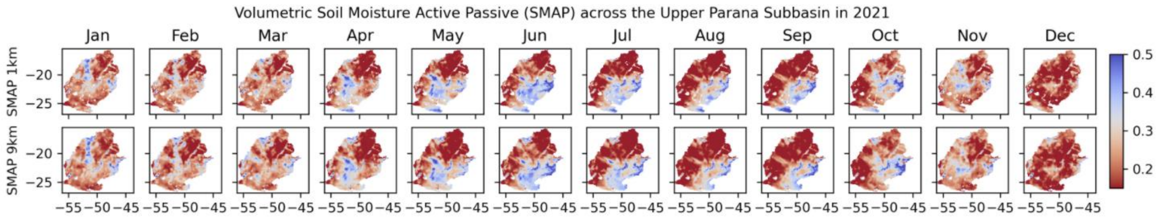


FIGURE 5: *Soil moisture variability at high spatial resolution for the Upper Parana Subbasin from 2019-2021*

Discussion

The primary objective of this study is to characterize the 2019-2021 drought in the La Plata River Basin (LPRB) and its subbasins through the joint utilization of GLDAS model output and high-resolution SMAP observations to achieve a comprehensive understanding of the drought dynamics. It emphasizes the transition from meteorological to hydrological droughts, recognizing the crucial role of soil moisture in comprehending droughts and assessing their agricultural and socioeconomic impacts. The research underscores the imperative of using satellite datasets due to the scarcity of in-situ observations across the basins, particularly for mapping spatial drought patterns in smaller subbasins to enhance drought understanding and facilitate more precise severity and spatial extent assessments.

Covering Argentina, Brazil, Bolivia, Paraguay, and Uruguay, this study sheds light on recent drought-related damages in Brazil, necessitating improved water management policies and closer collaborations between the scientific sector and the government (Getirana, 2016 and Getirana et al., 2021). Previous studies indicate water loss and underscore the need for improved drought planning and collaboration between the scientific sector and the government (Getirana, 2016). Moreover, studies underscore the importance of understanding land use and land cover changes, particularly in the Brazilian part of the LPRB, which have been primarily driven by population growth and agricultural expansions. Insights from previous studies demonstrate the consistency of GRACE data with observed drought conditions as seen in this study, underscoring the usefulness of satellite data in drought investigations (Chen et al., 2010; Melo et al., 2016).

Through an analysis of hydrological anomalies and trends, this study reveals significant water loss across the basin and subbasins, with distinct impacts observed in various regions (Naumann et al., 2021). It underscores the broader consequences of droughts, including ecological disruptions, agricultural vulnerabilities, and energy sector changes. The findings emphasize the urgency of proactive measures such as early warning systems, water conservation strategies, and collaborative water resource management to mitigate the adverse impacts of drought in the LPRB. Overall, understanding drought events in the region is crucial for informed decision-making and effective water resource management in the face of increasing climate variability.

Conclusion

The main findings of this paper are that SMAP and GLDAS can be used to better understand the drought throughout LPRB as well as in its subbasins. These assimilated data systems allowed for a comprehensive view of the hydrology in the basin before, during, and after the drought event in 2019-2021. The 9km and 1km SMAP data were also utilized to improve the spatial resolution, as this is the first study utilizing 1km SMAP in South America. Another limitation of this work involves only utilizing two different Earth observation systems, GLDAS and SMAP. To increase accuracy, future research could explore the connection between these and other remote sensing observations to characterize droughts in this region as well as narrowing in on specific subbasins and catchments.

This study can be used to aid in understanding hydrology and hydrological anomalies throughout droughts within LPRB using Earth observations. This work gives insight into the correlation between different data assimilation systems and how they can work together to provide knowledge about hydrological extremes. Additionally, this study shows that the use of downscaled soil moisture is an important asset when looking into droughts and water storage, especially for agriculture. Overall, studies such as this one work to improve understanding of satellite data in efforts to decrease the negative effects of droughts and other hydrological extremes in LPRB.

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