Contribution of the GRACE Satellite Mission to Mapping Water Mass Variations in River Basins

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Abstract

In the context of climate change, there is a need to understand the dynamics and temporal fluctuations of continental water. Such knowledge is essential for the development of more effective and sustainable management strategies for this indispensable resource. The Earth's gravitational field is not constant but varies over time due to factors such as mass redistribution during the hydrological cycle. The GRACE satellite mission (Gravity Recovery and Climate Experiment) provides valuable information about the geodynamic behaviour of our planet by estimating variations in the continental water storage from the temporal changes in the Earth’s gravity field. The aim of this work is to demonstrate the contribution of satellite gravimetry to identify patterns of variation in continental water masses within large river basins. For this purpose, a regional study of the TWS (Total Water Storage) derived from GRACE was carried out, focusing on the spatial and temporal changes detected in the La Plata Basin in South America. The periods with the most extreme variations between 2019 and 2023 were analyzed, and the TWS was compared with satellite precipitation data, to subsequently relate them to ENSO events that occurred in the region. The results show that GRACE detected the significant changes in water storage, highlighting in particular the severe drought that occurred in this basin in 2022.

1. Introduction

The fast development of disciplines and techniques has been a turning point in the analysis of environmental processes. In addition, global investment in satellite observations has been substantial in recent years, leading to extensive use of data from these missions in the Earth sciences. Remote sensing products such as satellite altimetry and space gravimetry missions have been very useful for studies of water balance at basin and sub-basin scales (Xavier et al., 2010).

Gravimetric satellite missions can monitor water mass distributions in the Earth system, which is closely related to the consequences of climate change. The GRACE-derived TWS is an approximate representation of surface mass density in terms of a thin layer of water, which allows mapping monthly changes in water storage with a spatial resolution of about 150,000km² (Landerer & Swenson, 2012). Since 2002, this mission has contributed to the understanding of the spatio-temporal variability of continental water storage and has supported a variety of Earth science studies (Alves Costa et al., 2012).

The La Plata Basin (LPB) is one of the largest in the world (approximately 3,100,000 km^2) and covers five South American countries. Due to the vast area of the basin, there is a wide variety of characteristics and physical and environmental conditions (Comité Intergubernamental Coordinador de los Países de la Cuenca del Plata CIC, 2017). The watershed is the source of many important rivers and sub-basins, such as the Paraná, Uruguay, and Paraguay basins (Figure 1). This hydrographic system also includes an important and valuable resource, like the Guaraní aquifer (the second largest fresh groundwater reservoir in the world). Therefore, knowledge of the LPB's behaviour in space and time is crucial, as it represents a great environmental, economic and strategic resource.

In the past 20 years, this basin has experienced episodes of extraordinary flooding with human losses and material damage, as well as severe situations of deficits in continental water storage. The evolution of El Niño and La Niña events, phenomena linked to the sea surface temperature of the tropical Pacific, has a major impact on the climate of much of the LPB, particularly on the inter-annual time scale, affecting the variability of precipitation (Comité Intergubernamental Coordinador de los Países de la Cuenca del Plata CIC, 2017).

In this work, data from the GRACE-FO mission (GRACE Follow-On) were used to analyze the water mass variation in the LPB between 2019 and 2023. Interpretation of results was carried out by associating the mass anomalies with satellite and ground-based information, such as global rainfall models and hydrometric heights, to provide insights into the hydrological context. Additionally, the drought episode from 2020 to 2022 was assessed throughout the LPB and its main sub-basins.

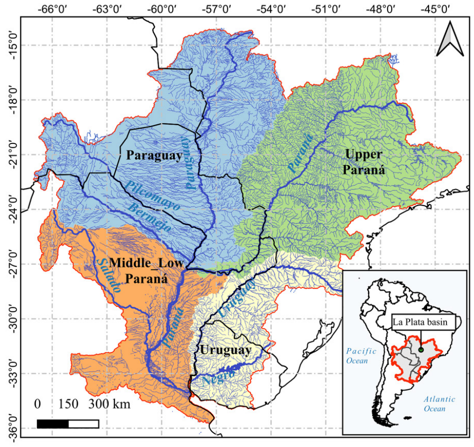

Figure 1. La Plata Basin and sub-basins.

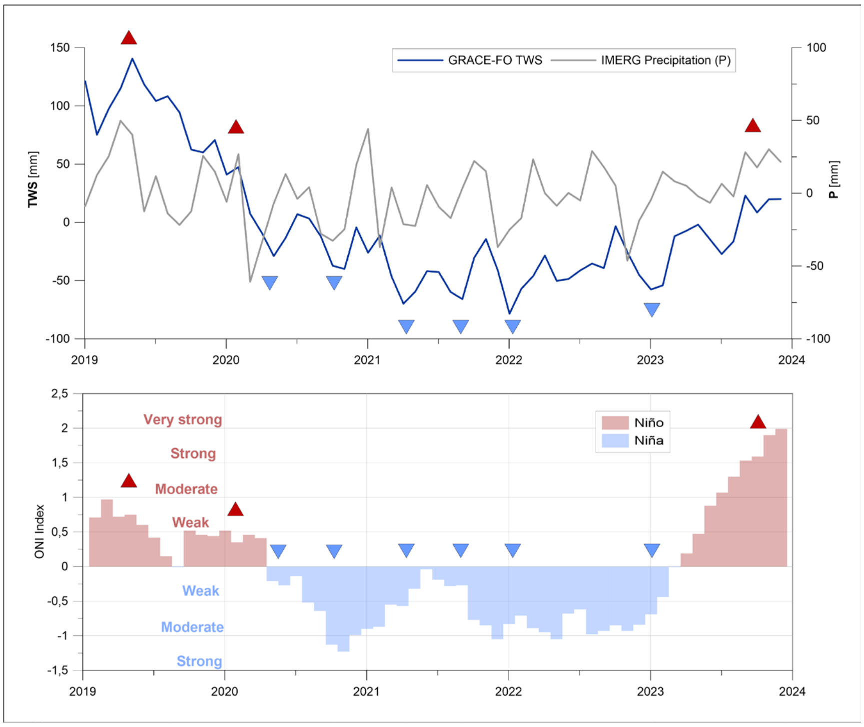

Figure 2. TWS and precipitation time series in LPB from 2019 to 2023 (above).

2. Methods

The TWS variations used in this study were estimated from the high-resolution solutions of the GRACE-FO mission (mascons), specifically the 0.5º x 0.5º CSR-RL06 monthly mass grids (Save et al., 2016; 2020), for the period January 2019 to December 2023. The use of this product requires neither additional processing, filtering, nor scaling factors (Save et al., 2016), but the corresponding land mask was applied in order to minimize leakage along the coastline. Then, the TWS anomalies were obtained for a well-defined grid based on the boundaries of each basin. To complete the TWS time series and have a time correspondence with the precipitation data, linear interpolation was applied to fill the gaps in the missing GRACE months.

The precipitation data for the LPB was obtained from the Integrated Multi-satellite Retrievals for GPM (IMERG, product GPM_3IMERGM_v07), which produces monthly precipitation grids at a resolution of 0.1º x 0.1º (Huffman et al., 2023).

To enhance the visibility of linear trends and short-term anomalies, seasonal variations were removed from the TWS and precipitation series by accounting for the mean annual cycle values during the 2019-2023 period.

Furthermore, the Oceanic Niño Index (ONI) for the Niño 3.4 region (5°N-5°S, 170°W-120°W) from the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/data/indices) was included to evaluate the ENSO (El Niño Southern Oscillation) events in the LPB. The ONI index is calculated from the 3-month mean Sea Surface Temperature (SST) anomaly and it is used to identify El Niño and La Niña events in the tropical Pacific, which are classified as “weak”, “moderate”, “strong”, and “very strong” (Larkin & Harrison, 2005).

River gauge time series data from ground stations provided by the General Administration of Ports of Argentina (https://www.argentina.gob.ar/transporte/administracion-general-puertos-se/via-navegable-troncal/hidrometros), and maps obtained from the Drought Information System for Southern South America (SISSA, https://sissa.crc-sas.org/monitoreo/estado-actual-de-la-sequia) were also incorporated into the analysis.

Thematic maps were generated using the open-source software GMT (Generic Mapping Tools), which simplified and automated the cartographic process through scripts that allowed for the creation of all maps in a single application (Wessel et al., 2019).

3. Results

Figure 2 (above) depicts the time series of TWS and precipitation from January 2019 to December 2023 for the LPB. Additionally, the El Niño and La Niña events are also presented in Figure 2 (below), which are associated with the occurrence of floods or droughts in South America, respectively, with their corresponding classification based on intensity. The most significant ENSO episodes affecting the water storage in the entire basin are indicated in both figures.

According to the results, four periods with significant increases in TWS can be observed in LPB (May and December 2019, and February 2020), associated with increments in precipitation, on one hand, and a moderate (2019) to weak (2020) El Niño episode, on the other. At the end of 2023, another TWS increment is detected, coinciding with a very strong Niño event.

Regarding the negative extremes for the TWS, the months of May and November 2020, April and September 2021, and January 2022 and January 2023 can be mentioned, which are related to an exceptional La Niña episode characterized by a duration of approximately three years and a greater than moderate intensity. Additionally, the minimum precipitation levels of the annual cycle recorded in certain months, contributed to the decrease in TWS during the cited periods, with a 1-2 month lag observed in GRACE-FO water storage relative to precipitation.

Table 1 presents the linear adjustment values for both series, showing a decreasing annual trend in TWS from 2019 to 2021, followed by a positive trend in 2022 and 2023.

Year	Variable	Trend	R^2
2019	TWS	-48.26	0.32
	P	-16.01	0.04
2020	TWS	-62.74	0.48
	P	2.37	0.00
2021	TWS	-2.49	0.00
	P	-7.20	0.01
2022	TWS	39.74	0.42
	P	-5.17	0.01
2023	TWS	73.75	0.69
	P	26.01	0.38

Table 1. Annual trend (mm/year) and coefficient of determination R^2 for TWS and precipitation (P) series.

The strongest negative slope for TWS was observed in 2020, possibly influenced by the weak to strong La Niña episode, while the most significant decline in precipitation occurred in 2019.

Regarding the maximum positive trends, both variables exhibited increases in 2023, consistent with an El Niño event that reached its highest intensity by the end of that year.

The coefficient of determination (R^2) was not significant throughout nearly the entire period, except for TWS in 2020 and 2023, indicating that the linear trend represented a considerable proportion of the overall data behavior during those years. In contrast, for the remaining years and the precipitation variable, the values suggest the application of a non-linear statistical adjustment (Pereira et al., 2024).

Figure 3a presents the maps of the annual mean TWS with the maximum positive and negative variations in water storage in the LPB region between 2019 and 2023. These results were compared with the SISSA maps of the basin areas affected by drought (Figure 3b), which are categorized based on accumulated precipitation percentiles according to the specifications of the United States Drought Monitor.

The year 2019 demonstrates a widespread increase in TWS across most of the basin, with the exception of the northeastern region corresponding to the Upper Paraná sub-basin (refer to Figure 1), which also coincides with the drought areas identified by SISSA.

In 2022, a pronounced decrease in TWS is observed, particularly in the northern and southern regions of LPB. The water storage deficit identified by GRACE-FO is also evident in the regions experiencing drought conditions with extreme to exceptional categories across a significant portion of the basin.

It is particularly noteworthy that the severe drought that affected the Middle-Low Paraná sub-basin (refer to Figure 1) in 2022 was the driest considering approximately 60 years of precipitation records. In fact, the city of Rosario, located within this basin, experienced the most important decline in the Paraná River's water level in the last 77 years (Servicio Meteorológico Nacional SMN, 2023). This was confirmed by negative hydrometric data recorded in January 2022 (Figure 3c), indicating that the water level was below the conventionally established benchmark, as measured by the hydrometer scale at the Port of Rosario. This observed water deficit occurred during a moderate and prolonged La Niña event (Figure 2).

In order to more accurately depict the extreme variations of TWS observed in LPB, Figure 4 presents the mean seasonal maps. The maximum TWS value in the basin occurred in autumn 2019 (May), while the lowest value was identified in the summer of 2022 (January). The figure clearly demonstrates the contrast in water storage variations across these seasons, with a notable increase (decrease) in most part of the LPB in autumn 2019 and summer 2022, respectively.

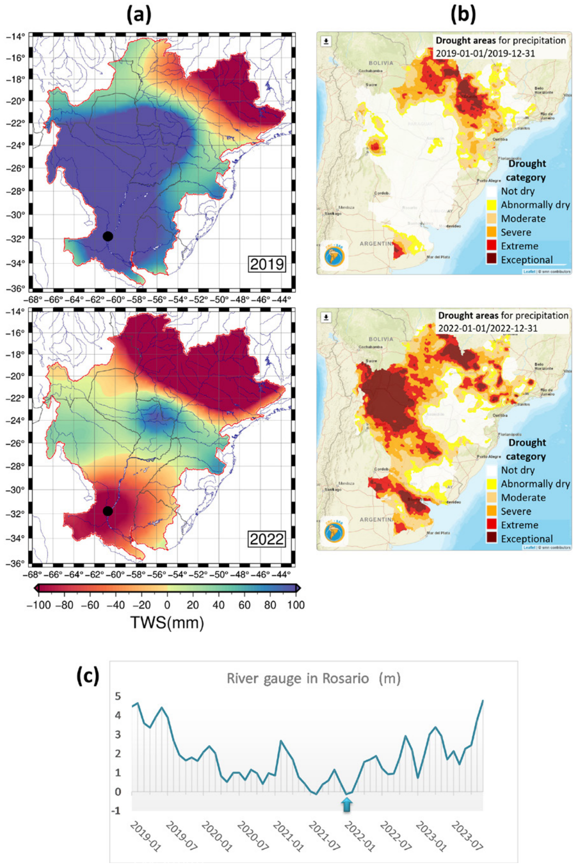

Figure 3. (a) Maximum and minimum mean annual TWS in the LPB for the period under study.
(b) Drought areas for 2019 (above) and 2022 (below). Source: SISSA (https://sissa.crc-sas.org/monitoreo/estado-actual-de-la-sequia).
(c) Hydrometric height from 2019 to 2023 at a station in Rosario, located in the Mid-Low Paraná sub-basin.

Figures 3 and 4 show that the water storage in the LPB presents significant spatial differences, mainly due to the coexistence of distinct precipitation regimes and behaviour of each of its sub-basins (refer to Figure 1).

Monthly TWS from GRACE-FO mascons were estimated for each of the main sub-basins in the LPB (Upper Paraná, UPP; Mid-Low Paraná, MLP; Paraguay, PAR; and Uruguay, URU), and the deseasonalized time series from 2019 to 2023 were analyzed to search for a connection with ENSO episodes at sub-basin level. The results are shown in Figure 5. The four basins exhibit the highest values of the period during 2019, which can be associated with the occurrence of a moderate El Niño episode.

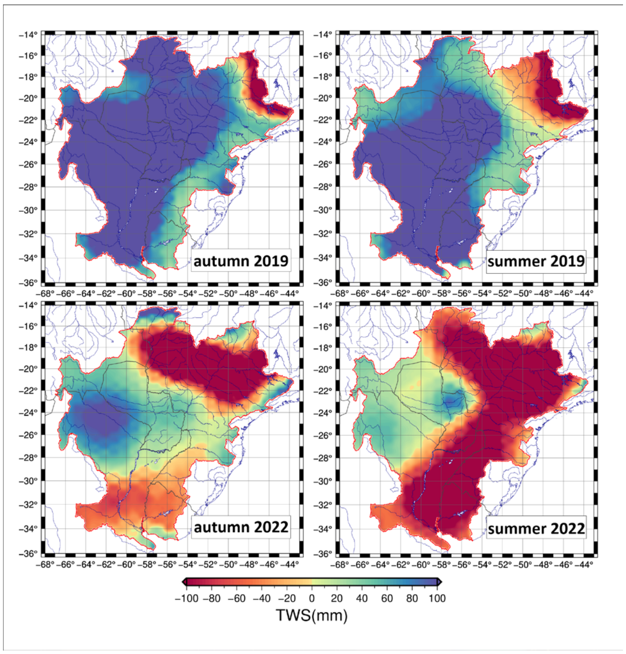

Figure 4. Mean seasonal TWS in LPB for 2019 (above) and 2022 (below).

The MLP series clearly shows a negative trend until mid-2023, when an El Niño event begins. Two significant minimum peaks are observed throughout the series, in January 2022 (which coincides with Figure 3) and in February 2023, which can be related to the extensive and intense La Niña episode (refer to Figure 2).

In UPP, the series presents a progressively negative trend from mid-2019 until May 2021, coinciding with a La Niña event that exceeded moderate intensity. This phase is followed by a period of increasing values, which continues until September 2023. Considering the 2019-2021 period, the most pronounced declining trend occurred in this basin. This aligns with a recent study on the characterization of the drought in the La Plata Basin, which used data from the GLDAS (Global Land Data Assimilation System) model and the SMAP (Soil Moisture Active Passive) satellite mission. The study demonstrated that the UPP experienced the largest water loss during the 2019-2021 period (Besnier et al., 2024). However, for the entire drought period, the most affected region was the MLP.

The PAR basin recorded its minimum TWS in January 2023, towards the end of a La Niña episode. Additionally, this series demonstrates a more seasonal behavior compared to the other basins, particularly from mid-2020 to 2023. This can be related to the fact that the vast Pantanal wetland plays a key role in the runoff caused by rainfall in the Upper Paraguay Basin, delaying its peak contributions to the Paraná by almost six months. In the Paraguay River, the flow regime is more uniform throughout the year, with a maximum in early winter, demonstrating the Pantanal's influence as a regulator and retarder of floods (Comité Intergubernamental Coordinador de los Países de la Cuenca del Plata CIC, 2017).

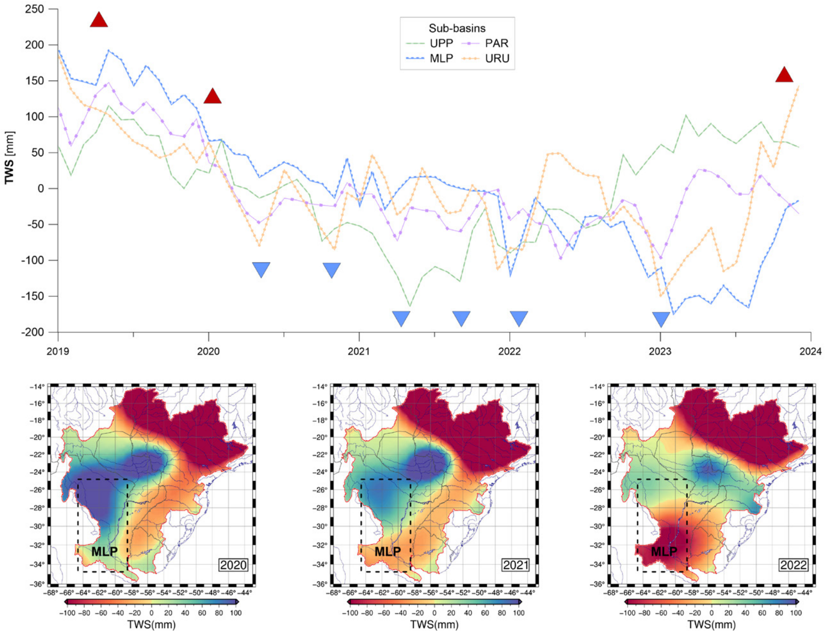

Figure 5. Above: TWS series for main sub-basins of LPB from 2019 to 2023. The extreme water storage decreases and increases related to ENSO episodes are indicated. Below: Annual TWS maps for the LPB during the drought period.

The URU basin also exhibited its minimum water storage peak in early 2023, along with another peak of similar magnitude in December 2021. An increase is evident from September 2023, coinciding with a strong El Niño event.

Figure 5 also presents the annual TWS maps for the 2020-2022 drought period. A progressive decrease in water storage can be observed in the PAR, URU, and MLP regions, with the most critical drought situation evident in the latter. In the case of the UPP, negative TWS values are perceived throughout all three years.

The annual TWS trends were analyzed for the four basins over the period 2019-2023. The results in Table 2 indicate that the UPP basin was the only one exhibiting a positive trend (0.28 mm/year), in contrast to the negative values of the other sub-basins, with MLP showing the maximum decline (-61.39 mm/year).

Furthermore, to assess the extraordinary drought that occurred in the LPB, trends were obtained for the period from January 2020 to December 2022. These trends were negative for all basins, with MLP exhibiting the greatest decrease (-45.24 mm/year).

	TWS Trend	
Sub-basin	2019-2023	Jan 2020 - Dec 2022
UPP	0.28	-8.28
MLP	-61.39	-45.24
PAR	-25.36	-16.32
URU	-23.53	-4.67

Table 2. TWS trends (mm/year) for the LPB sub-basins from 2019 to 2023 (complete time span), and for the 2020-2022 drought period.

4. Conclusion

The application of new technologies to geomatics has revealed insights into the temporal variation in continental water storage, which is associated with the hydrological behavior of LPB.

The results indicate that the GRACE-FO mission was able to detect significant variations in water mass changes over the timespan of the study. Furthermore, these outcomes indicate that the majority of the TWS variations are associated with extreme climatic events, such as the 2022 drought linked to La Niña and the impact of El Niño in 2019. Additionally, positive and negative fluctuations in TWS can also be attributed to the highest and lowest precipitation levels observed in the region taking into account the annual cycles of both variables. These series presented a similar behavior of the trends in 2019, 2021, and 2023.

The LPB seasonal maps demonstrated the relationship between TWS response and changes in climate conditions, highlighting the progressive basin-wide deficit during 2022. The results also revealed a clear signal of ENSO events across the four main LPB sub-basins, including the increases observed during the El Niño years of 2019 and 2023, as well as the minimums TWS values during the La Niña phase from 2020 to 2022.

The trend analysis of the sub-basins indicates a decrease in water storage during the drought period, with the MLP being the most affected. Moreover, this basin exhibited the most pronounced negative trend between 2019 and 2023.

Since the effects of ENSO episodes and hydroclimatic extremes occur across different temporal and spatial scales, the relationship between them is not direct. Moreover, their influence in South America depends on various factors, such as inter-basin interactions and climate variability (Pereira et al., 2024). However, the results for the LPB demonstrate that that hydrological systems do respond to ENSO events, which are considered the major source of climate variability in South America.

By combining the data provided by the GRACE-FO satellites with information from other satellites and ground-based observations, it is possible to study the water storage variations in large basins, as the LPB. This can be used to create early warning systems for extreme hydrological events, as well as to monitor changes occurring in aquifers or groundwater. The findings of this study contribute to a more comprehensive understanding and assessment of the hydrological cycle within the LPB region, highlighting the significance of integrating data from contemporary satellite missions such as GRACE-FO.

5. References

Alves Costa, S. M., de Matos, A. C. O. C., & Blitzkow, D. (2012). Validation of the land water storage from gravity recovery and climate experiment (GRACE) with gauge data in the Amazon Basin. Boletim de Ciencias Geodesicas, 18(2), 262–281. https://doi.org/10.1590/S1982-21702012000200006

Besnier, J., Getirana, A., Beaudoing, H., & Lakshmi, V. (2024). Characterizing the 2019-2021 drought in La Plata River Basin with GLDAS and SMAP. Journal of Hydrology: Regional Studies, 52(May 2023), 101679. https://doi.org/10.1016/j.ejrh.2024.101679

Comité Intergubernamental Coordinador de los Países de la Cuenca del Plata CIC. (2017). Análisis diagnóstico transfronterizo de la Cuenca del Plata ADT (1a). Comité Intergubernamental Coordinador de los Países de la Cuenca del Plata CIC-Organización de los Estados Americanos - OEA.

Landerer, F. W., & Swenson, S. C. (2012). Accuracy of scaled GRACE terrestrial water storage estimates. Water Resources Research, 48(4), 1–11. https://doi.org/10.1029/2011WR011453

Larkin, N. K., & Harrison, D. E. (2005). Global seasonal temperature and precipitation anomalies during El Niño autumn and winter. Geophysical Research Letters, 32(16), 1–4. https://doi.org/10.1029/2005GL022860

Pereira, A., Cornero, C., Oliveira Cancoro de Matos, A. C., Seoane, R., Pacino, M. C., & Blitzkow, D. (2024). Assessing water storage variations in La Plata basin and sub-basins from GRACE, global models data and connection with ENSO events. Hydrological Sciences Journal, 00(00), 1–20. https://doi.org/10.1080/02626667.2024.2349277

Save, H., Bettadpur, S., & Tapley, B. D. (2016). High-resolution CSR GRACE RL05 mascons. Journal of Geophysical Research: Solid Earth, 3782–3803. https://doi.org/10.1002/2016JB013007

Servicio Meteorológico Nacional SMN. (2023). Estado Del Clima en Argentina 2022. In Reporte final.

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., & Tian, D. (2019). The Generic Mapping Tools Version 6. Geochemistry, Geophysics, Geosystems, 20(11), 5556–5564. https://doi.org/10.1029/2019GC008515

Xavier, L., Becker, M., Cazenave, A., Longuevergne, L., Llovel, W., & Filho, O. C. R. (2010). Interannual variability in water storage over 2003-2008 in the Amazon Basin from GRACE space gravimetry, in situ river level and precipitation data. Remote Sensing of Environment, 114(8), 1629–1637. https://doi.org/10.1016/j.rse.2010.02.005