

Non-tidal ocean loading from Río de la Plata storm surges: empirical modeling at the Argentine–German Geodetic Observatory (AGGO) over its first decade of operation

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Abstract Frequent storm surges in the Río de la Plata estuary produce non-tidal ocean loading signals detectable at the Argentine–German Geodetic Observatory (AGGO), affecting the space geodetic and gravimetric techniques co-located at the site. An empirical model of water level variations across the estuary is developed for the period 2016–2025, covering the first decade of operation of AGGO, using observations from seven tide gauge stations distributed along the Río de la Plata, complemented by two modeled stations derived from astronomical tidal predictions and a global storm surge model. The storm surge propagation is characterized using the tidal propagation parameters from the Simplified Empirical Astronomical Tide (SEAT) model, and the gravimetric effect and elastic crustal displacements are computed with SPOTL (Some Programs for Ocean-Tide Loading) software. The resulting gravimetric effect series ranges between -14.7 and $+18.8 \text{ nm s}^{-2}$, while the vertical displacement ranges between -7.0 and $+5.5 \text{ mm}$, with smaller horizontal displacements in the East and North components. The loading-effect correction is validated against the International Geodynamics and Earth Tide Service (IGETS) Level-3 gravimetric residuals from the SG038 instrument at AGGO for the period January 2016 – October 2022. A wavelet analysis applied to the gravimetric residuals reveals spectral power reductions of up to 70% in the 1–12 day period band associated with storm surge activity. The 10-year time series of gravimetric effect and crustal displacements produced in this study provides, for the first time, a continuous correction dataset for the geodetic techniques co-located at AGGO, contributing to improved station coordinate repeatability and to the realization of terrestrial reference frames in the Southern Hemisphere.

Keywords non-tidal ocean loading, storm surge, AGGO, Río de la Plata, superconducting gravimeter

Carga oceánica no mareal por ondas de tormenta del Río de la Plata: modelado empírico para el Observatorio Argentino-Alemania de Geodesia (AGGO) durante su primera década de operación

Resumen Las frecuentes ondas de tormenta en el estuario del Río de la Plata producen señales de carga oceánica no mareal detectables en el Observatorio Argentino-Alemania de Geodesia (AGGO), que afectan a las técnicas geodésicas espaciales y gravimétricas colocalizadas en el sitio. En este trabajo se desarrolla un modelo empírico de la variación del nivel del agua en el estuario para el período 2016–2025, cubriendo la primera década de operación de AGGO. Para ello se utilizan observaciones de siete estaciones mareográficas distribuidas a lo largo del Río de la Plata, complementadas por dos estaciones modeladas derivadas de predicciones astronómicas y de un modelo global de ondas de tormenta. La propagación de la onda de tormenta se caracteriza utilizando los parámetros de marea del modelo de mareas astronómicas empíricas simplificadas (SEAT, por sus siglas en inglés), y el efecto gravimétrico y los desplazamientos elásticos de la corteza se calculan con el software SPOTL (Some Programs for Ocean-Tide Loading). La serie del efecto gravimétrico resultante varía entre -14.7 y $+18.8 \text{ nm s}^{-2}$, mientras que el desplazamiento vertical varía entre -7.0 y $+5.5 \text{ mm}$, con desplazamientos horizontales menores en las componentes Este y Norte. La corrección del efecto de carga es validada con los residuos gravimétricos de Nivel 3 del Servicio Internacional de Geodinámica y Mareas Terrestres (IGETS) del instrumento SG038 de AGGO, para el período enero 2016 – octubre 2022. Se aplica un análisis wavelet a los residuos gravimétricos que muestra reducciones de potencia espectral de hasta el 70% en la banda de períodos de 1 a 12 días asociada a la actividad de ondas de tormenta. La serie temporal de 10 años del efecto gravimétrico y desplazamientos corticales producida en este trabajo proporciona, por primera vez, un conjunto de correcciones continuas para las técnicas geodésicas colocalizadas en AGGO, contribuyendo a mejorar la repetitividad de las coordenadas de la estación y a la realización de marcos de referencia terrestres en el Hemisferio Sur.

Palabras clave carga oceánica no mareal, onda de tormenta, AGGO, Río de la Plata, gravímetro superconductor

INTRODUCTION

The Argentine–German Geodetic Observatory (AGGO) is one of the few geodetic observatories in the Southern Hemisphere that co-locates Global Navigation Satellite System (GNSS), Very Long Baseline

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Interferometry (VLBI), Satellite Laser Ranging (SLR), absolute gravity, and superconducting gravimetry (SG) at a single site. These techniques provide fundamental information for the determination of parameters describing the geometry of the Earth, its rotation, and gravity field, and their temporal variations (Plag & Pearlman, 2009; Schuh & Behrend, 2012).

The co-location of these techniques at fundamental stations is a key requirement for the realization and long-term maintenance of terrestrial reference frames, as it enables the integration of the individual networks into a common frame, ensures scale consistency among techniques, and allows for the mutual validation of their results, thereby improving the accuracy, consistency, and long-term stability of the frame (Altamimi et al., 2016; Angermann et al., 2016; Delva et al., 2023; Plag & Pearlman, 2009).

The development of global terrestrial reference frames requires that space geodetic techniques achieve millimeter-level accuracy and stability better than 0.1 mm yr^{-1} , a prerequisite for investigating geodynamic processes, sea-level change, and the variability of the Earth system (Altamimi et al., 2016; Plag & Pearlman, 2009). Reaching this level of performance demands the identification, measurement, and rigorous modeling of all geophysical and environmental processes affecting the observations, in order to reduce systematic errors and ensure consistency among co-located techniques (Petit & Luzum, 2010; van Dam et al., 2012).

Crustal deformations induced by surface mass loading represent one of the geophysical signals that must be accurately modeled to avoid millimeter-level biases in station coordinates and in the realization of the reference frame (Petrov & Boy, 2004; van Dam et al., 2012). In particular, corrections for non-tidal water loading have been shown to reduce systematic signals and improve coordinate repeatability across different space geodetic and gravimetric techniques. For GNSS, the application of atmospheric, hydrological, and non-tidal ocean loading models leads to significant reductions in vertical scatter and in the amplitude of residual annual signals in position time series (Männel et al., 2019; Tregoning & van Dam, 2005; Wang et al., 2025). In VLBI, the inclusion of non-tidal loading effects decreases the weighted root mean square (WRMS) of station heights and baseline lengths, mitigating spurious annual signals and improving parameter repeatability (Glomsda et al., 2020). For SLR, station displacements caused by ocean loading produce detectable signatures in the coordinates which, when modeled, improve solution repeatability and reference frame consistency, particularly in the vertical component (Sośnica et al., 2013). In gravimetry, non-tidal mass redistributions generate gravity signals of the order of tens of nm s^{-2} , well above the nm s^{-2} precision of modern gravimeters, that must be removed to enable geophysical interpretation of the time series and to meet the accuracy requirements of modern reference frames (Van Camp et al., 2017).

Oreiro et al. (2018) showed that water level variations in the Río de la Plata generate tidal and predominantly non-tidal ocean loading signals associated with frequent storm surges that affect the superconducting gravimeter observations at AGGO. The tidal contribution is largely removed through the application of tidal models and numerical filtering when the solid Earth tide is subtracted, as the dominant frequencies overlap. To correct for the non-tidal variations produced by storm surges, the authors developed an empirical model of the estuary for the year 2016 and converted the corresponding water height variations into gravimetric effects using SPOTL (Some Programs for Ocean-Tide Loading) software (Agnew, 2012). The application of this correction reduced the variability of the superconducting gravimeter residuals and enabled a clearer identification of other geophysical signals, such as subsurface water storage associated with precipitation. Their results demonstrate that water level changes in the Río de la Plata must be considered for a proper interpretation of superconducting gravimeter measurements, as they represent a modelable geophysical process. Using the same empirical model, they also computed the associated elastic displacements and found vertical variations of up to approximately 1 cm between consecutive peaks. Displacements of this magnitude are expected to introduce detectable systematic effects in VLBI, SLR, and GNSS observations (Glomsda et al., 2020; Sośnica et al., 2013; Tregoning & van Dam, 2005).

In this study, the non-tidal ocean loading effect time series is calculated for the AGGO location for the period 2016–2025, covering the first decade of observations at the observatory, based on an empirical modeling of Río de la Plata water level variations. Following Oreiro et al. (2018), a similar

Table 1. Location, sampling interval, and period covered by the tide gauge stations used in this study. Modeled stations (*) were derived from tidal predictions and the Dynamic Atmospheric Correction (DAC) model. (A) Argentina, (U) Uruguay. SHN: Servicio de Hidrografía Naval Argentino; AGP: Administración General de Puertos; ANP: Administración Nacional de Puertos; CARP: Comisión Administradora del Río de la Plata.

Station	Latitude	Longitude	Samp. int. (min)	Institution / model	Period
Buenos Aires (A)	34° 34' S	58° 24' W	15	SHN	1/1/2016–31/12/2025
La Plata (A)	34° 50' S	57° 53' W	15	SHN	1/1/2016–31/12/2025
Oyarvide (A)	35° 06' S	57° 08' W	20	AGP	1/1/2016–31/12/2025
San Clemente (A)	36° 21' S	56° 43' W	10	AGP	1/1/2016–31/3/2017
San Clemente (A)*	36° 21' S	56° 43' W	–	DAC	1/4/2017–31/12/2025
Colonia (U)	34° 28' S	57° 51' W	5	ANP	1/1/2016–31/12/2025
Colonia (U)	34° 28' S	57° 51' W	6	CARP	1/1/2016–31/12/2025
Montevideo (U)	34° 54' S	56° 15' W	5	ANP	1/1/2016–31/12/2025
Punta del Este (U)*	34° 58' S	54° 57' W	–	DAC	1/1/2016–31/12/2025

methodology is adopted, using water level observations from tide gauge stations distributed along the estuary, together with two modeled stations, i.e. stations where the water level is obtained from tidal predictions and a storm-surge model. The propagation of the tide and the storm surge, entering from the South Atlantic Ocean, as well as the linkage between stations, is modeled using tidal propagation information from the Simplified Empirical Astronomical Tide (SEAT) model (D'Onofrio et al., 2012), and the corresponding loading effects are computed with the SPOTL software. The resulting gravimetric effect series is then subtracted from the International Geodynamics and Earth Tide Service (IGETS) Level-3 superconducting gravimeter residuals to assess its impact on the gravity residual time series. In addition to the gravimetric effect, the associated elastic crustal displacements in the East, North, and Up components are derived for the entire period, providing for the first time an estimate of the displacements affecting all geodetic techniques co-located at AGGO between 2016 and 2025 due to storm surges in the Río de la Plata. These series are expected to reduce the residual scatter introduced by the time-varying water level loading in the geodetic observations and to support the realization of terrestrial reference frames, highlighting the relevance of empirical modeling based on observations in regions where numerical hydrodynamic models do not adequately reproduce water level variations.

DATA

Observed water-level data

Digital water level records from 31 December 2015 to 1 January 2026 at seven tidal stations located along the Río de la Plata (Figure 1) were used for the development of the empirical model. On the Argentine side, observations from the Buenos Aires and La Plata stations belonging to the Servicio de Hidrografía Naval Argentino (SHN), and Oyarvide and San Clemente belonging to the Administración General de Puertos (AGP) were used. On the Uruguayan side, observations from the Colonia and Montevideo stations of the Administración Nacional de Puertos (ANP) were used, and the Colonia series was completed with data from the Comisión Administradora del Río de la Plata (CARP). Table 1 shows the location of the stations, the sampling interval, and the period covered in each case.

All data were processed following the methodology proposed by D'Onofrio (1984), including the verification of the station datums. To eliminate local effects at each station, a 4-hour low-pass Butterworth filter of order 4 was applied to the original observed water level series. This filter removes high-frequency local effects such as seiches generated by the particular geographical conditions at each tide gauge location. Montevideo is the station with the highest high-frequency variability (Dragani et al., 2024; Perez et al., 2022) and was the one contributing the most noise to the model. As the sampling interval required for the empirical model is 60 minutes, series with a coarser sampling interval were interpolated using cubic spline interpolation and referenced to the historic Mean Sea Level using the available tidal datum information from each tide gauge. The filtered water levels, including the

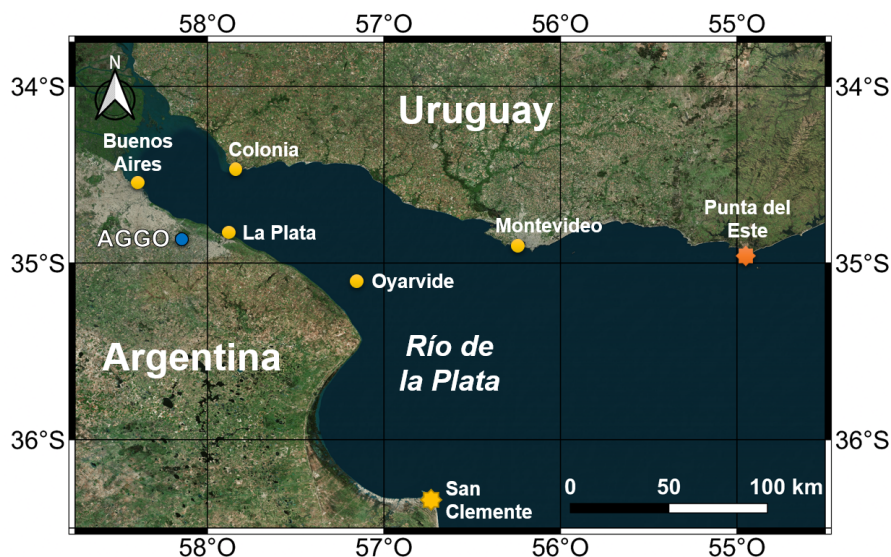


Figure 1. Location of the tide gauge stations and the AGGO observatory in the Río de la Plata estuary. Yellow circles indicate real tide gauge stations, the yellow star indicates the San Clemente station, which combines observed and modeled data, the orange star indicates the Punta del Este modeled station derived from tidal predictions and the Dynamic Atmospheric Correction (DAC) model, and the blue circle indicates the location of AGGO.

astronomical tidal variation, were used to examine the propagation of the model along the Río de la Plata. However, for the computation of the gravimetric response and the crustal deformation, the residual series were used. For this purpose, water level predictions were generated for each station using the tidal amplitudes and phases provided by the SHN, as published in the H-610 Tide Tables ([Servicio de Hidrografía Naval, 2026](#)). The hourly residual water level series at each station was obtained after removing the astronomical tide prediction from the observed series. A 15-hour low-pass Butterworth filter of order 4 was then applied to remove spurious tidal residuals generated when high or low tides are advanced or delayed due to positive or negative storm surge effects. The resulting filtered residual series at each station was then used to compute the empirical model characterizing the propagation of the storm surge along the river.

Modeled water-level stations

To complete the storm surge propagation, two modeled stations were required: San Clemente and Punta del Este ([Figure 1](#), [Table 1](#)). In the case of San Clemente, a modeled station was required because the available observed data do not cover the entire period. These stations are located at the outer ends of the river mouth and therefore define the origin of the water level and storm surge wave propagation into the estuary. At these stations, the water level was assigned as a combination of the astronomical tidal prediction, derived from the tidal harmonic constants provided by the SHN, and the storm surge signal obtained from the global Dynamic Atmospheric Correction (DAC) model ([LEGOS/CNRS/CLS, 1992](#)). This model combines a high-frequency barotropic ocean response computed with the Mog2D-G model and a low-frequency inverse-barometer correction, and is used as an auxiliary correction for satellite altimetry missions.

As with the tide gauge stations, the tidal prediction combined with the DAC storm surge signal was used at both modeled stations to examine the empirical model propagation, while for the computation of the gravity effects and elastic crustal deformation series, only the DAC storm surge heights were used. This is because the astronomical tidal signal is already removed from the gravimetric data through the harmonic analysis performed by the Ecole et Observatoire des Sciences de la Terre (EOST) analysis center as part of the IGETS Level-3 processing ([Boy, 2022](#)). The performance of the DAC model was evaluated against the available observed data at San Clemente, yielding a standard deviation of the differences of 0.14 m over more than 10000 compared hourly water levels, with 88% of the compared

heights falling within ± 0.20 m. These values are similar to those obtained for open-ocean stations such as Mar del Plata ($38^{\circ} 02' \text{ S} - 57^{\circ} 31' \text{ W}$), and approximately double when the same analysis is performed for stations in the interior of the Río de la Plata estuary like Buenos Aires or La Plata. Punta del Este could not be evaluated because no water level data were available for the study period. The modeled station water levels obtained from the DAC model for the analysis period are combined with the residual series from the tide gauge stations for the development of the empirical model.

Superconducting gravimeter data

Superconducting gravimeter observations were obtained from the SG038 instrument operated at AGGO, accessed through the IGETS database. Level-3 products processed by the EOST analysis center were used, which provide 1-minute gravity residual time series together with the modeled geophysical corrections and the original gravity and atmospheric pressure records. All available level-3 processed data from IGETS were incorporated into this work, covering the period from 1 January 2016 to 31 October 2022.

The Level-3 products are derived from calibrated 1-minute gravity and pressure measurements (Level-1) following a two-stage processing (Boy, 2022; Boy et al., 2020; Voigt et al., 2016). First, instrumental perturbations including offsets, gaps, and spikes are removed to generate Level-2 time series suitable for tidal analysis. Gravity residuals are then obtained by subtracting the main modeled geophysical contributions: solid Earth tides, ocean tidal loading, atmospheric loading, polar motion and length-of-day effects, and instrumental drift. Tidal corrections apply a hybrid strategy that combines locally adjusted parameters for the diurnal and sub-diurnal bands with theoretical models for long-period tides, using the DDW99 gravimetric factors (Dehant et al., 1999), the HW95 tidal potential (Hartmann & Wenzel, 1995), and the FES2014c ocean tidal loading model (Lyard et al., 2021). Atmospheric loading is computed from ERA5 surface pressure fields assuming an inverted barometer ocean response, supplemented by the local 1-minute pressure record in the near field of the station. This processing preserves long-period geophysical signals such as seasonal hydrological loading, making the Level-3 products suitable for studies of surface mass redistribution and non-tidal loading effects (Boy, 2022; Boy et al., 2020). It should be noted that the Level-3 products do not include a correction for non-tidal ocean loading, as the atmospheric loading model applies an inverted barometer assumption without a barotropic ocean model component (J.-P. Boy, personal communication, January 2026). The non-tidal ocean loading effect signal associated with storm surges in the Río de la Plata therefore remains present in the gravity residuals. This is consistent with the regional non-tidal ocean loading correction developed in this work, since both corrections act on physically distinct mass contributions. The Level-3 atmospheric correction removes, at the global scale, the air-pressure mass and its inverted-barometer ocean response. The wind-driven water redistribution of the storm surge, on the other hand, is modeled regionally from the observed tide gauge residuals.

Figure 2 shows the resulting gravity residual series for the available period, which exhibits a pronounced decrease of approximately 400 nm s^{-2} between October 2019 and October 2022. Figure 3, reproduced from Cañas (2025), shows part of the gravimeter series together with the evolution of the groundwater level. Cañas (2025) identifies a marked seasonal component in the groundwater level, followed by a sustained decline from early 2020, coinciding with a reduction in monthly and annual precipitation. To isolate the storm surge effect signal in the gravimeter residuals more clearly, a linear trend is fitted and removed for the period 13 August 2019 – 31 October 2022, coinciding with the groundwater decline (Figure 4). The storm surge impact is assessed both on the original gravity residual series and on the detrended series from which the drought-related groundwater contribution has been removed.

METHODOLOGY

Empirical model computation

The methodology applied for the computation of the empirical model follows that of Oreiro et al. (2018), extended to cover the period 2016–2025. The propagation of the tidal and storm surge waves is based

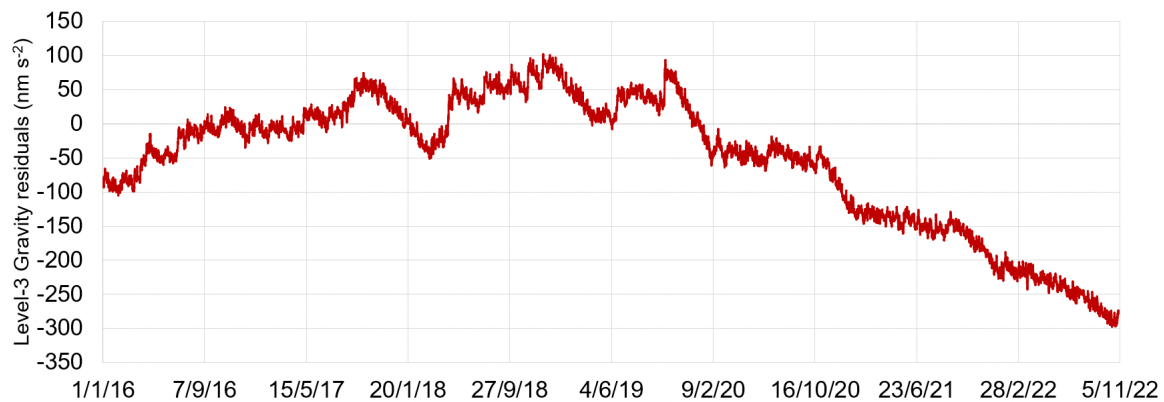


Figure 2. Level-3 gravity residual series for the period January 2016 – October 2022.

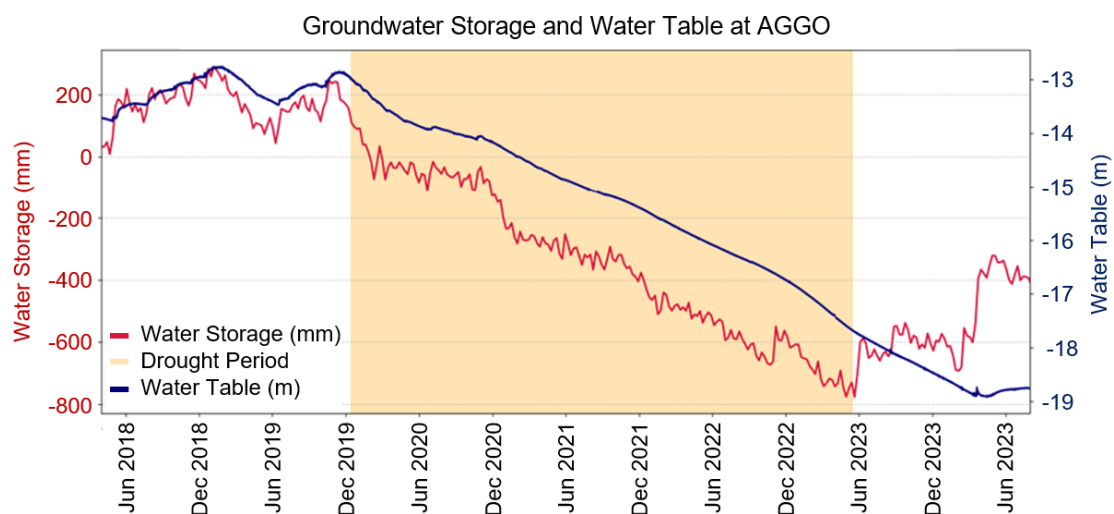


Figure 3. Gravity residual series from the SG038 superconducting gravimeter at AGGO (red) and groundwater level evolution (blue) for the period 2018–2024. Adapted from [Cañas \(2025\)](#).

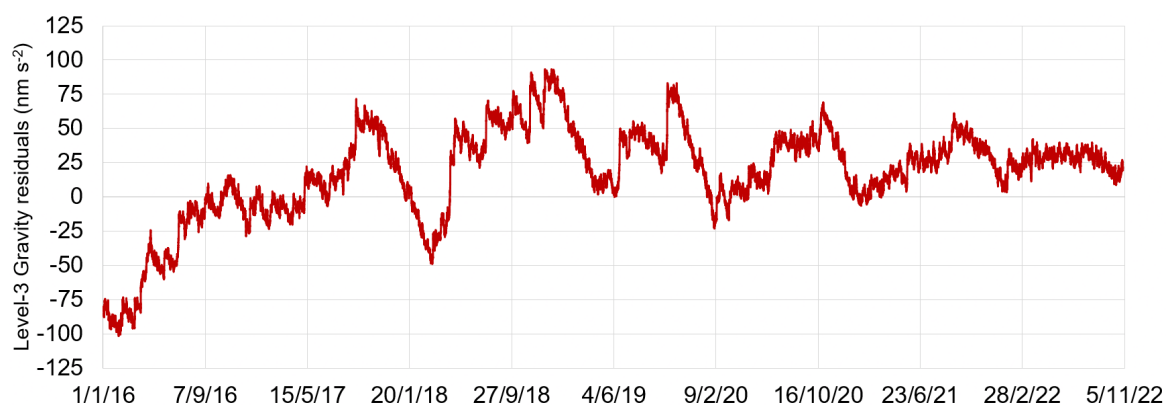


Figure 4. SG038 gravity residual series at AGGO after fitting and removing a linear trend for the period 13 August 2019 – 31 October 2022, corresponding to the groundwater decline identified by [Cañas \(2025\)](#).

on the tidal propagation parameters of the M2 constituent from the SEAT model ([D’Onofrio et al., 2012](#)), which is the dominant tidal constituent in the estuary. As the tide and storm surge propagate as shallow-water waves, the M2 phase field — the largest-amplitude constituent — is used to redistribute the water level at the grid points between gauged stations, providing a non-linear, observation-consistent interpolation rather than a linear one. Unlike the previous version of the empirical model, two modeled stations derived from the DAC model are incorporated to ensure complete spatial coverage of the Río

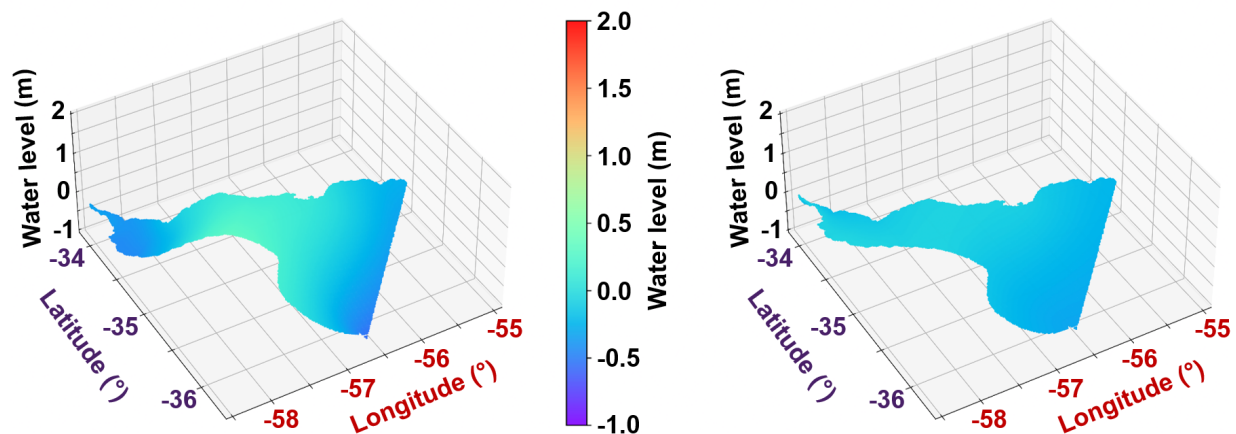


Figure 5. Water level distribution over the Río de la Plata grid on 10 January 2016. Left panel: total water level including the astronomical tide, used to examine the full wave propagation. Right panel: storm surge residual after removal of the astronomical tide, used to characterize the storm surge propagation and compute the gravimetric and crustal deformation response at AGGO.

de la Plata throughout the entire period. In addition, an improvement in the spatial resolution of the model was implemented: whereas the model proposed by Oreiro et al. (2018) used 5-minute time intervals to discretize the domain of the Río de la Plata — which introduced angular rounding in the wave propagation — the present model takes advantage of the high resolution of the SEAT model by obtaining the M2 phase for each 500 m grid cell, enabling a continuous propagation without spatial discretization. The model is computed at hourly intervals, consistent with the sampling interval of the water level residual series at each station. Figure 5 shows two examples of the model output for 10 January 2016: the left panel shows the total water level model including the astronomical tide, used to examine the full wave propagation, while the right panel shows the residual model after removal of the astronomical tide, used to characterize the storm surge propagation. In the left panel, the tidal wave propagation along the river is clearly visible, reaching maximum amplitude in its middle section. This spatial distribution is related to the M2 wavelength, which approximately matches the total length of the river. The validation of the new model was performed by comparing the gravimetric response at AGGO with that obtained by Oreiro et al. (2018) for the overlapping period in 2016.

Calculation of the gravimetric and deformation response at AGGO

The gravimetric response and elastic crustal deformation at AGGO are computed following the methodology of Oreiro et al. (2018), using the nloadf package of the SPOTL software (Agnew, 2012) with the same grid configuration, Earth model, and physical parameters. The grid covers the Río de la Plata between 54.935°W–58.515°W and 33.835°S–36.37°S at a resolution of $0.005^\circ \times 0.005^\circ$, comprising 125321 wet cells, each assigned with hourly water level values, out of 363012 total cells. The convolution is performed using the Green's functions computed following Farrell (1972) and assuming the Gutenberg-Bullen Earth model A, a water density of 1000 kg m^{-3} , and the center of mass of the solid Earth as the origin of the coordinate system. The value of 1000 kg m^{-3} is representative of the predominantly freshwater regime of the inner and middle Río de la Plata, where most of the load relevant to AGGO is located and where the salt wedge is restricted to the distant outer estuary (Guerrero et al., 1997). The methodology is applied here to the extended period 2016–2025, providing for the first time hourly time series of loading effects for both the gravity change and the North, East, and Up elastic crustal displacements at AGGO for the full decade.

Comparison with the IGETS superconducting gravimeter series

The gravimetric loading effect series computed with SPOTL is compared with the IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022. The assessment is performed on two versions of the gravity residual series: the original Level-3 residuals, and a detrended

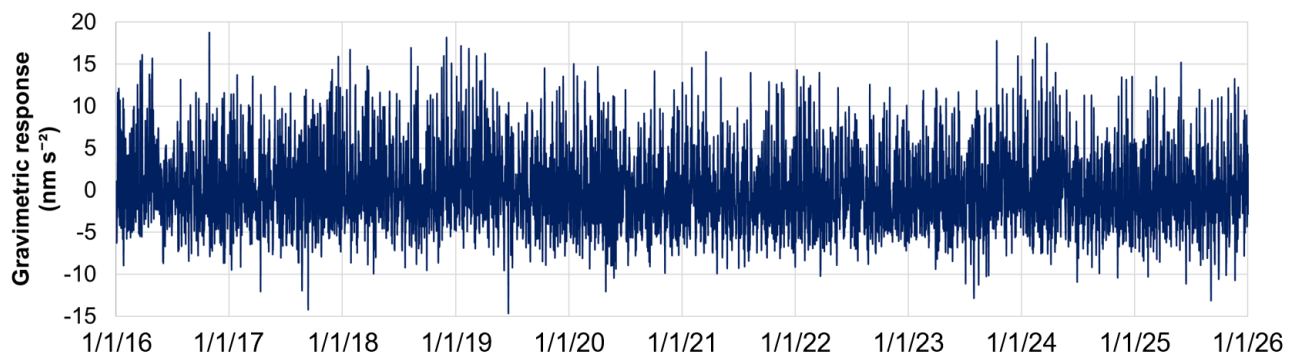


Figure 6. Hourly gravimetric effect time series at AGGO computed from the empirical storm surge model of the Río de la Plata for the period 2016–2025.

version from which the long-period signal associated with the groundwater decrease identified by Cañas (2025) has been removed by fitting and subtracting a linear trend for the period 13 August 2019 – 31 October 2022. This two-series approach allows the impact of the storm surge correction to be evaluated both in the presence and absence of the dominant hydrological signal.

For each series, the storm surge gravimetric loading effect is subtracted and the standard deviation of the residuals is computed before and after the correction, providing a global measure of the improvement in variability over the entire period. To further characterize the frequency-dependent impact of the correction, a continuous wavelet transform is applied to both the original and corrected series using the Morlet wavelet, following the approach of Oreiro et al. (2018). The resulting wavelet power spectra are compared to identify reductions in spectral energy at the periods associated with storm surge activity in the Río de la Plata. In addition, the globally averaged wavelet power spectrum is computed for each series, and the relative reduction in spectral power as a function of period is quantified, allowing a precise identification of the frequency bands where the empirical model has the greatest impact on the gravity residuals.

RESULTS

Gravimetric effect and crustal deformation time series at AGGO

Figure 6 shows the hourly gravimetric effect time series at AGGO computed from the empirical storm surge model for the period 2016–2025, with values ranging between -14.7 and $+18.8 \text{ nm s}^{-2}$. Figure 7 shows the corresponding elastic crustal displacement series in the East, North, and Up components for the same period.

The Up component exhibits the largest displacements, ranging from -7.0 to $+5.5 \text{ mm}$, whereas the East and North components are considerably smaller, with ranges of -1.4 to $+2.1 \text{ mm}$ and -1.2 to $+1.0 \text{ mm}$, respectively. As expected for an elastic surface load, the horizontal displacement scales with the vertical displacement and is directed toward the center of the water mass. The partitioning of this horizontal motion between the East and North components is controlled by the azimuth of the loading centroid relative to AGGO. Accordingly, the East component is almost linearly related to the vertical displacement ($R = -0.98$), whereas the North component exhibits a weaker relationship ($R = -0.87$), indicating that the effective loading centroid is preferentially aligned along the East–West direction. Because AGGO is located west of the Río de la Plata, positive storm surge events, associated with an increase in water mass, produce downward and eastward displacements. The northward displacement is less intuitive from a purely geometric perspective and instead reflects the azimuth of the effective loading centroid. Negative storm surge events produce displacements in the opposite directions.

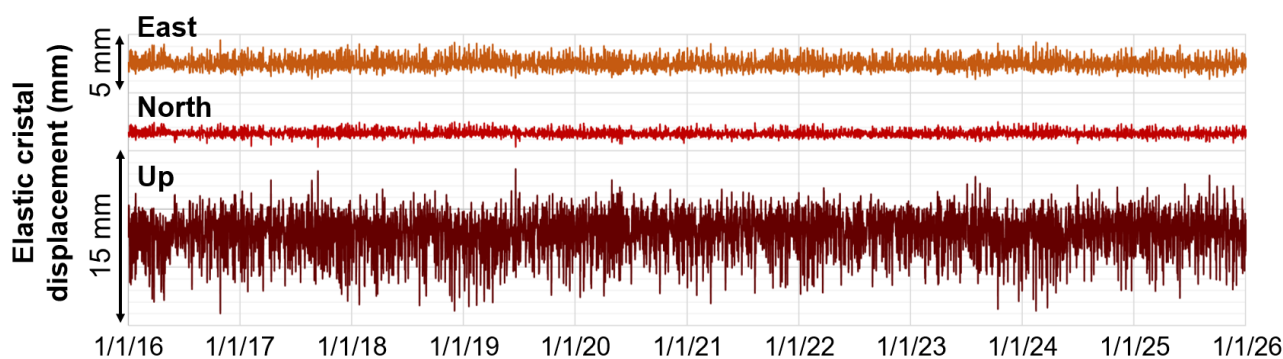


Figure 7. Elastic crustal displacement time series at AGGO computed from the empirical storm surge model of the Río de la Plata for the period 2016–2025. From top to bottom: East, North, and Up components in mm.

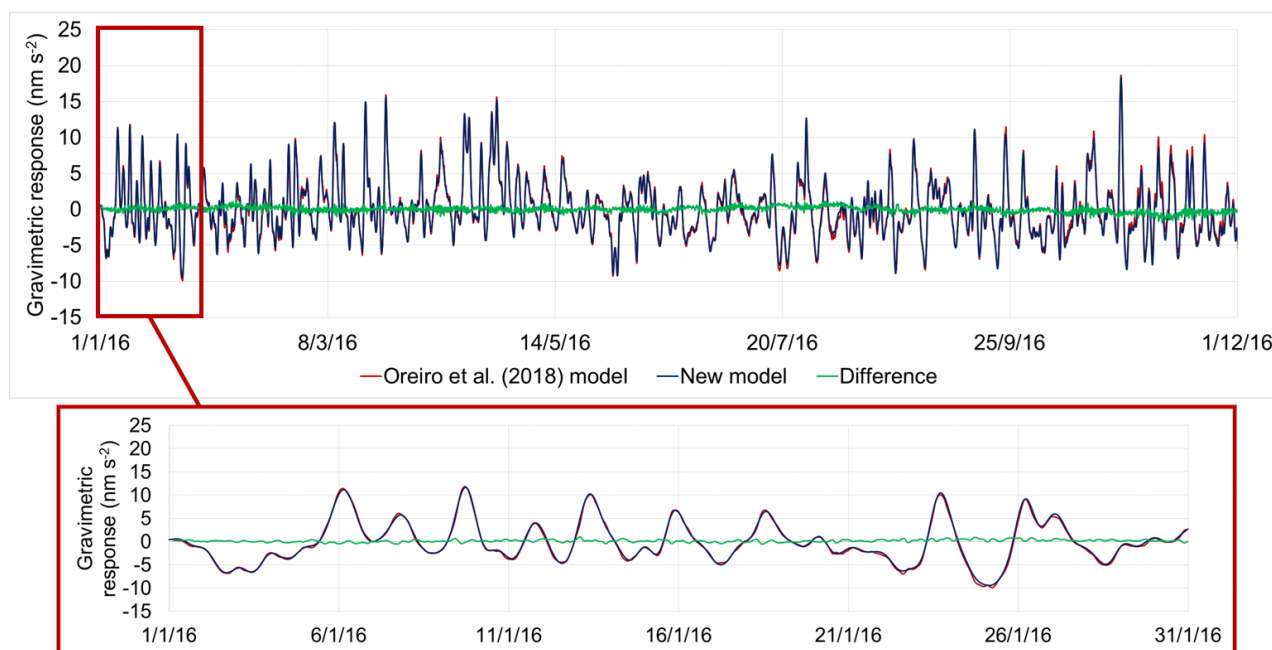


Figure 8. Comparison between the gravimetric response derived from the empirical model developed in this work (blue line) and the results from Oreiro et al. (2018) (red line) for the overlapping period in 2016. The green line shows the differences between both series.

Assessment of the estimated gravimetric loading effect

To assess the capability of the empirical model to provide the gravimetric response, its output is compared with the results obtained by Oreiro et al. (2018) for the overlapping period from 1 January to 30 November 2016. Figure 8 shows both series together with their differences, revealing a clear agreement between the two models. The differences present a standard deviation of 0.4 nm s^{-2} and a range of $\pm 2 \text{ nm s}^{-2}$, with the largest discrepancies coinciding with the highest-amplitude storm surge events. These differences originate in the modifications introduced in the new model — namely the incorporation of two modeled stations derived from the DAC storm surge, the increase in spatial resolution, and the application of the Butterworth filters to remove high-frequency local effects and spurious tidal residuals.

Since the largest storm surge amplitudes occur in the inner part of the Río de la Plata (Buenos Aires, La Plata, and Colonia), and the greatest contribution to the gravimetric effect observed at AGGO is due to the proximity of the water mass, the influence of the outer modeled stations on the final result is limited. To illustrate the limited influence of these stations, Figure 9 shows a synthetic scenario computed with SPOTL in which a water level of 1 m is assigned to the San Clemente and Punta del Este modeled stations while all remaining stations are set to 0 m with respect to Mean Sea Level. The resulting

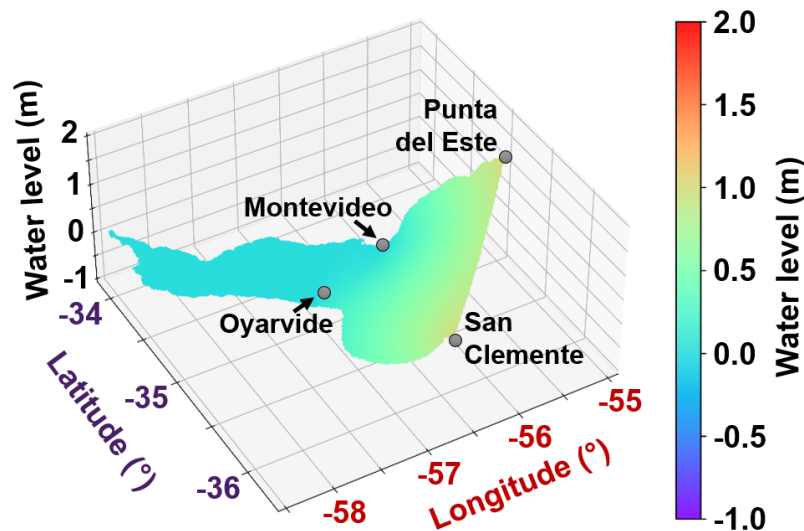


Figure 9. Example of the water level distribution along the Río de la Plata used to assess the influence of the outer modeled stations on the gravimetric effect at AGGO. San Clemente and Punta del Este are assigned a water level of 1 m, while all remaining stations are set to 0 m with respect to Mean Sea Level.

gravimetric effect of only -1.57 nm s^{-2} , compared to the -11.1 nm s^{-2} obtained when a uniform 1 m storm surge is applied across all stations simultaneously, confirms that the outer stations account for less than 15% of the total effect. This limited contribution reduces the impact of any uncertainty introduced by the use of modeled storm surge levels at those locations. Given the agreement found between the DAC model and the San Clemente observations, the use of modeled stations introduces no relevant uncertainty in the computed results. The differences between the two models therefore arise primarily from the improved water level modeling in the inner estuary and from the additional filtering applied in the present model, which removes high-frequency local oscillations (e.g. seiches) and spurious tidal residuals. These components do not represent genuine storm-surge loading and, in the case of the tidal residuals, have already been removed from the IGETS Level-3 gravity residuals by the tidal analysis; their removal therefore makes the new model more consistent with the Level-3 residuals.

Comparison with the IGETS superconducting gravimeter series

The gravimetric loading effect series is subtracted from the IGETS Level-3 gravity residuals of the SG038 for the period January 2016 – October 2022. Figure 10 presents the original and the corrected gravity residual series together with the gravimetric effect series computed from the empirical model, considering both the original and the detrended gravity series. In both cases the coincidence between the model peaks and the storm surge signal in the gravity residuals is clearly visible, as well as the consistent reduction of those peaks in the corrected series — the original series appears behind the corrected one at every surge event, confirming that the empirical model captures and removes the loading-effect signal effectively.

The correction reduces the standard deviation from 96.9 to 96.4 nm s^{-2} for the original series, and from 34.7 to 34.5 nm s^{-2} for the detrended series, representing a reduction of 0.5% and 0.7%, respectively. These small reductions reflect the fact that the standard deviation integrates contributions from all frequency bands present in the gravity residuals, including the hydrological signal associated with groundwater variations, rainfall-induced loading, and other geophysical processes of larger amplitude that dominate the overall variability. Since the storm surge signal is confined to a specific range of periods, a frequency-dependent analysis is required to properly quantify its impact on the gravity residuals.

A closer inspection of the largest events in Figure 10 shows that, although the model reproduces the timing and sign of the surge-induced peaks, the corrected series still retains a residual of the

same sign at the extremes, suggesting that the empirical model may underestimate the amplitude of the gravimetric loading effect. To obtain a first estimate of this underestimation, both the modeled effect and the SG residual were high-pass filtered to retain periods shorter than ~12 days, thereby isolating the storm-surge band and removing the long-period hydrological component (groundwater and seasonal loading) that dominates the residual but is not represented by the model. Within this band the comparison yields an amplitude underestimation of the order of 20%, taken as the value that minimizes the standard deviation of the differences between the observed and modeled series. This value, however, should be regarded as a single, preliminary estimate representative of the surge band as a whole. A complete assessment requires verifying whether the underestimation is consistent across each period interval within the storm-surge band and confirming that correcting for this underestimation does not degrade the spectral content at periods outside it.

To characterize the frequency-dependent impact of the correction, a continuous wavelet transform is applied to both the original and detrended gravity residual series, before and after subtracting the empirical model. [Figures 11](#) and [12](#) show the wavelet power spectra and the frequency-dependent impact of the correction for the original series, while [Figures 13](#) and [14](#) show the equivalent results for the detrended series. In both cases, a clear reduction in spectral energy is observed at periods between approximately 1 and 12 days, coinciding with the characteristic periods of storm surge activity in the Río de la Plata. The globally averaged wavelet power spectrum and the relative reduction in spectral power as a function of period, shown in [Figures 12](#) and [14](#), reveal a maximum reduction of approximately 70% and 80% for the original and detrended series, respectively. The higher reduction observed in the detrended series reflects the fact that the removal of the long-period hydrological trend reduces the overall variability of the series, allowing the storm surge signal to represent a larger fraction of the remaining variance and making the impact of the correction more clearly visible. Outside the storm surge frequency band, the original correction introduces no significant changes in the spectral content of either series, confirming that the empirical model acts selectively on the periods of interest without degrading the signal at other frequencies.

To evaluate the possible underestimation identified at the largest surge peaks in [Figure 10](#), the wavelet analysis was repeated after applying uniform scaling factors of 1.1, 1.2 and 1.3 to the modeled effect, shown together with the unscaled case in the left and right panels of [Figures 12](#) and [14](#). The results reveal a threshold at a period of 2.75 days. Below this value the unscaled model yields the largest power reduction, so that no amplitude rescaling improves the correction in the band of the shorter and most frequent storm surges. Above 2.75 days, the scaled models remove a slightly larger fraction of the power, although the improvement remains below 10%. This indicates that the apparent underestimation of the storm surge effect is confined to periods longer than 2.75 days, and that applying a uniform scaling factor would degrade the correction at shorter periods. For this reason, the unscaled model is retained as the optimal representation of the storm surge loading effect, while the residual contribution at longer periods may be associated with other processes not represented by the modeled estuarine water-level field.

CONCLUSIONS

The results of this study demonstrate that the non-tidal ocean loading of the Río de la Plata constitutes a geophysical signal that is both measurable and correctable in superconducting gravimeter observations. Its impact is strongly frequency-dependent and conventional ocean tide loading corrections are insufficient to account for the full loading effect of the estuary. Consequently, storm surge models are a necessary complement to standard geodetic data processing at this site.

The selective action of the empirical correction on the 1–12 day period band—achieving a spectral power reduction of up to 80% despite a modest reduction in overall standard deviation—confirms that the storm surge signal is spectrally distinct from other geophysical contributions, such as groundwater variations and rainfall-induced loading. This spectral separability is advantageous for geodetic applications, as it implies that the correction can be applied without degrading other signals of interest in the residuals. Moreover, this result highlights that global variance metrics are often poor indicators of the effectiveness of frequency-specific corrections in the presence of broadband noise. Frequency-domain

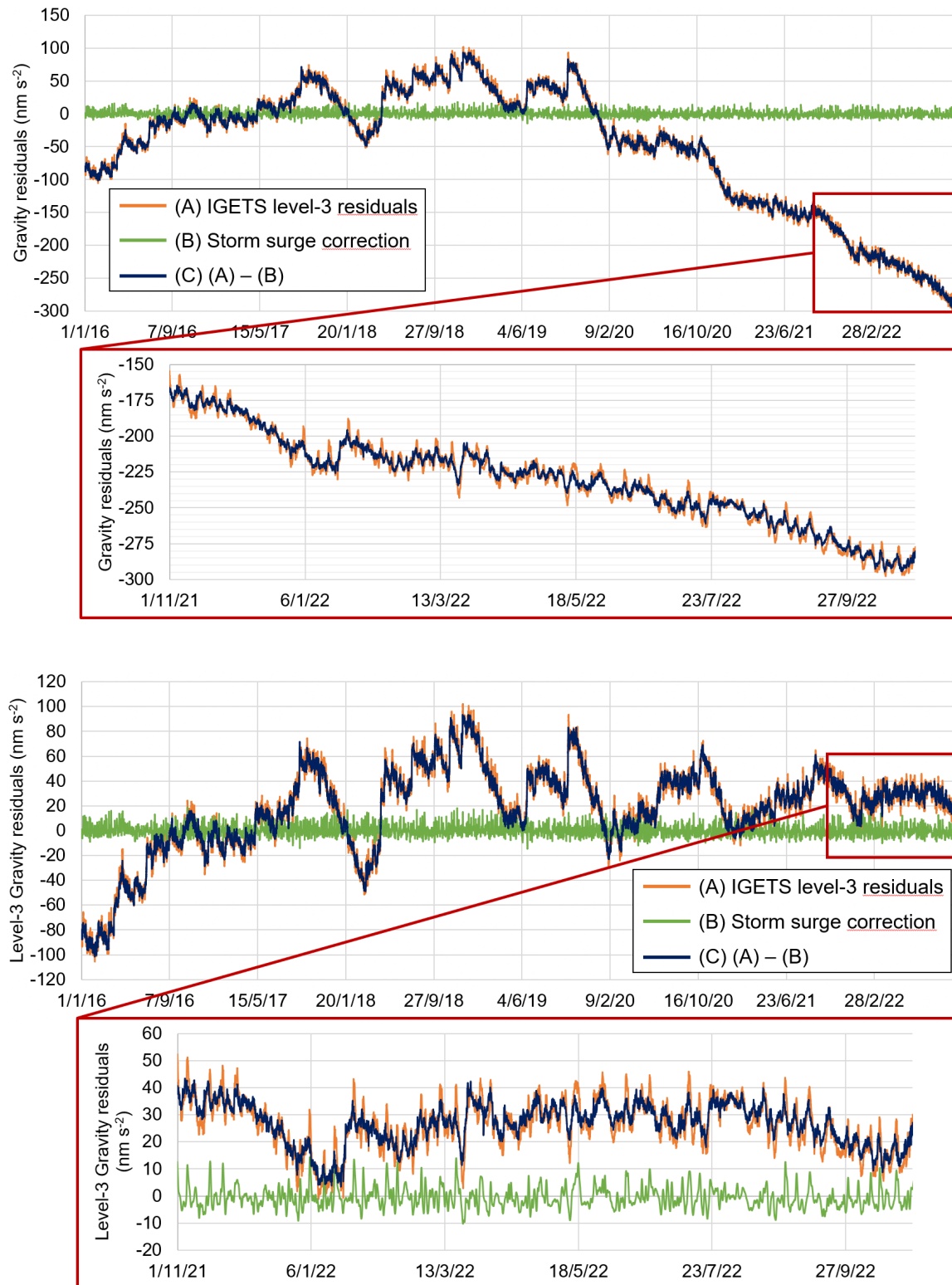


Figure 10. IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022 before (orange) and after (blue) applying the gravimetric effect series computed from the empirical model (green). Upper panel: original series. Lower panel: detrended series after removal of the linear trend associated with the groundwater decline identified by [Cañas \(2025\)](#). The insets show a detail of the last year of the period.

diagnostics, such as wavelet analysis, therefore provide more appropriate tools for evaluating the quality of geophysical corrections. Even in the presence of higher-variability signals, analyzing the signal by frequency bands allows for the precise quantification of the surge-induced loading effect.

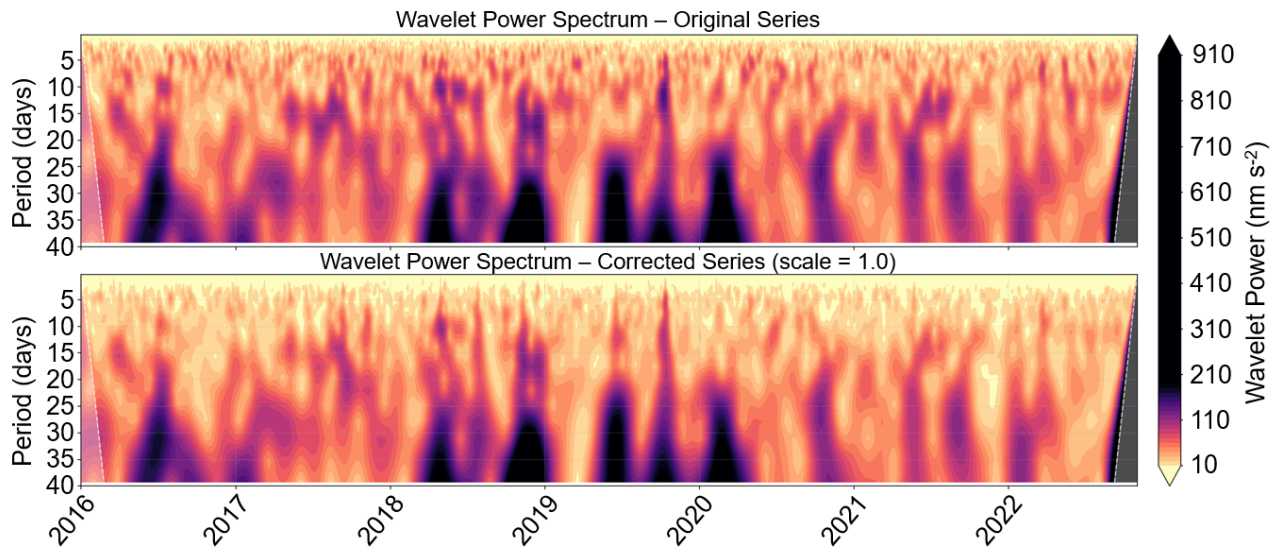


Figure 11. Morlet wavelet power spectra of the IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022. Upper panel: original series. Lower panel: series corrected by subtracting the empirical storm surge gravimetric loading effect. The dashed line indicates the cone of influence.

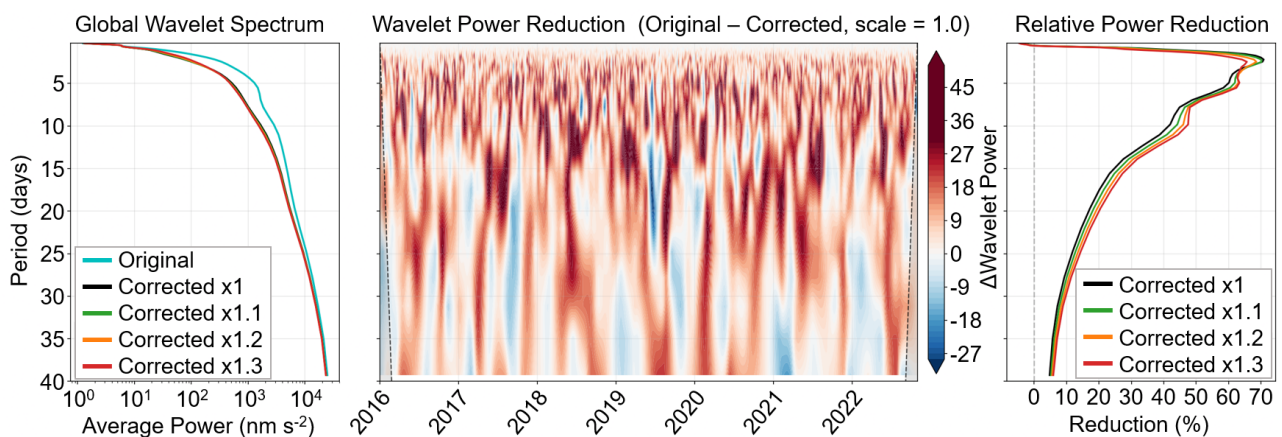


Figure 12. Frequency-dependent effect of the empirical storm surge correction on the IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022. Left panel: globally averaged wavelet power spectrum of the original series (cyan) and of the corrected series obtained by subtracting the modeled effect scaled by factors of 1.0, 1.1, 1.2 and 1.3. Central panel: difference in wavelet power between the original and corrected (unscaled) series (red: reduction, blue: increase). Right panel: relative reduction in globally averaged wavelet power as a function of period, for the same scaling factors. The dashed line in the central panel indicates the cone of influence.

Empirical models are highly effective provided they accurately represent water level variability. While numerical models often struggle to reproduce the complex dynamics of the middle and inner Río de la Plata, they generally perform better in the outer estuary. Since the gravimetric contribution of the outer region on AGGO is relatively small, a global model based on strategically located stations, such as San Clemente and Punta del Este, proved sufficient. The ability to compensate for the limitations of numerical models through strategically placed tide gauge stations has practical implications for observatories in similar estuarine environments, where complete tide gauge coverage may not be available. A simplified model based on observations of near stations may be adequate if the propagation and amplification/attenuation processes of the surge are properly modeled. However, when using local data, it is essential to filter out site-specific oscillations, such as seiches, to ensure that the derived loading signal reflects estuary-scale dynamics.

The frequency-dependent analysis also shows that the empirical model effectively represents the

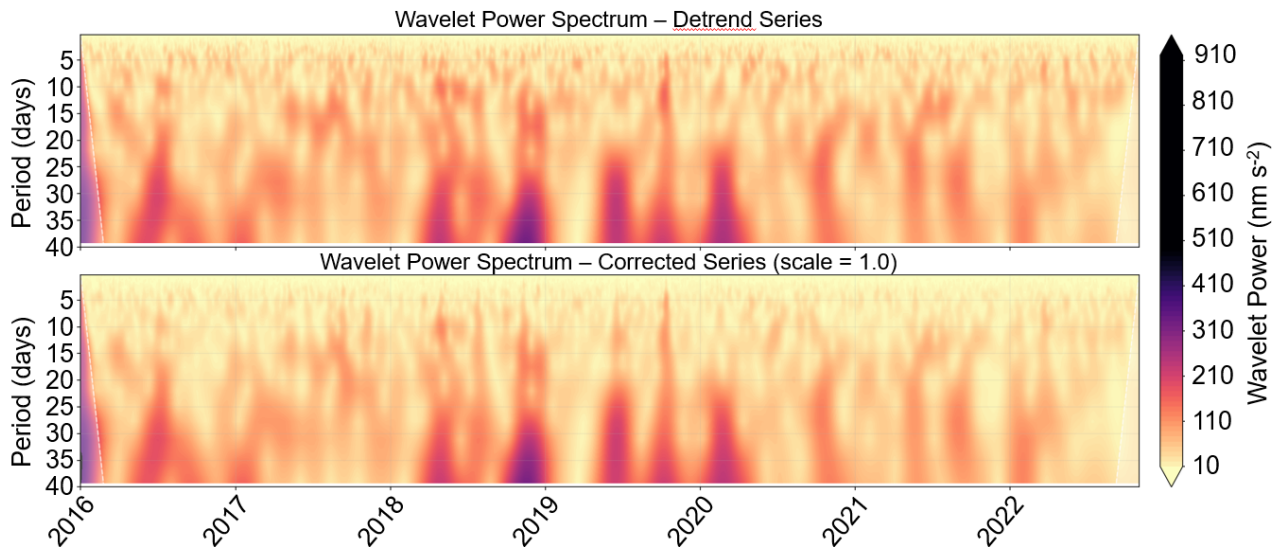


Figure 13. Morlet wavelet power spectra of the detrended IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022. Upper panel: detrended series. Lower panel: detrended series corrected by subtracting the empirical storm surge gravimetric loading effect. The dashed white line indicates the cone of influence.

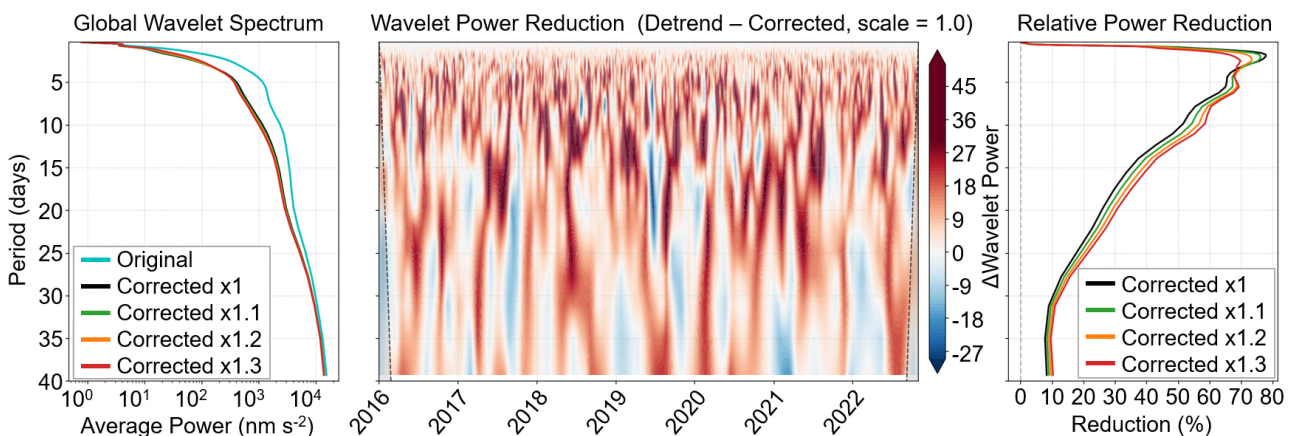


Figure 14. Frequency-dependent effect of the empirical storm surge correction on the detrended IGETS Level-3 gravity residuals of the SG038 at AGGO for the period January 2016 – October 2022. Left panel: globally averaged wavelet power spectrum of the detrended original series (cyan) and of the corrected series obtained by subtracting the modeled effect scaled by factors of 1.0, 1.1, 1.2 and 1.3. Central panel: difference in wavelet power between the detrended original and corrected (unscaled) series (red: reduction, blue: increase). Right panel: relative reduction in globally averaged wavelet power as a function of period, for the same scaling factors. The dashed line in the central panel indicates the cone of influence.

gravimetric loading effect of storm surges at periods shorter than approximately 3 days. This range encompasses the shorter and most frequent storm surge events, for which amplitude rescaling does not improve the correction. At longer periods, a small residual contribution remains, accounting for less than 10% of the power and not removable by a uniform scale factor, suggesting the presence of additional processes that warrant further investigation. Overall, the unscaled empirical model provides an effective correction of the non-tidal ocean loading effect across the storm surge band, reproducing both the timing and the dominant fraction of the signal.

The decade-long correction series produced in this study provides a continuous, high-resolution dataset that can significantly improve the quality of all geodetic techniques at AGGO. Given that the non-tidal ocean loading effect contributes to position time series at nearly the centimeter level, the model developed here can be directly integrated to refine GNSS, VLBI, and SLR solutions, thereby

reducing a source of noise that is not accounted for in standard processing chains. This represents an important step toward achieving the precision objectives of the Global Geodetic Observing System (GGOS). Moreover, because the empirical model describes the loading effect over the whole estuary, its applicability is not restricted to AGGO: the modeled displacements can be used to correct the coordinate time series of other GNSS stations in the region, such as the International GNSS Service (IGS)/Red Argentina de Monitoreo Satelital Continuo (RAMSAC) stations IGM1, LPGS and MTV1, extending the benefit of the correction to the regional geodetic network.

Finally, the identification of residual signals attributable to rainfall and groundwater variations underscores the need for a comprehensive hydrological loading model for AGGO. Furthermore, it is recommended that IGETS and similar geodetic services incorporate a broader range of geophysical correction models into their platforms. Enabling users to select between global and site-specific models would not only improve the accuracy of global products but also encourage the development and publication of high-quality local studies for other observatories worldwide.

DATA AVAILABILITY

The correction time series and other derived products generated in this study are available from the corresponding author upon reasonable request.

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