An extreme negative sea level in the Mediterranean Basin: San Giorgio case study compared with Adriatic Sea

Claudia Stramaccioni
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
cl.stramaccioni@gmail.com

Andrea Bianco
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
andrea.bianco@isprambiente.it

Saverio Devoti
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
saverio.devoti@isprambiente.it

Domenico Macaluso
Scientific Director of WWF Sicilia
Area Mediterranea
Agrigento, Italy
mimmomac57@gmail.com

Giuseppe Mazzotta
President of WWF Sicilia
Area Mediterranea
Agrigento, Italy
g.mazzotta54@gmail.com

Arianna Orasi
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
arianna.orasi@isprambiente.it

Luca Parlagreco
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
luca.parlagreco@isprambiente.it

Marco Picone
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
marco.picone@isprambiente.it

Gabriele Nardone
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
gabriele.nardone@isprambiente.it

Maurizio Ferla
ISPRA - Italian Institute for Environmental Protection and Research
Rome, Italy
maurizio.ferla@isprambiente.it

***Abstract*—The aim of this paper is to discuss the case of an extreme negative sea level phenomenon that occurred along Sicily Island's coasts (Italy). Sea level time series associated to six stations that are part of the Italian tide gauge network have been analysed. By deriving the tidal residual and by evaluating meteorological parameters' trends, it was possible to give an explanation to this phenomenon.**

Keywords—tides, meteorological residual, negative sea level, sea monitoring, RMN

I. Introduction

Monitoring activities are really important to be carried out in many fields of application. In the civil engineering sector, for example, monitoring activities are essential in order to guarantee infrastructure safety during and after its construction. In the case under consideration, that is the sea domain, monitoring systems for the sea, both in terms of tidal waves and wind waves observations, are strongly needed for many reasons: assuring a qualitative planning, designing and operating of coastal and marine infrastructure, guaranteeing coastal cities' safety, calibrating and validating forecasting models and quantifying the amount of energy associated to water masses movements.

The Mediterranean basin, in which the Italian peninsula is situated, is characterised by moderate tidal variations [1], but in some areas of the world tidal cycles are related to huge energy fluxes along the coasts. This may result in coastal morphology variations, temporarily submergence of urbanised areas and other phenomena that are needed to take constantly in consideration. Therefore, implementing monitoring systems for the sea means also protecting our natural, cultural and historical heritage.

The Italian national tide gauge network "Rete Mareografica Nazionale" (hereinafter RMN) and the Italian national wave network "Rete Ondametrica Nazionale" (hereinafter RON) are both in charge of ISPRA. Their aim is to continuously monitor the sea state along Italian coasts both in terms of tidal waves by the RMN and wind waves by the RON, paying attention to differentiate between the two contributions. Indeed, stations that are part of the RMN are usually situated in more protected areas such as harbours, whereas stations that constitute the RON are located in deep-water conditions in order to avoid waves propagation effects. The most representative parameters measured by the RMN and the RON are the sea level and the significant wave height respectively, in addition to other noteworthy variables such as water temperature, air temperature, percentage of humidity, atmospheric pressure, wind speed and wind direction.

In this paper, the attention will be focused on measurements carried out by the RMN. Sea level variations that occur because of tide cycles are measured by tide gauges located in structures that allow filtering of high frequency sea surface movements. The longer sea level time series the better: it allows to more accurately distinguish the astronomical contribution of tide from the meteorological one and to better interpret these phenomena from a statistical point of view. The meteorological residual is mainly due to wind and atmospheric pressure variations effects, hence assessing sea level means reading tide gauge measurement in conjunction with the previously mentioned parameters values.

Starting with these theoretical premises, this paper discusses the case of an extreme negative sea level phenomenon that occurred in the Mediterranean basin, examining the relationship between astronomical and meteorological contribution of tide and consequently highlighting the importance of implementing and maintaining monitoring systems for the sea. In addition to that, the present work also compares trends associated to the site of interest with those peculiar to the Adriatic Sea. Indeed, it is worthy to mention that the Mediterranean basin is characterised by a high rate of alternation between cyclones and anticyclones [2] which differently affect each geographical area depending on its shape, water depth, available fetch [3] and coast orography [2].

INTERREG V-A IT HR ADRIACLIM PROJECT

Much of the current literature on sea level phenomena pays particular attention on extreme positive events [4], [5], [6], [7], [8], [9], [10], [11], whereas there is a smaller body of literature that is concerned with the occurrence of extreme negative sea level phenomena [3], [12], [13].

Among the latter, [12] examined sea level, atmospheric pressure and wind time series, namely from 1939 to 2001, in order to study, in terms of frequency and effects, the evolution of negative sea level extremes at Trieste. The aforementioned city is located in the Northern Adriatic Sea, that is a well-known area for the occurrence of positive sea level anomalies that often happen in Venice city and nearby [10]. This is the reason why positive extreme events are usually analysed in more detail, even if negative sea level phenomena sometimes take place in that area. Reference [12] investigated both negative and positive sea level events at Trieste and showed that the negative ones are strongly correlated with local high atmospheric pressure and Easterly or Northeasterly winds conditions. The final results indicated that negative events occur mostly in winter, that is the period in which Easterly and Northeasterly winds are typically more frequent and in which the atmospheric pressure field is more active and therefore characterised by the largest extremes.

Just as [12] focused on a specific location, so [3] and [13] evaluated sea level phenomena considering a bigger scale, that is the whole Mediterranean Sea coastline.

More specifically in [3], data collected by tide gauges located along the northern Mediterranean coast, mean sea level pressure (MSLP) and surface wind fields obtained by a model hindcast, MSLP and wind fields produced by climate model simulations and hourly sea level fields calculated by a model are all embedded in a climate model ensemble in order to analyse positive and negative sea level phenomena in the area of interest. Overall, this study set out some important concepts associated to the physics of sea level phenomena. First, it is stated again that negative sea level anomalies can be produced by high atmospheric pressure conditions in deep waters and by wind that blows offshore in shallow waters. Second, two different regimes have been identified: the wind is deemed as the main cause for sea level anomalies both in the North Adriatic and in the Gulf of Gabes because of the long fetch and shallow waters conditions whereas MSLP is the main cause in all the other cases. Final results showed that the largest negative sea level phenomena occur in the Gulf of Gabes.

At the same time, in [13] it is argued that both positive and negative sea level events are correlated to the position and intensity of cyclones and to their associated winds. Moreover, the western Mediterranean area, that includes both Spain and Italy, is considered as the main cyclogenesis region for positive and negative sea level anomalies.

As mentioned previously, a considerable amount of literature has been published on positive sea level phenomena. In particular, [4] focused on the sea level rise effects on the Adriatic Sea in terms of tidal characteristics and events, whereas [5] consists in an ex-post analysis of the meteorological and oceanographic conditions associated to the storm that took place along Italian coasts, and not only, in November 1966. Research activities carried out in [6], [7] and [8] describe the obtained sea level trends for the Mediterranean Sea and the North Atlantic region. Reference [9] reported an analysis on sea level extremes in southern Europe and [10] enriched these results extrapolating them on a seasonal basis. Finally, [11] evaluated synoptic information related to high-frequency sea level events in the Mediterranean Sea.

Other studies regarding extreme negative sea level phenomena can be found in [14] and [15]; the events under examination take place really far from the area of interest in the present work, but considering them might be useful to enrich the presented overview.

Reference [14] examined exclusively negative sea level phenomena that occur in Rio de la Plata estuary (South America): monitoring activities of levels are crucial to ensure both the navigability of the river and the proper availability of drinking water. Results showed that low levels are usually measured during the austral winter in which a combination of two anticyclones, a cyclone and Northwesterly winds typically happen.

Finally, the research proposed by [15] focused the attention on the southeastern coast of China and, by means of numerical techniques and the use of an asymmetry index, they accomplished the task of modelling both positive and negative sea level phenomena. In particular, they studied the link existing between sea level events and the parameters related to tropical cyclones.

Therefore, the current study contributes to a better understanding of the less investigated extreme negative sea level phenomena that occur in the Mediterranean Basin.

The site that is of interest in this research is located in Sciacca (Sicily Region, Italy), more specifically along the Village of San Giorgio’s coast; the international non-governmental organization “WWF Sicilia Area Mediterranea” noticed an uncommon low-tide phenomenon on the 22-23 March 2022 and they asked ISPRA to critically examine it. This has made it possible to observe the so-called “Isolotto di San Giorgio”, that, according to inhabitants’ testimonies, hadn’t been seen for more than hundred years (Fig.1).

The remaining part of the paper proceeds as follows: Chapter II analyses the RMN network in more detail, Chapter III described methods used in this study, Chapter IV shows results and discussion and in Chapter V conclusions are outlined.

Fig. 1. Low-tide phenomenon: emergence of “Isolotto di San Giorgio” (Photo provided by WWF Sicilia Area Mediterranea)

II. RMN NETWORK

The RMN is composed of 36 stations, each one being able to measure both sea level and meteorological parameters. Generalizing, it is possible to distinguish two types of stations: the ones in which equipment is placed in a stilling well inside a civil structure sustained by dolphins and the ones in which instruments are located in a protected stilling well but without the presence of the surrounding civil structure. The last and more recent option takes advantage of reduced maintenance costs and times. In any case, both types of stations are equipped with a radar sensor and a hydrometer.

Data that are going to be considered in the present paper are the ones collected by radar sensors, characterized by a frequency of acquisition of 1 observation per minute; in some stations this frequency switches to 15 seconds for experimental purposes. Concerning levelling necessities, it is worth mentioning that measurements of the vertical displacements of tide gauges benchmarks are periodically carried out; moreover, fixed GNSS antennas have also been implemented in some stations in order to continuously monitor vertical displacements.

Since its birth in 1998, RMN data have been managed by different organisations. Currently, all processes associated to tidal data, namely data acquisition, validation and manipulation, are in charge of the same institution since 2010. Furthermore, tidal data collected by Hydrographic Local Services prior to the RMN creation also exist; ISPRA is at-present working on data alignment in order to guarantee validated and up-to-date sea level time series.

It is useful to highlight some of the processes that are needed to be applied in order to classify tidal data as validated: identification of spike, measurement interruptions, missing data and data without any physical meaning, extrapolation of hourly data, application of filters such as the Doodson [16] and the Bloomfield [17] ones, analysis of the meteorological residual and all the other statistical studies that are part of the Interreg IT-HR AdriaClim Project requirements.

In the present paper six stations have been selected to examine the case of interest, namely Sciacca, Lampedusa, Palinuro, Taranto, Vieste and Ortona. All the stations are equipped with a civil structure, except for Sciacca in which the instruments are located in a stilling well close to the harbour's dock. In Fig. 2 a map with all the stations that are part of the RMN is shown. The ones that are considered in this paper are pointed out with different colour symbols.

III. METHODS

In order to evaluate and to interpret the extreme negative tide phenomenon that took place along the coast of the Village of San Giorgio (37°29'07.0"N 13°10'30.8"E), sea level timeseries, in addition to atmospheric pressure time-series, have been considered. This is because, as previously stated, the meteorological contribution of tide strongly depends on this parameter's behaviour.

Six stations have been selected: Sciacca and Lampedusa have been used because they are close to the site of interest, whereas Palinuro, Taranto, Vieste and Ortona have been chosen for comparison purposes. More specifically, they have been considered in order to appreciate and to assess atmospheric pressure conditions effects on different areas of the Mediterranean region, including the Adriatic Sea.

The analysed time span, varying according to the stations, starts in January/February 2010/2011, except for Taranto time series that starts in January 2009, and ends at the end of April 2022/beginning of May 2022. The extreme phenomenon has been observed on the 22-23 March 2022.

Going into the details, the following steps have been applied to the sea level time-series:

- Outliers have been removed from raw data according to (1) or (2), in case of values located either on the far left or on the far right of the distribution that represents them:

$$SL < Q1 - 3 \cdot IQR \quad (1)$$

$$SL > Q3 + 3 \cdot IQR \quad (2)$$

  where SL is the sea level, Q1 is the first quartile, Q3 is the third quartile and IQR = Q3-Q1.

- Starting from the original frequency of acquisition, mainly equal to 1 observation per minute, data have been aggregated on an hourly basis.
- A Python package called Pytides [18] based on harmonic constituents [19] has been used to derive the astronomical contribution of tide from tidal observations by doing a fitting of amplitudes and phases through a least-squares minimisation function. This procedure has been applied to the whole available time series, that is more than ten years long. Thereafter, the meteorological residual has been obtained by subtracting the predicted tides from the measured ones.
- After having identified an exceeding threshold equal to the quantile of order 0.02, groups of consecutive events above this exceeding threshold have been selected.
- The duration of time for which the minimum values of the meteorological contribution of tide occur has been calculated. In other words, negative residuals persistence has been evaluated for each group.

The whole procedure has been applied to the six stations under examination.

Fig. 2. RMN stations. In white: stations studied in the present work

IV. RESULTS AND DISCUSSION

Following the procedure outlined in Chapter III, time series associated to the six stations have been examined. In particular, the one of Sciacca is the closest to the site of interest, being about 10 kilometres away from the village of

San Giorgio. Lampedusa, Palinuro, Taranto, Vieste and Ortona stations have been studied for comparison purposes in order to evaluate atmospheric pressure conditions' influence.

As previously stated, the meteorological contribution of tide has been calculated by subtracting the astronomical tide from the observed one; assessing the behaviour of meteorological residuals can be really helpful in understanding both causes and magnitude of an extreme tide phenomenon.

In Table 1 minimum values of the observed, astronomical and meteorological tide associated to the six stations under examination and related to the month of March 2022 have been reported; in addition to it, the duration of these events is also indicated.

Furthermore, meteorological residual's trends related to Sciacca, Palinuro and Vieste stations are shown in Fig. 3, having focused the attention specifically on the time span of interest, that is the month of March 2022. The exceeding thresholds equal to the quantile of order 0.02 are also shown; they have been calculated considering the whole available time series, namely 6 February 2011-27 April 2022, 1 January 2010-12 May 2022 and 1 January 2010-12 May 2022 for Sciacca, Palinuro and Vieste respectively. Threshold values vary according to the time series' length: the longer time series the better it is at highlighting anomalous events such as tides. Moreover, on the right-hand side of Fig. 3 there are also three graphs representing the persistence's duration, in terms of hours, of negative residuals below thresholds for Sciacca, Palinuro and Vieste stations.

During the period in which the extreme negative sea level has been observed, the meteorological tide is clearly below the thresholds in all graphs. However, since these data need to be read in conjunction with the ones on which they depend, such as atmospheric pressure data, it is important to notice that the time period of interest is characterised by persistent high atmospheric pressure conditions (Fig.4 and 5).

Table 1: Minimum values of the observed, astronomical and meteorological tide that occurred in March 2022 and event's duration for each station

Station	**Observed tide - min (m)**	**Astronomical tide - min (m)**	**Meteorological tide - min (m)**	**Duration (h)**
Sciacca	-0.45	-0.15	-0.32	148
Lampedusa	-0.37	-0.11	-0.28	124
Palinuro	-0.53	-0.30	-0.27	157
Taranto	-0.63	-0.36	-0.30	151
Vieste	-0.63	-0.33	-0.33	163
Ortona	-0.58	-0.26	-0.37	160

Considering that geopotential height is the height above mean sea level of a given atmospheric pressure value, Fig. 4 represents the 850 hPa geopotential height field related to the 22 March 2022, whereas Fig. 5 refers to the 850 hPa geopotential height anomalies associated to the period 19 March 2022-25 March 2022 and obtained by subtracting the zonal mean.

According to [13], there are different factors that can contribute to induce sea level anomalies. Among these, it is worth considering the inverse barometric effect, which can cause either a negative or a positive sea level anomaly, in case of either a maximum or a minimum of atmospheric pressure respectively. Moreover, in their research [13], it is stated that a cyclone located in the opposite part of a study area can

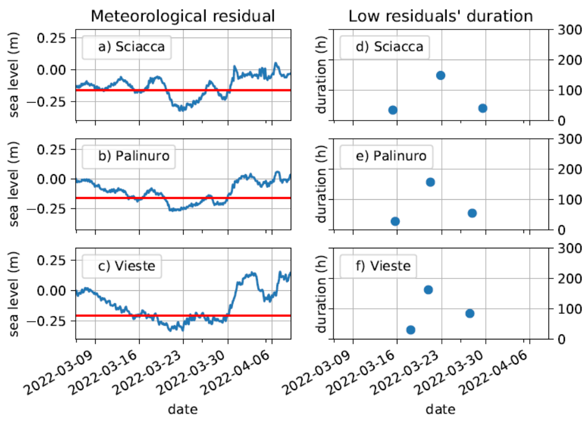

Fig. 3. Meteorological residual (a, b and c) and low residuals' duration (d, e and f) for three stations selected by way of example. Red lines: thresholds equal to the quantile of order 0.02

trigger a cross-basin pressure gradient that often coincides with the presence of an anticyclone above the site of interest.

In the case under consideration, it is possible to notice a geopotential height anomaly located above the study area (Fig.5) and that lasted until the end of March 2022. After that date the meteorological contribution of tide rose above the threshold again (Fig.3 on the left-hand side). Indeed, as reported by [13], sea level anomalies usually last from few hours to days.

Finally, it is important to highlight that the period of interest is associated to spring tides conditions in which lowest astronomical tides typically occur.

Therefore, the key to understanding this extreme negative sea level phenomenon lies in considering the casual occurrence of all the above-mentioned conditions, thus describing it as a temporary event, more specifically about five days long (Fig. 3).

V. CONCLUSIONS

The purpose of the present paper was to discuss the case of an extreme negative sea level phenomenon that occurred in the Mediterranean basin, more specifically along the Village of San Giorgio's coast (Sicily Region, Italy). In order to achieve this objective, sea level and atmospheric pressure time series associated to the closest RMN station, that is the one of

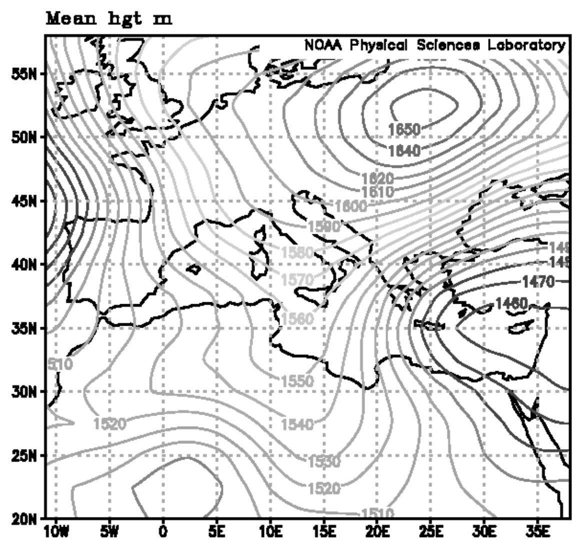

Fig.4. 850 hPa geopotential height field (Image provided by Physical Sciences Laboratory, NOAA, Boulder, Colorado, from their Web site at https://psl.noaa.gov/)

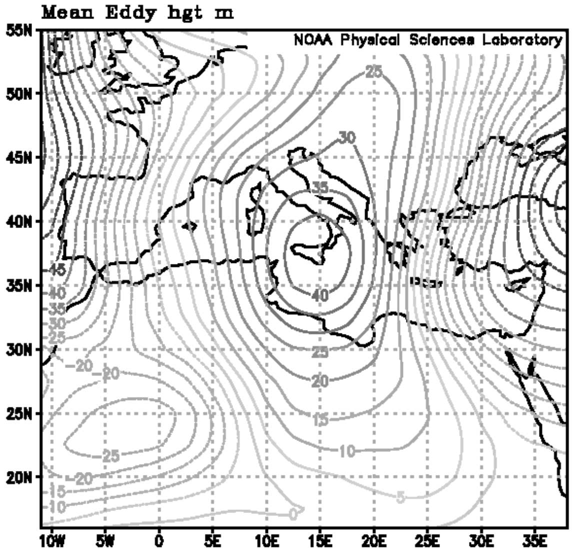

Fig.5. 850 hPa geopotential height anomaly above the study area (Image provided by Physical Sciences Laboratory, NOAA, Boulder, Colorado, from their Web site at https://psl.noaa.gov/)

Sciacca, have been analysed. Furthermore, aiming to evaluate meteorological conditions effects on different areas of the Mediterranean region, other five stations have also been studied; namely Lampedusa, Palinuro, Taranto, Vieste and Ortona. The first situated south of Sicily Region, the second facing the Thyrrenian Sea, Taranto's one in the Gulf of Taranto and the last two stations projecting into the Adriatic Sea.

After having differentiated the meteorological contribution of tide from the astronomical component by means of a method based on harmonic constituents, the meteorological contribution has been analysed in more detail.

During the period in which the extreme negative sea level has been observed, the meteorological component is below the threshold equal to the quantile of order 0.02 at three reference stations. High pressure conditions above the study area can be considered one of the main responsible of the negative extreme because of the inverse barometric effect. Furthermore, the time span of interest is associated to spring tide conditions in which lowest astronomical tides typically occur.

The finding that emerges from this study is that the extreme negative sea level phenomenon took place because of the casual occurrence of all the above-mentioned conditions. Therefore, it is possible to classify it as a temporary event that, as confirmed by scientific literature, usually lasts few days.

In conclusion, it is important to highlight that it is crucial to analyse these phenomena on a Mediterranean scale in order to observe to which extent meteorological perturbations can affect areas surrounding the site of interest and to better identify the frequency of occurrence of these sea level extremes.

Acknowledgment

This research activity was gratefully supported by a research grant within the INTERREG V-A IT HR ADRIACLIM Project.

References

[1] D. Canesso, M. Cordella and G. Arena, "Manuale di mareografia e linee guida per i processi di validazione dei dati mareografici", ISPRA Manuali e Linee Guida 77/2012, p. 2.

[2] P. Lionello, J. Bhend, A. Buzzi, P.M. Della-Marta, S.O. Krichak, A. Jansà, P. Maheras, A. Sanna, I.F. Trigo and R. Trigo, "Cyclones in the Mediterranean region: climatology and effects on the environment", Developments in Earth and Environmental Sciences 4 (2006): 325-372.

[3] D. Conte and P. Lionello, "Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios", Global and Planetary Change 111 (2013): 159-173.

[4] P. Lionello, R. Mufato and A. Tomasin, "Sensitivity of free and forced oscillations of the Adriatic Sea to sea level rise", Climate Research 29 (2005): 23-39.

[5] S. De Zolt, P. Lionello, A. Nuhu and A. Tomasin, "The disastrous storm of 4 November 1966 on Italy", Natural Hazards and Earth System Sciences 6 (2006): 861-879.

[6] M. N. Tsimplis, E. Àlvarez-Fanjul, D. Gomis, L. Fenoglio-Marc and B. Pérez, "Mediterranean Sea level trends: Atmospheric pressure and wind contribution", Geophysical Research Letters 32 (2005).

[7] M. Marcos and M. N. Tsimplis, "Forcing of coastal sea level rise patterns in the North Atlantic and the Mediterranean Sea", Geophysical Research Letters 34 (2007).

[8] M. N. Tsimplis and A. G. Shaw, "The forcing of mean sea level variability around Europe", Global and Planetary Change 63 (2008): 196-202.

[9] M. Marcos, M. Tsimplis and A. G. P. Shaw, "Sea level extremes in southern Europe", Journal of Geophysical Research Atmospheres 114 (2009).

[10] M. N. Tsimplis and A. G. P. Shaw, "Seasonal sea level extremes in the Mediterranean Sea and at the Atlantic European coasts", Natural Hazards and Earth Systems Sciences 10 (2010): 1457-1475.

[11] J. Sepic, I. Vilibic, A. Lafon, L. Macheboeuf and Z. Ivanovic, "High-frequency sea level oscillations in the Mediterranean and their connection to synoptic patterns", Progress in Oceanography 137 (2015): 284-298.

[12] F. Raicich, "Recent evolution of sea-level extremes at Trieste (Northern Adriatic)", Continental Shelf Research 23 (2003): 225-235.

[13] P. Lionello, D. Conte and M. Reale, "The effects of cyclones crossing the Mediterranean region on sea level anomalies on the Mediterranean Sea coast", Natural Hazards and Earth System Sciences 19 (2019): 1541-1564.

[14] C. M. Campetella, E. D'Onofrio, S.B. Cerne, M. E. Fiore and N. Possia, "Negative storm surges in the Port of Buenos Aires", International Journal of Climatology 27 (2007): 1091-1101.

[15] D. Chu, H. Niu, W. Qiao, X. Jiao, X. Zhang and J. Zhang, "Modeling Study on the Asymmetry of Positive and Negative Storm Surges along the Southeastern Coast of China", Journal of Marine Science and Engineering 9 (2021).

[16] A.T. Doodson, 1921, "The harmonic development of the tide-generating potential", Proceedings of the Royal Society of London, A. vol. 100, 305-329.

[17] P. Bloomfield, 1976, "Fourier analysis of time series: An introduction", John Wiley and Sons, New York, pp. 274.

[18] Cox, S (2013) Pytides [Source code]. https://github.com/sam-cox/pytides.

[19] P. Schureman, Manual of Harmonic Analysis and Prediction of Tides, Revised (1940) ed., U.S. Department of Commerce Coast and Geodetic Survey, Washington, 1958.