The Influence of Sea Level and Wave Storms on Beach Erosion Along Apulian Coastline

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Abstract. The coastline of Apulia extends for approximately 1000 km, of which about 29% consists of sandy beaches. It represents one of the main factors of socio-economic development in the region, but, at the same time, it has been subject over the years to progressive coastal erosion. Studies conducted, indeed, show a clear retreat of the coast, with non-negligible consequences on economically relevant sectors, such as tourism and land use planning.

In this study, the evolution of the coastline in the medium and short term has been analyzed, revealing a significant exacerbation of the phenomenon in the last decade. In an attempt to shed light on the intensification of these phenomena, an analysis of meteomarine events that occurred in those years and the variation of mean sea level has been carried out using data collected in situ or sourced from datasets made available by the Copernicus portal. The analysis of sea levels and sea storms has highlighted the occurrence of particularly stormy years and a significant sea level rise.

Keywords: Shoreline evolution · Sea storms · Sea Level

1 Introduction

Coastal areas are heavily exposed to several hazards weakening their environmental quality and sustainability and observations and forecasts of ongoing climate change (e.g. sea level rise, frequency of intense storm surges, etc.) also show an increasing exposure of coastal zones [1,2] erosion and flooding risk. In the long term, pressures cause a considerable deterioration in the quality of the coastal environment, causing important social changes in the development of economic activities and in the lifestyle of the coastal populations [3]. The great extension of the coastal territories threatened by climate change must also deal with the great extension of those at risk and the availability of economic resources for the protection and for the need to safeguard the natural environment. At the same

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time with the prediction of the impact on the coast of medium-long term events, it is also necessary to analyze the impacts of events that have already occurred [4] and which have led to a substantial change to the coastal environment, affecting the resilience of coastal regions with respect to future events.

In the last two centuries, starting from historical data series of continuous and reliable sea level data are available, the mean sea level of the Mediterranean Sea has risen and, more than in others, a significant rising trend has been found in the Adriatic Sea [5]. Hence, over the last century, the Relative Sea Level Rise (RSLR) of the Adriatic Sea has increased between 0.5 ± 0.2 mm/year and 1.2 ± 0.1 mm/year [6,7]. Even higher values have been observed in Venice (in the Northern Adriatic) where the tide gauge has recorded a variation of 2.5 ± 0.1 mm/year also due to anthropogenic subsidence, too. In the last years, this trend considerably increased; SLA dataset reported an average sea level increase over Mediterranean Sea equal to 2.5 mm/yr in the period 1993–2019 with an average local sea level trend uncertainty equal to 0.83 mm/yr [8]. An abrupt increase in sea level has been recorded throughout the Mediterranean during the period 2007–2009, when tide gauges in the northern Adriatic have recorded a rise of about 15 cm [9,10].

In the last decade a widespread coastal erosion has aroused a strong warning in the Mediterranean countries [11] and mostly in Puglia region (Southern Italy) [12], where the number of eroding sandy beaches has greatly increased. To deeply investigate the recrudescence of the erosive phenomena available sea level and wave datasets have been analyzed to find a relation between shoreline degradation and weather and climatic events.

2 Materials and Methods

2.1 Case Study

The coastal region of Apulia, which is bordered by both the Adriatic and Ionian Seas, spans a distance of 1034 km, including the Tremiti Islands. The coastline is divided into 6 provinces and covers the territory of 69 municipalities where approximately 43% of the total regional population lives.

Seven primary littoral cells (Physiographic Units - PUs) are identified along the coastline [12], with each capable of further division into sub-units, the boundaries of which are reported in Fig. 1.

The coastline in Puglia adheres to a microtidal regime, with a tidal range less than 0.5 m [13]. Analysis of observed wave data reveals that the wave conditions present a moderate climate, characterized by sea states with low to medium energy levels [14].

Upon classification according to shoreline typology, it is observed that cliffs cover approximately 33% of the total, sandy beaches account for 29%, rocky coast constitutes 22%, and anthropogenic structures are present in about 10%. Each Physiographic Unit (PU) encompasses a diverse coastal landscape, featuring several types of shoreline: (i) extensive sandy beaches flanked by coastal dunes (PU1, PU4, PU7), (ii) beach barriers dividing coastal lagoons from the open

sea (PU1, PU5), (iii) flat areas with lengthy sandy beaches (PU2), (iv) pocket beaches (present in nearly all PUs), and (v) rocky coastlines and cliffs, with or without accompanying protective beaches (PU1, PU3, PU5, PU6) [12].

As emphasized by numerous recent studies, the Apulian coastline has been experiencing long-term erosion since the latter half of the 20th century [12,15,16]. Due to the erosion process, numerous coastal protection structures have been constructed along the coast, particularly in PU2 [17]. Coastal regions are pivotal to the local economy, with coastal tourism alone contributing over 8% to the regional GDP in 2022. Over the past two decades, the influx of tourists to these areas has seen significant growth [18].

2.2 Data Sources and Methods

The position of the current coastline has been digitized based on orthophotos acquired in 2017 with a spatial resolution of 0.2 m. In the calculation of the regional coastal perimeter, the littoral zone within the inner basin of the Mar Piccolo in Taranto, which extends for approximately 30 km, has also been taken into account, while the perimeter of protruding coastal structures (e.g., external docks, breakwaters and piers) along the coastline has not been included.

The evolutionary trend in the medium and short term has been assessed by leveraging the available cartography (IGMI map dated 1960 and orthophotos acquired in 1992, 2005, 2008, 2010, 2011). Shorelines have been digitized and overlaid and the evolutionary trend was assessed through a polygon overlay analysis, evaluating erosion and deposit areas.

The analysis of sea level changes has been carried out by exploiting the daily global observations of the Sea Level Anomalies (SLA) on a regular grid (0.25° resolution) based on satellite altimetric measurements covering the period from 1993 to 2020 distributed by Copernicus Climate Change Service (C3S) [19]. The sea level anomaly is defined as the Sea Surface Height (SSH) with respect to the Mean Sea Surface (MSS) estimated for a 20-year reference period (1993–2012). Moreover, hourly sea level data recorded by tidal gauges belonging to Italian National Tide Gauge Network (RMN) [13] positioned along the Apulian coastline (Fig. 1) have been analyzed.

The existence of a monotonic trend in the period 1993–2020 was assessed using the non-parametric Mann-Kendall test [20–22]. Being non-parametric, the test is independent of the population distribution and is less influenced by the presence of any outliers in the time series. In this study, P-values <0.05 were considered significant.

The analysis of storm events has been carried out using the ERA5 wave dataset produced by the Copernicus Climate Change Service (C3S) at ECMWF [23]. ERA5 is the latest generation ECMWF atmospheric reanalysis of the global climate and it provides 0.5° gridded resolution wave data with a hourly sampling [24,25]. Figure 1 illustrates the geographic coordinates of the data extracted from the ECMWF dataset. With respect to the former ERA-Interim wave dataset [26], ERA 5 wave data have been improved in spatial and temporal resolution

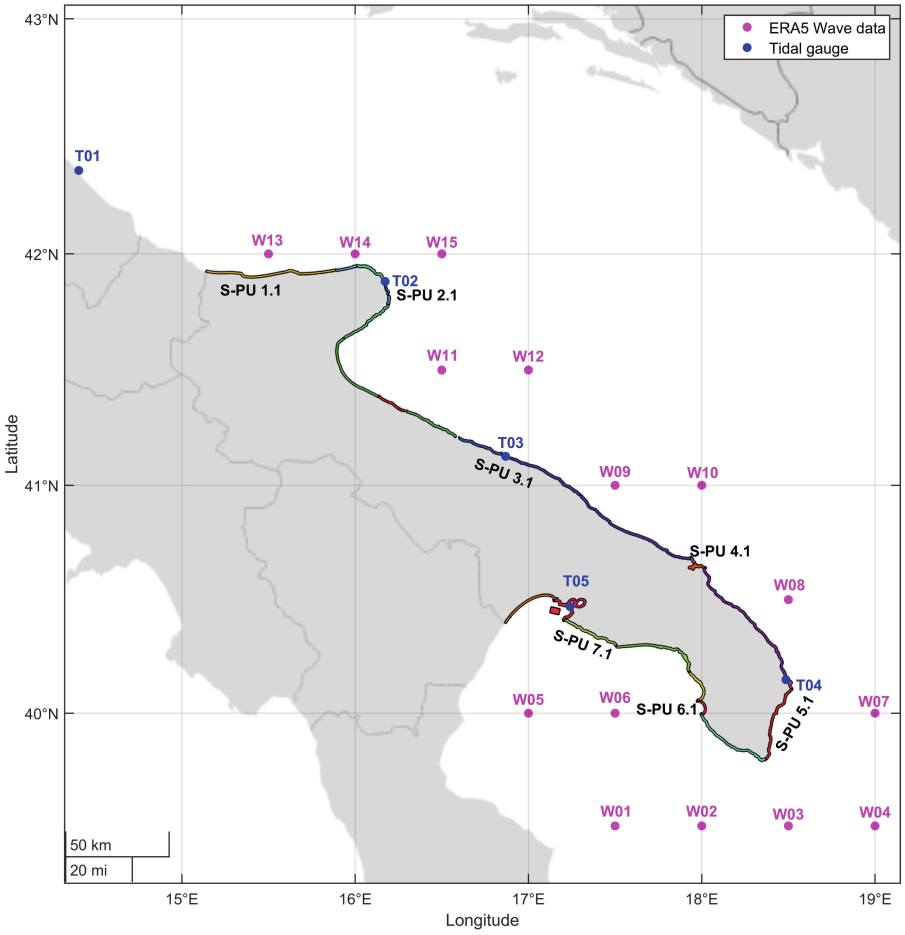

Fig. 1. Coastal physiographic sub-units (S-PU) are marked along the Apulian coastline. Position of examined RMN tidal stations (blue points) and wave data extracted from the ERA5 dataset (represented as magenta points) along the Apulian coastline are also reported. (Color figure online)

of ERA5 wave data have been significantly enhanced and tropical cyclones and troposphere have been also improved [25].

Significant wave height (H_s), peak wave period (T_p) and mean wave direction have been extracted at 15 grid points offshore the area of interest. The wave energy flux has been estimated as:

$$P_0 = \frac{\rho g^2}{64\pi} T_e H_s^2 (W/m) \tag{1}$$

where P_0 is the energy flux per unit of wave crest (W/m), ρ is the water density, and T_e is the energy mean period, estimated as $T_e = 0.9T_p$.

Storm events have been selected from the wave time series following the storm definition proposed by Boccotti [27] and for each storm the total wave energy flux of each storm has been obtained by applying a time-integration along every single event. In this phase, particular attention has been reserved to the identification of independent events, assuming that the independence of the storms is verified when the interval between two consecutive events is at least 48 h [28]. Storm events have then been classified using the Fisher-Jenks optimization algorithm [29,30] for splitting the storm dataset into five classes based on total wave energy flux spanning from Weak (Class I) to Extreme (Class IV) [31].

3 Results

The digitization based on high-resolution orthophotos has allowed for a more detailed and accurate description of the coast compared to previous studies, particularly regarding rocky shorelines, where greater lengths are observed compared to what was mapped based on orthophotos with lower spatial resolution [12].

For each S-PU, beaches were identified and mapped, including in the analysis sandy or pebbly sandstone beaches, as well as those along the rocky coast, both high and low, with sandy or gravel beaches found at their foot. The analyses thus encompassed a total beach length of 366 km. Geometric attributes, such as surface area, length, and width, have been defined for each beach (Table 1).

The analysis of the evolution trend of the Apulian coast, carried out by overlapping the shorelines extracted from several maps available, had shown that in the period 1960–1992 more than one third of the mapped beaches experienced erosion, while the shoreline degradation seemed to be halved in 1992–2005 [12,17]. In the subsequent period the erosion processes greatly increased affecting again more than one third of sandy beaches in 2005–2017. The analysis has disclosed that erosion has impacted the 34% of the coastlines, and also segments previously deemed relatively stable (Table 1).

To identify exactly the period when the erosive phenomena got worse, the evolution trends were also examined between 2005 and 2017. To do this, aerial photos acquired in 2008, 2010 and 2011 have also been analyzed. It should be noted that, unfortunately, maps related to 2009 are not available.

Table 2 reports the ratio of shoreline classified as eroded along the Apulian coast as carried out by the aforementioned analysis (percentages are calculated respect to the sandy coastline length). From 2010, a sudden increase of the erosive phenomena can be easily recognized from Table 2.

The substantial coastline stability observed during the period from 1992 to 2005 persisted over the subsequent three years, as evidenced by the 2005–2008 analysis. However, a notable increase in erosion rates was observed in the post-2008 period, coinciding with significant setbacks and damage to the dune belt on certain beaches of higher environmental and tourist significance. The significant increase in erosion has been observed along the Apulian Ionian side during the

Table 1. Geometric attributes (beach length and width) and shoreline change rates in the periods 1960–1992, 1992–2005 and 2005–2017.

S-PU	Beach length in 2017 (km)	Average Beach Width in 2017 (m)	Erosion 1960–1992 (%)	Erosion 1992–2005 (%)	Erosion 2005–2017 (%)
1.1	58.65	26.30	24.39	24.15	43.87
1.2	9.39	24.83	28.23	17.64	46.86
1.3	9.24	43.95	0.00	14.71	30.62
1.4	4.64	65.18	5.30	24.45	36.09
2.1	0.96	18.63	0.00	0.00	0.00
2.2	8.90	14.37	0.00	6.60	19.02
2.3	37.47	25.30	42.85	32.15	37.80
2.4	14.30	71.97	42.76	47.80	36.51
2.5	12.23	16.95	25.45	21.03	26.56
2.6	4.04	17.56	0.00	1.19	17.94
3.1	4.88	17.90	0.00	7.05	0.82
3.2	31.43	18.58	63.26	3.45	56.59
4.1	0.69	13.72	33.20	0.00	0.00
4.2	2.30	15.28	0.00	0.00	66.21
4.3	59.77	20.04	68.22	30.32	30.78
4.4	0.03	0.00	0.00	0.00	0.00
5.1	0.12	30.31	0.00	0.00	0.00
5.2	18.55	23.22	19.30	14.32	36.61
6.1	5.50	24.47	69.58	0.00	0.00
6.2	3.30	22.94	11.90	18.91	0.00
6.3	33.31	19.44	19.93	5.61	32.31
7.1	12.49	20.31	61.02	5.90	22.04
7.2	4.74	14.31	10.22	20.03	3.72
7.3	29.27	37.40	14.42	1.09	31.77
Total	366.18	25.50	35.54	18.33	34.74

period 2005–2010. Conversely, erosion on the Adriatic side has manifested with particular severity after 2011.

In order to investigate the shoreline variations that occurred in the recent period along the Adriatic and Ionian coasts, sea level data from the SLA dataset and tidal gauges have been examined. The Mann-Kendall test applied to the SLA dataset revealed the presence of significant trends at all collected points around the Apulian coastline. Consequently, a spatial trend map of SLAs was estimated (Fig. 2). The Adriatic Apulian coastline has experienced a notable rising trend in SLA, ranging from 2 mm/year to 3 mm/year. Conversely, along the Ionian coast, the increase in SLA appears to be comparatively lower, except for the southernmost part of the region, where the trend is almost similar to that observed in the case of the Adriatic side (Fig. 2).

Table 2. Eroded shoreline rates in the periods 2005–2008, 2005–2010, 2005–2011 and 2005–2017 in each Physiographic Unit (PU)

PU	Erosion 2005–2008 (%)	Erosion 2005–2010 (%)	Erosion 2005–2011 (%)	Erosion 2005–2017 (%)
1	18.03	30.57	37.15	42.27
2	15.96	20.59	22.52	32.16
3	29.24	25.8	34.64	49.09
4	20.71	18.25	15.18	31.72
5	28.05	51.22	44.51	36.38
6	19.96	40.92	29.34	25.56
7	8.20	47.24	22.46	26.30
Total	18.47	30.65	27.45	34.74

An even higher rising trend was identified when analyzing tidal data recorded across the Adriatic and the Ionian seas. The annual mean level has been computed with reference to the meteorological year spanning from September 1st to August 31st, so mitigating the effects related to the splitting of the winter season.

An analysis of the tidal data, extended to all the stations present in the lower and middle Adriatic, both of the RMN (Ortona - T01, Vieste - T02, Bari - T03, Otranto - T04), highlighted a generalized increase in the mean sea level starting from 2008, with a variation between 2007 and 2009 exceeding 10 cm, with a maximum recorded at T01 (13.5 cm) and a minimum at T04 (9.9 cm). After a sudden decrease in 2011, the MSL has again risen reaching the maximum value in 2012 at the Southern Adriatic stations (Ortona, Vieste, Bari) (Fig. 3).

Tidal data recorded in the Ionian sea - Taranto (T05) - exhibit a similar trend, differently to the SLA data (Fig. 3). The MSL recorded at T05 has risen by approximately 13 cm in the period 2007–2009.

The analysis of the total wave energy recorded during the period 1950–2019 has revealed significant variability over time across all examined points in the Ionian and Adriatic Seas (Fig. 4). The Ionian Sea appears to have an higher wave energy if compared to the Adriatic Sea, except for points located in the Gulf of Taranto (WG05, WG06).

When the analysis is focused on the most recent period, it can be observed as in the Ionian Sea, in the 2005–2007 period, was characterized by wave energy significantly lower than in previous periods, while a sharp increase was observed during 2008–2009 winter, in which the maximum value of the wave energy during the period 1950–2019 was recorded. The analysis of data from the Adriatic Sea, on the other hand, shows that the peak of energy occurred from the winter of 2011–2012 onwards. Similar trends was observed at all examined points in both Ionian and Adriatic Sea.

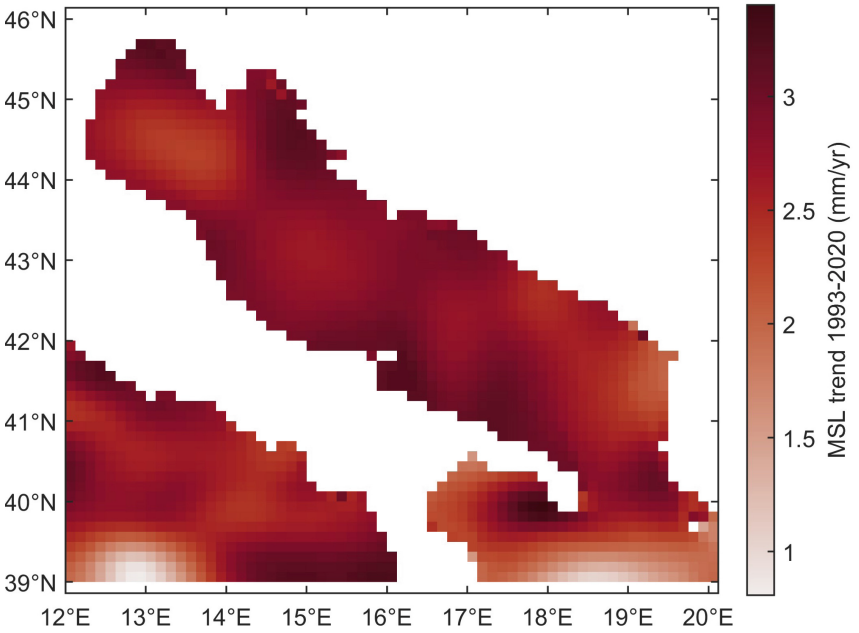

Fig. 2. Spatial trend map of SLAs in the period 1993–2020 based on satellite altimetric measurements [19].

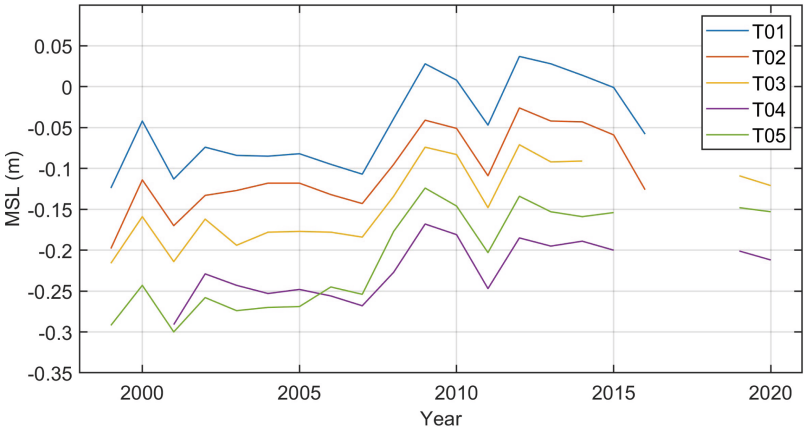

Fig. 3. MSL variation in the examined RMN tidal stations in 1999–2020.

The effect of the sea storm on the coast depends on various factors such as wave height at the peak of the storm, duration, wave periods and the direction of incidence. Moreover, in case of closer storm events, or when a series of years characterized by particularly intense events occurs, the effects on the coastline can be destructive [32,33]. The intensity and occurrence of sea storm during

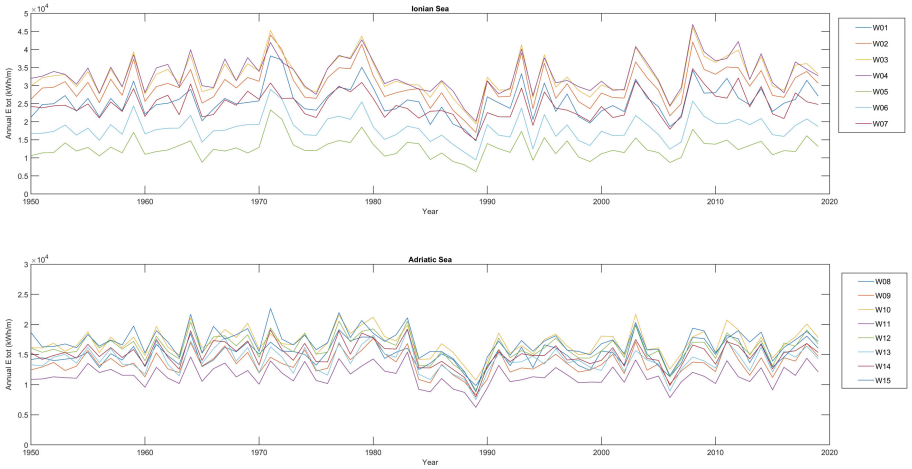

Fig. 4. Annual energy flux in the Ionian Sea (top panel) and in the Adriatic Sea (bottom panel).

the examined period have been therefore investigated. For each storm the total energy has been calculated and the storms classified using their total wave energy flux values.

Considering that sandy coastlines are more severely impacted by storms falling within classes III, IV, and V [31], a more comprehensive analysis has been conducted on such storm events. By employing a threshold value of the total energy of storms equal to the mean of total energy (μ) plus the standard deviation of the total energy (σ) calculated within the whole period of 70 years for the identification of the most severe years, the stormy years have been selected. For WG01 in the Ionian Sea 2008, 2011 and 2014 have been selected, while for WG09 in the Adriatic Sea, 2011 and 2018 have been identified (Fig. 5). In any case, it is noteworthy that, with reference to the average energy values, the data points within the Ionian Sea region consistently show values exceeding the mean throughout the years spanning from 2008 to 2014.

Exclusively focusing on storms falling within classes III, IV, and V, an analysis has been conducted on the number of events, their duration, and the interval between the occurrences of two events. Figure 6 reports that at WG01 in the period 2008–2011 the number of storm events has consistently increased, with very short intervals between them. In 2008, specifically, there were 10 storm events with an average interval of 12 days between each occurrence and a long duration (with an average value of about 100 h). Examining instead what occurred at point WG09, it can be observed that 2011 emerged as the worst year concerning the combination of the number of storm surges, their intervals, and duration.

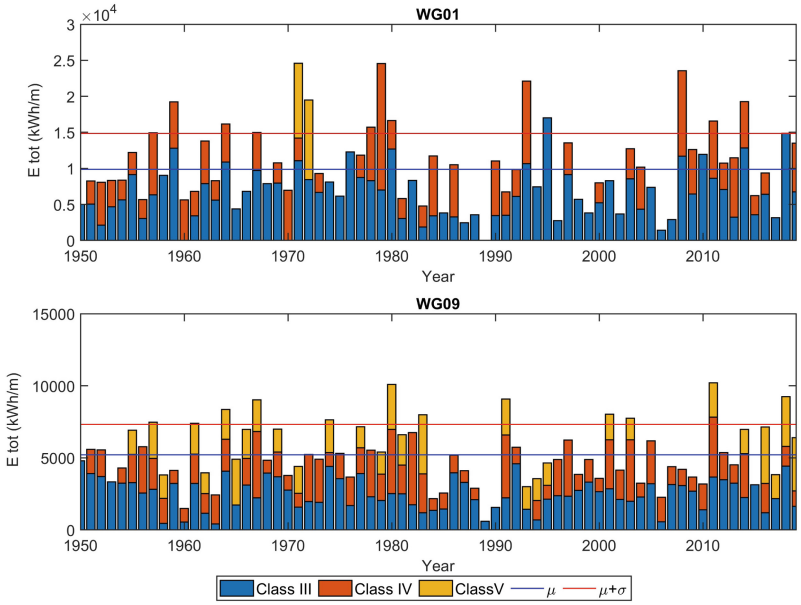

Fig. 5. Total energy of storms per year for Classes III, IV, and V at WG01 (Ionian Sea) and WG09 (Adriatic Sea). Blue and red lines respectively represent the average value (μ) and the average plus one standard deviation ($\mu + \sigma$). (Color figure online)

4 Discussion

An analysis of the sea level variation and higher storms that occurred during the last decades has been carried out in order to relate these variables and the erosive trend observed in 2005–2017 period. In the recent period, erosion has affected 34.7% of the regional sandy beaches, as opposed to the 18.5% observed in 1992–2005. These phenomena do not spare any of the physiographic units under analysis. However, it is noteworthy that PU3 (along the Adriatic coastline) and PU5 (Ionian coastline) have exhibited the most adverse trends, with respective transitions from 3.2% to 49% and from 16.1% to 36.4% of sandy coastline undergoing erosion.

The analysis of sea levels has shown a widespread increase along the Adriatic and Ionian coasts, with a remarkably large increment exceeding 10 cm occurred starting from 2007 to 2009. The rising MSL recorded in that period seems to be closely related to the large-scale forcing of the North Atlantic Oscillation (NAO), resulting in the ingress of substantial water masses into the Mediterranean Sea [9,10]. As reported in [34], the storminess in the Mediterranean region is also influenced by NAO values: winter average H_s results anti-correlated with the NAO index so that lower values of the NAO index corresponds to the increase of H_s.

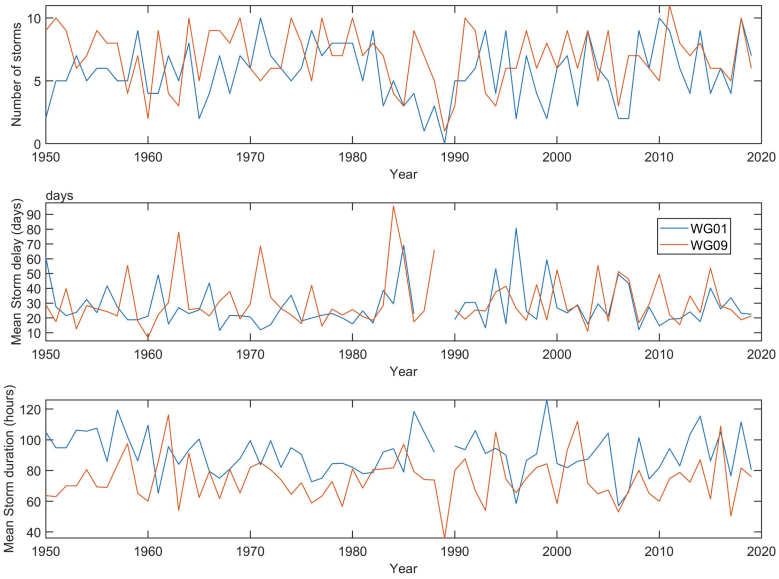

Fig. 6. Characteristics of the higher sea storms observed at WG01 (Ionian Sea) and WG09 (Adriatic Sea) during the period 1950–2019: number of storms, mean storm delay and mean storm duration.

The analysis of wave energy has revealed that in the Ionian Sea, the total energy of the extreme storms often exceeded the average value for the period 2008–2014, with the presence of very short intervals between successive storm events. Considering that the physiographic units along the Ionian Sea (PU5, PU6 and PU7) recorded the highest erosion rates after 2008, and that clusters of exceptional storm events occurred precisely from the winter of 2008, it can be inferred that this remarkable combination of high mean sea levels and sea storms characterized by high energy content and short intervals between them has certainly contributed to enhance the observed erosive phenomena.

Similarly, it can be noticed as the coastal erosion in the Adriatic side (PU2, PU3 and PU4) has significantly worsened after 2011, when the most intense storm events occurred. Indeed, in the Adriatic Sea the most severe sea storms occurred in the period 2011–2014.

On the Adriatic side, only the PU1 area exhibited a pronounced increase in erosive phenomena shortly after 2008. This situation may have been influenced by the significant rise in sea level, as made clear by the data of the nearest station (T01), which recorded a peak (+13.5 cm) during the winter of 2008–2009 winter, in addition to other local phenomena due to both the reduction of river solid discharge and to the effect related to the presence of coastal infrastructure. Indeed, it is emphasized that the coastlines within the PU1 areas (see areas close to the Lake Lesina and Lake Varano) are characterized by very flat beaches.

5 Conclusions

Analyses of the ongoing evolutionary dynamics along the Apulian regional coastline have highlighted the presence of numerous segments of sandy beaches undergoing erosion, with future projections indicating scenarios of widespread coastal retreat and a progressive reduction in beach width [35], already characterized by limited expanses.

To better understand the intensification of these occurrences, an analysis of meteomarine events during those years and the fluctuation of mean sea level has been conducted, utilizing data collected on-site or sourced from datasets provided by the Copernicus portal.

A comprehensive analysis of sea storms characteristics and the sea level variations report that in the Ionian Sea in the period 2008–2011 the number of storm events has consistently increased, with very short intervals between them and in the period post-2008 the worst cases of beach recession occurred along the Ionian coasts (PU5, PU6, and PU7).

At the same time, the Adriatic PUs (PU2, PU3, and PU4) have also suffered substantial impacts from erosive phenomena starting from 2011, a year marked by very severe storm events very closely spaced in time.

In the near future, the aim is to investigate the analyzed evolutionary processes using morphodynamic models as well.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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