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# Extreme low tides: coastal evidence from the Mediterranean Sea

**Abstract:** Scardino G., Rizzo A., De Santis V., Mastronuzzi G., *Extreme low tides: coastal evidence from the Mediterranean Sea.* (IT ISSN 0391-9838, 2026). Climate change profoundly impacts coastal systems by altering their natural equilibrium. These systems are primarily influenced by medium to long-term processes, including sea-level rise, intensifying storm events, vertical land movements (both natural and anthropogenic subsidence), and human activities that lead to resource overexploitation and structural overloads. However, short-term atmospheric anomalies can also induce significant coastal responses. This study examines the coastal impacts of positive pressure anomalies that affected the Mediterranean region in recent years. During these events, tidal records indicated a relative sea-level lowering, ranging from -0.2 m to -0.6 m, resulting in seaward shoreline migration of several meters along the Adriatic and Tyrrhenian coasts of Italy and in Greece. Additionally, channels and piers experienced drying, as documented in Venice and Pozzuoli (Naples). These pressure anomalies influenced large regional areas, as documented during the February-March 2021 extreme low tides. After the end of the pressure anomalies, we observed a rapid adaptive response of mobile coastal systems, with complete restoration of initial conditions following each event. This temporary adaptive response contrasts with permanent coastal changes driven by sea-level rise and sustained anthropogenic pressures.

**Key words:** Coastal systems, Sea-level, Tides, Resilience, Anthropogenic impact.

**Riassunto:** Scardino G., Rizzo A., De Santis V., Mastronuzzi G., *Basse maree estreme: evidenze costiere dal Mar Mediterraneo.* (IT ISSN 0391-9838, 2026). Il cambiamento climatico ha un profondo impatto sui sistemi costieri, alterandone il naturale equilibrio. Questi sistemi sono influenzati principalmente da processi di medio-lungo termine, tra cui l'innalzamento del livello del mare, l'intensificazione degli eventi ciclonici, i movimenti verticali della terra (sia subsidenza naturale che antropogenica) e le attività umane che portano a uno sfruttamento eccessivo delle risorse e a sovraccarichi strutturali. Questo studio analizza gli impatti costieri delle anomalie positive della pressione atmosferica che hanno interessato la regione mediterranea negli ultimi anni. Durante questi eventi, le registrazioni mareografiche hanno evidenziato un abbassamento relativo del livello del mare compreso tra -0.2 m e -0.6 m, con conseguente migrazione verso mare della linea di riva lungo le coste sabbiose adriatiche e tirreniche italiane e lungo le coste greche. Inoltre, sono stati documentati fenomeni di prosciugamento di canali e isolamento di pontili, come osservato a Venezia e a Pozzuoli (Napoli). Queste anomalie di pressione hanno influenzato vaste aree regionali, come documentato durante gli eventi di maree estremamente basse del febbraio-marzo 2021. Al termine delle anomalie di pressione, si è osservata una rapida risposta adattiva dei sistemi costieri mobili, con un completo ripristino delle condizioni iniziali dopo ciascun evento. Questa risposta adattiva temporanea si contrappone ai cambiamenti costieri permanenti indotti dall'innalzamento del livello del mare e dalle pressioni antropiche sostenute nel tempo.

**Termini chiave:** Sistemi costieri, Livello del mare, Maree, Resilienza, Impatto antropogenico.

## INTRODUCTION

The effects of global warming manifest in multiple phenomena, such as sea-level rise, increased rainfall, and the intensification of storms. A more unique phenomenon is the occurrence of extreme low tides, which alter the sedimentary balance in various ways (Haigh *et al.*, 2020). It is crucial to note that, while sea-level rise is a major threat, variations in tidal range also have significant impacts on coastal areas (Pickering *et al.*, 2017; Hague and Talke, 2024). Over the past two centuries, the global mean sea level has risen with an average rate of 1.65 ± 0.2 mm/year (Cazenave *et al.*, 2001; Vermeer and Rahmstorf, 2009; Church and White, 2011; Kemp *et al.*, 2011; Cazenave and Cozannet, 2014) and in the last few decades with a rate of 3.2 ± 0.4 mm/year (Meyssignac and Cazenave, 2012; Wöppelmann and Marcos, 2012; Jevrejeva *et al.*, 2014). As for the future projections of sea-level rise, the latest reports

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published by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019, 2021) show that the global sea level will continue to rise during the coming decades. The primary causes of global sea-level rise are thermal expansion, driven by increasing ocean temperatures, and the influx of meltwater from melting ice sheets and glaciers (Lambeck and Purcell, 2005; Lambeck *et al.*, 2011; Anzidei *et al.*, 2014; Rovere *et al.*, 2016). Projections for global mean sea-level rise by 2100 vary by scenario, ranging from about 0.3-0.6 m under low-emissions pathways (SSP1-2.6) to over 1.0 m under high-emissions scenarios (SSP5-8.5), with low-likelihood, high-impact outcomes suggesting a possibility of exceeding 1.5 m, or even greater (Rahmstorf, 2007; Rahmstorf *et al.*, 2012; Bamber *et al.*, 2019). Numerous studies have highlighted that additional factors, such as vertical land movements (VLMs), anthropogenic water pumping, and alterations in the sedimentary balance may determine local subsidence that enhances sea-level rise and increases, therefore, the vulnerability of coastal areas (Antonioli *et al.*, 2017, 2020; Aucelli *et al.*, 2017; Anzidei *et al.*, 2021, Rizzo *et al.*, 2025).The adaptive responses of the coasts depend on the interaction between the intensity of the ongoing processes and the overall sediment supply. The coastal system's energy balance is governed by waves, currents, wind, and tides across multiple temporal scales, whereas its mass balance is determined by marine, continental, and biogenic processes. The interplay between these energy and mass fluxes defines the system's morphology and sedimentary budget, both subaerial and underwater, thereby enabling the assessment of its dynamic evolution (Caldara *et al.*, 1998; Moretti *et al.*, 2016; Mastronuzzi *et al.*, 2020).

In the dynamic of a coastal system, alterations in the volume of the available sediment can increase, such as determining temporary or irreversible changes, which can be described through the resilience model (Westman, 1978, 1986). Westman's model considers resilience as a dynamic process in which ecological disturbances can trigger responses that not only repair damage but also create new resources and interactions, leading to a more robust and adaptable system over time. In this framework, coastal resilience is defined as "the intrinsic capacity of the coast to withstand sea-level changes, extreme events and sporadic anthropogenic impacts, maintaining the functions of the coastal system unaltered for a long period" (MATTM, 2018). The availability of sediments, the accommodation space, and the energy of physical processes acting in a coastal system are the key factors that determine the resilience capacity in relation to the effects of climate change and anthropogenic impact.

Nowadays, many Italian coasts are subject to severe erosion, and the alluvial coastal plains are the most susceptible areas to flooding (Delle Rose, 2015; Aucelli *et al.*, 2017; Reimann *et al.*, 2018; Toimil *et al.*, 2020). Although the various factors contributing to the alteration of the natural dynamic equilibrium of coastal areas, mainly due to changes in sedimentary balance and ongoing global warming, are known, the identification of processes related to coastal system resilience is still debated among international scientific communities (Lele, 1998; Martinez *et al.*, 2017; Wu *et al.*, 2018; Hong, 2021; De Santis *et al.*, 2023).

Here, one recent example of the short-term adaptive response of the coasts was reported during the occurrence of a positive pressure anomaly that affected the Mediterranean Sea between February and March 2021, and on August 2021. During this event, the weather conditions resulted in a significant lowering of the mean sea level down to -0.2 m compared to the mean sea level (m.s.l.) in the entire Mediterranean basin, with extreme values of -0.66 m observed in Venice and -0.41 m in the dock of Pozzuoli (Naples). Such weather conditions have resulted in a significant shoreline migration in many beaches, as observed in many Italian beaches and along the coasts of Greece. Although the extreme tide phases and pressure fluctuations have affected the coasts for a relatively short period, their effects were observed in most of the Mediterranean coasts, highlighting how coastal systems highlighted a rapid adaptive response to weather variations. Nevertheless, the variations associated with the coastal adaptive response have assumed a temporary character and have allowed the restoration of the initial conditions of the coasts after the end of the pressure anomaly. This phenomenon has made it possible to highlight how the coasts can adapt to temporary physical alterations, while they may be more susceptible to permanent alterations that therefore could determine irreversible changes, such as submersion due to sea-level rise (Marsico *et al.*, 2017; Antonioli *et al.*, 2020; Anzidei *et al.*, 2021), coastal erosion due to the decrease in sedimentary budget (Sabatier *et al.*, 2009; Bonaldo *et al.*, 2019; Toimil *et al.*, 2020), and the contamination of groundwater as a consequence of the seawater intrusion (Masciopinto and Liso, 2016; Petio *et al.*, 2024).

## RECENT LOW TIDES AND SEA-LEVEL CHANGES IN THE MEDITERRANEAN SEA

In the twentieth century, the ever-increasing diffusion of tidal stations made it possible to monitor the state of the sea level in numerous sites on the Earth. At the same time, the creation of geodetic networks has made it possible to carry out topographic surveys of high accuracy along with the coastal areas, thus making it possible to perform local assessments of relative sea-level variation (Serpelloni *et al.*, 2013; Anzidei *et al.*, 2014, 2021; PSMSL, 2024; Vecchio *et al.*, 2024). Furthermore, since the 1990s, satellite altimetric measurements provided the height of the sea surface with a high spatial and temporal resolution, thus allowing to obtain an in-depth knowledge of sea-level rise at the global scale (Nicholls and Cazenave, 2010; Bamber *et al.*, 2019; Vacchi and Pappalardo, 2019).

At the regional scale, sea-level rise is conditioned by local factors (Lambeck *et al.*, 2011; Aucelli *et al.*, 2017; Antonioli *et al.*, 2020; Anzidei *et al.*, 2021), including anthropogenic activities. According to (Lambeck *et al.*, 2004a; Lambeck and Purcell, 2005; Lambeck *et al.*, 2011; Roy and Peltier, 2017; Mastronuzzi *et al.*, 2020), the relative sea level ($\Delta\zeta rsl$) is determined by the sum of the eustatic ($\Delta\zeta E$), isostatic ($\Delta\zeta I$), tectonic ($\Delta\zeta T$), steric ($\Delta\zeta S$), sediment compaction ($\Delta\zeta CN$), and anthropogenic ($\Delta\zeta A$) contributions (eq. 1):

$$\Delta\zeta rsl = \Delta\zeta E + \Delta\zeta I + \Delta\zeta T + \Delta\zeta S + \Delta\zeta CN + \Delta\zeta A \qquad \text{(eq. 1)}$$

These factors are particularly important for the assessment of sea-level rise in the Mediterranean Sea, which is a semi-enclosed basin connected with the Atlantic Ocean through the Gibraltar Strait and with the Black Sea through the Dardanelles Strait and characterized by a micro-tidal regime (Anzidei *et al.*, 2014; Moatti and Thiébault, 2018; Lin-Ye *et al.*, 2020; López-Dóriga and Jiménez, 2020). The analysis of the tide gauge records showed that, in the Mediterranean Sea, the rate of sea-level change in the first half of the twentieth century showed a positive trend (Anzidei *et al.*, 2014; Vecchio *et al.*, 2019). In this period, the Italian coasts showed an equilibrium in the sedimentary balance with localized accretion phenomena (Caldara *et al.*, 1998, 2002; Lambeck and Purcell, 2005; Scardino *et al.*, 2020). However, starting from the mid-twentieth century, the intensification of anthropogenic activities along the coastal areas has deeply altered the sedimentary balance with the destruction of the dune belt and consequent loss of geological, hydrological, and ecological functionality. Other negative factors are due to the overexploitation of wells with consequent compaction of the sedimentary strata, dams along the river paths, coastal defences that have altered the long-shore drift (Bonora *et al.*, 2002; Caldara *et al.*, 2006; Aucelli *et al.*, 2009; Nederhoff *et al.*, 2015), and the intense building development that has determined phenomena of structural overload. The interaction between these processes has caused strong erosion along many coastal areas and has enhanced anthropogenic subsidence phenomena, as observed in the Veneto-Friuli coast (Carbognin *et al.*, 2004; Tosi *et al.*, 2018; Floris *et al.*, 2019; Bonì *et al.*, 2020), in the Po delta (Fiaschi *et al.*, 2018; Cenni *et al.*, 2021; Fabris, 2021), in the Nile delta (Gebremichael *et al.*, 2018), in the Manfredonia plain (Caldara *et al.*, 1998, 2014) and in the Volturno and Sele plains (Aucelli *et al.*, 2017; Di Paola *et al.*, 2018).

Although the msl in the Mediterranean Sea has undergone a general rise with a rate of 1.8 mm/year in the twentieth century (Lambeck *et al.*, 2004b; Anzidei *et al.*, 2014; Vecchio *et al.*, 2019), some peculiar conditions of high pressure have led to negative fluctuations at certain historical moments. Between the years 1960-1990, the msl of the Mediterranean Sea underwent a relative lowering, as recorded in different tidal stations, due to a positive anomaly of atmospheric pressure that was established on the entire basin (Tsimplis *et al.*, 2005; Lionello *et al.*, 2017). Then, starting from the 1990s, a fast sea-level rise was observed, which ended in the early 21st century (Marcos *et al.*, 2011b, 2011a). This rapid rise in sea level has been attributed to the combined effect of the exchange of water masses from the Atlantic Ocean towards the Strait of Gibraltar and to the volume variation of water as a consequence of temperature and salinity variations (Cazenave *et al.*, 2001; Calafat *et al.*, 2010; Lionello *et al.*, 2017; García-Lafuente *et al.*, 2021)

In recent years, the Italian scientific community has studied the possible impacts of sea-level rise due to global warming and the related risks on coastal areas (i.e.: Anzidei *et al.*, 2014, 2018; Antonioli *et al.*, 2017). These kinds of analyses are based on global and regional projections of sea-level in 2050 and 2100, modelled on the evidence of global warming, paleoclimatic reconstructions, tidal data, historical variations of the average temperature of the Earth, potentially melting of the ice sheet, and the thermal expansion of the oceans related to global warming (Rahmstorf, 2007; Lambeck *et al.*, 2011; IPCC, 2013, 2019; Rovere *et al.*, 2016; Vecchio *et al.*, 2019).

These projections are generally supplemented by data on local vertical movements, such as isostasy and tectonics, in order to include the geological component in the calculation of the relative sea-level change (Lambeck *et al.*, 2011; Antonioli *et al.*, 2020). Furthermore, to take into account the induced subsidence trends, the most recent risk assessments also use the subsidence data obtained from the analysis of satellite interferometry and from the permanent GPS stations (Aucelli *et al.*, 2017; Anzidei *et al.*, 2021).

In this context of sea-level change, the most susceptible areas to submersion are represented by the coastal plains of the main river systems (De Santis and Caldara, 2016; Antonioli *et al.*, 2017; Aucelli *et al.*, 2017; De Santis *et al.*, 2018, 2019; Di Paola *et al.*, 2018; Scardino *et al.*, 2022). These areas are characterized by low altitudes compared to the sea-level rise and are involved in phenomena of vertical deformation caused by the natural compaction of alluvial sediments and by intense anthropogenic extraction mainly carried out for agricultural and industrial purposes, as observed for example in the Tavoliere delle Puglie plain (Scardino *et al.*, 2022; Petio *et al.*, 2024), in the Catania plain (Anzidei *et al.*, 2021), in the Venice lagoon (Antonioli *et al.*, 2017; Tosi *et al.*, 2018; Zanchettin *et al.*, 2021; Vecchio *et al.*, 2024), in the Volturno plain and in the Sele plain (Aucelli *et al.*, 2017; Di Paola *et al.*, 2018; Amato *et al.*, 2020). These coastal plains are also highly susceptible to the seawater intrusion phenomenon, which determines an alteration of the chemical and ecological components (Masciopinto and Liso, 2016), causing a negative state of the coastal ecosystems. Finally, a further factor of coastal risk is represented by the increase in intensity and frequency of high-energy marine events, such as extreme storm surges, medicanes, and river flood events (Lionello *et al*., 2008; Cavicchia *et al*., 2014; Scicchitano *et al*., 2020, 2021), which can determine temporarily flooded areas with a wider landward extent.

## RECENT EXTREME LOW TIDE EVENTS: EVIDENCE FROM COASTAL SITES IN ITALY AND GREECE

In the months of February and March 2021, the entire Mediterranean basin was affected by a positive air pressure anomaly, which showed its effects on a large part of the Mediterranean coasts.

Examples of this phenomenon were observed in various Italian sites, such as Venice, where the low tide reached values of about -0.6 m with the consequent water withdrawal from the small canals in the city (fig. 1). The same phenomenon occurred in the dock of Pozzuoli (Naples), where the low tide caused the water withdrawal with the drying up of the piers (fig. 2). Furthermore, this area has been affected in recent years by a local land uplift (a phenomenon known as negative bradyseism) with a consequent relative lowering of the sea level (Cannatelli *et al*., 2020). Analyses of the INGV data showed that, from January 2016 to date, the maximum uplift was about 44.5 cm and that the average speed of this uplift, calculated on the basis of weekly data starting from September 2020, is 13 ± 2 mm/month (INGV Bullettin, 2021). In this area, the combined effects between the low tide event that occurred in the period February-March 2021 and the local ongoing uplift (Aucelli *et al*., 2020; Cannatelli *et al*., 2020) resulted in the exposure of large coastal areas generally submerged.

However, the piers are not the only areas where the effects of extreme low tide have been observed. An emblematic case was reported in Vieste (Foggia, southern Italy), in particular at the Pizzomunno sea stack (fig. 3). Under normal conditions of tidal excursion, in this site, the shoreline position is located in the proximity of the sea stack; however, in the first days of March 2021, a seaward shoreline migration of about 30 m was observed (fig. 3). Higher shoreline migration was observed during the summer of 2021 for the same area, in particular in

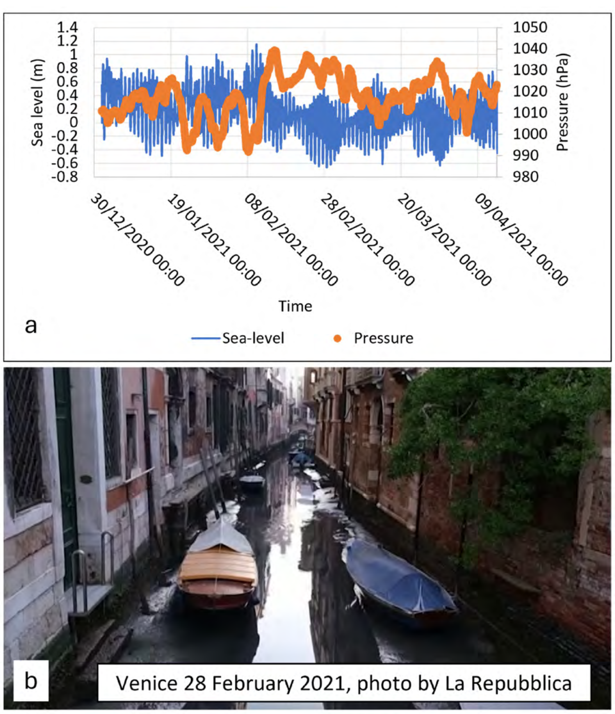



Figure 1 - Evidence of extreme low tide; a) Atmospheric pressure at 10 m height and sea-level data were recorded in Venice (property of ISPRA) in the months of February-March 2021; b) drainage of the canals was observed during low tide in the city of Venice (photo credits from La Repubblica).

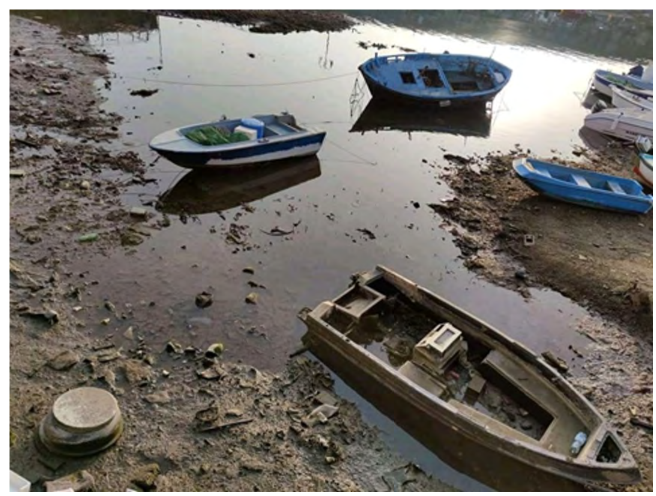


Figure 2 - Effects of extreme low tide on the Tyrrhenian coast relative lowering of the sea level recorded in the dock of Pozzuoli with consequent drying up of the piers in March 2021.

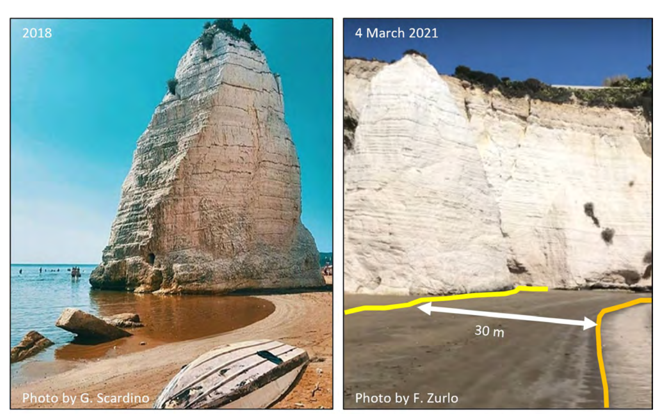



Figure 3 - Pizzomunno sea stack (Vieste, Foggia); note the position of the shoreline in 2018 at the base of the stack, while in the photo of March 2021 it has migrated for about 30 meters seaward.

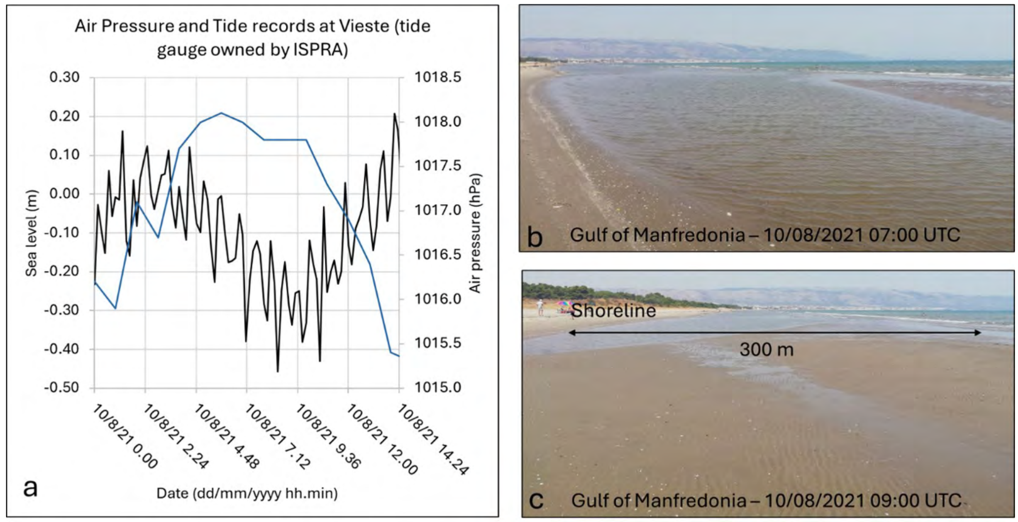



Figure 4 - Anomalies in air pressure and sea level observed at the coastal plain of the Gulf of Manfredonia; a) air pressure and sea level recorded at the tide gauge of Vieste on 10/08/2021 (owned by ISPRA); b) nearshore area at the hour 07:00 UTC; c) shoreline migration due to the persistence of a positive air pressure anomaly at 09:00 UTC.


Figure 5 - Effects of extreme low tide on Torre Canne (Brindisi) recorded by the Puglia Basin Authority video camera, data provided by the SIMOP Project (2020).

the proximity of the coastal plain of the Gulf of Manfredonia (fig. 4). Similar effects of shoreline migration have also been observed in other Mediterranean beaches. An example was reported from the video recordings in the pocket beach of Torre Canne (Brindisi), where a progressive progradation of the shoreline was observed on different days (fig. 5). This progradation was very evident until the first two weeks of March 2021; then, with the ending of the positive pressure anomaly, rapid recovery of the initial coastal conditions was observed at the end of March.

Evidence of an extreme low tide has been reported on the island of Kavouri (Athens). In this coastal area, the isthmus that connects the island of Kavouri with the coast is always submerged while, during the first weeks of March 2021, it emerged because of the extreme sea level lowering (fig. 6).


Figure 6 - Comparison between the aerial photo of the island of Kavouri (Greece) in March 2021 (picture from https://www.keeptalkinggreece.com/ (accessed on 8 August 2021)) with the satellite image of May 2019 (the image background is derived from ESRI World Imagery-sources: Esri, Maxar, Earthstar Geographics, and the GIS User Community) where the submergence of the isthmus is clearly evident.

## DATA ANALYSIS

Data analysis of the tide gauges located in the Mediterranean area has allowed obtaining the frequency components of the low tide event that occurred in the period February-March 2021. On the other hand, tide records showed a relative lowering of the msl starting from the middle of February 2021, exactly coinciding with the onset of the positive pressure anomaly in the Mediterranean area. Time-series data from 12 tide gauge stations (owned by ISPRA) in the Mediterranean Sea from January 1 to April 30, 2021 (fig. 7) and August 2021 (fig. 8) were analyzed. For each time series, the minimum value of the water level was extracted in order to assess the extent of the extreme low tide phase. Then, the minimum value of water level was compared with the spatial distribution of mean sea-level pressure (MSLP) extracted from the reanalysis dataset of ERA5 (Dee *et al.*, 2011; Hersbach *et al.*, 2020; Barbariol *et al.*, 2021).

The frequency components of the tide records were processed through spectral analysis, using the continuous wavelet transform (CWT) (Araszkiewicz and Bogusz, 2010; Cohen, 2019). The CWT transform allowed us to obtain coefficients representative of the energy percentage, which can be represented in a scalogram at different frequency intervals. The higher the energy content, the greater the absolute value of the coefficients represented in the scalogram.

## RESULTS AND DISCUSSION

The relative lowering of sea level as a consequence of a recent positive pressure anomalies that occurred in the period February-March and August 2021 were observed in the analyzed tide records of the Mediterranean area. In fig. 9, the CWT transform for the tide records of the Bari station (available by consulting the ISPRA website) for the

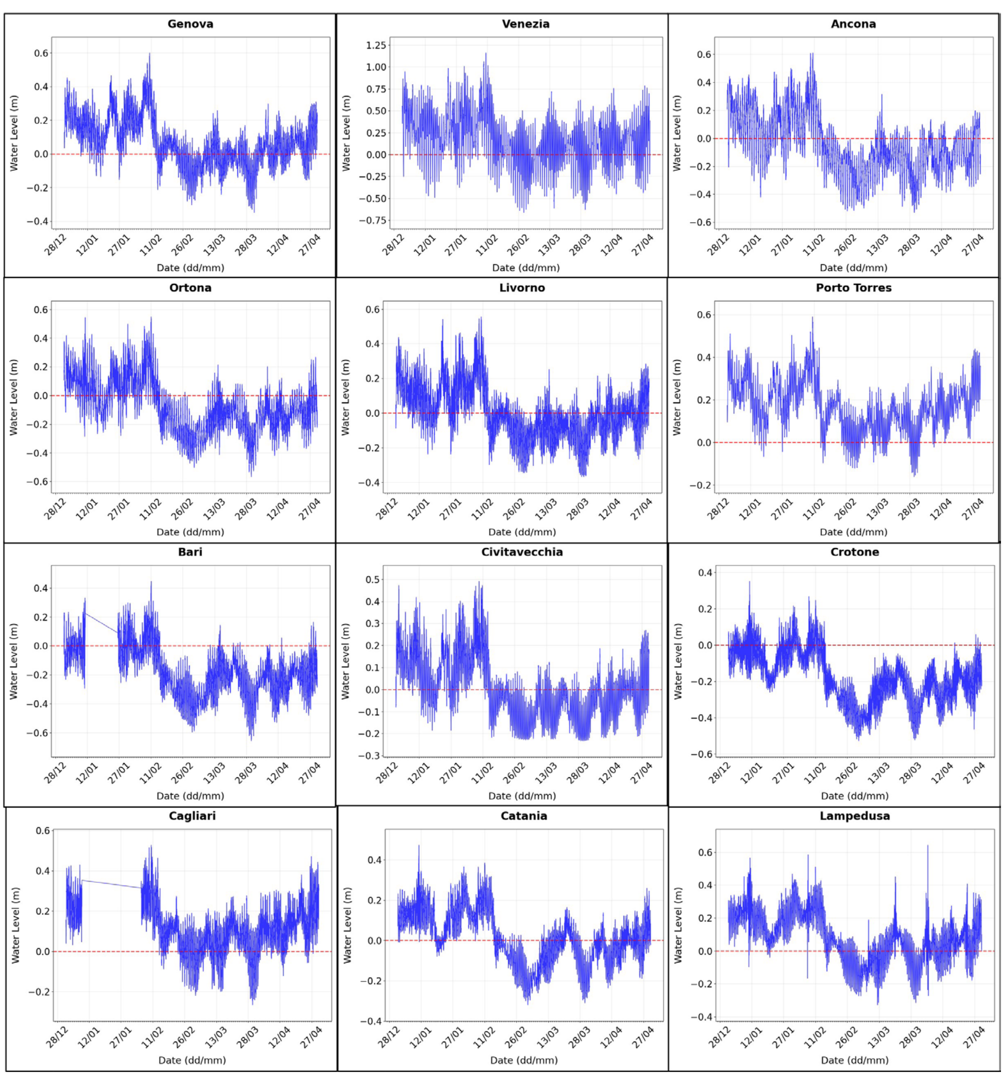



Figure 7 - Time-series of sea level extracted from the tide gauges considered in this study for February-April 2021; dashed red line indicates the zero-reference level.

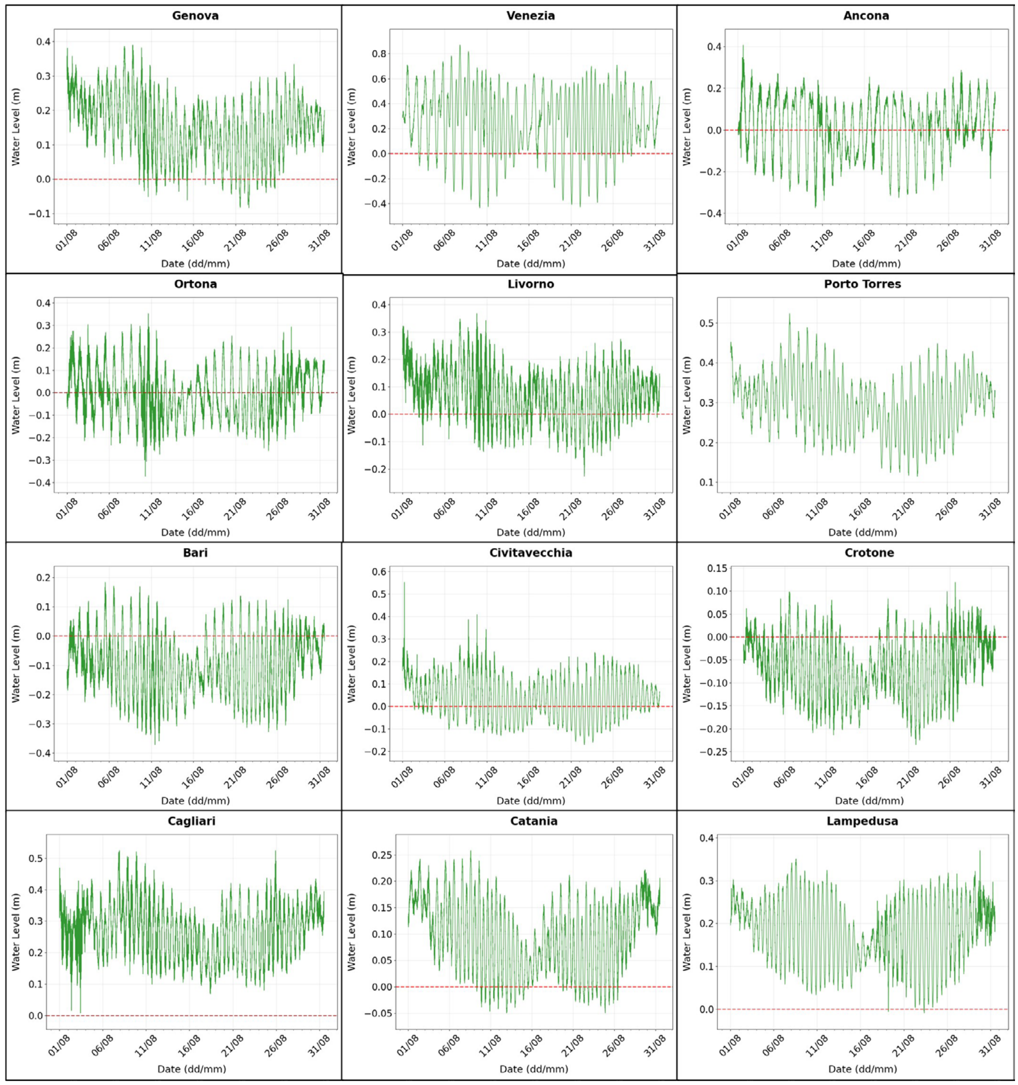



Figure 8 - Time-series of sea level Time-series of sea level extracted from the tide gauges considered in this study for August 2021; dashed red line indicates the zero-reference level.

months January-April 2021 is shown. Content of the higher energy percentage is shown at spring tides, where the tidal phases are large, while in the lower frequency components, a lowering of the energy content is observed corresponding to the phase of relative lowering of the sea level in response to the pressure anomaly (fig. 9).

This anomaly was marked after 16 February, and MSLP extracted from ERA5 revealed values higher than 1035 hPa (fig. 10a). However, the pressure anomaly occurred in August 2021 was lower than in February, with MSLP value of 1018 hPa, with extreme low tides observed only along the Adriatic coasts (fig. 10a).

Although such anomalies and consequent effects on sea level have also occurred in past historical moments (Tsimplis *et al*., 2005; Lionello *et al*., 2008), widespread effects on the Mediterranean coasts have rarely been observed. These effects can be explained through the resilience model of Westman (Westman, 1986), which is valid for ecosystems but can be modified and adapted for coastal systems.

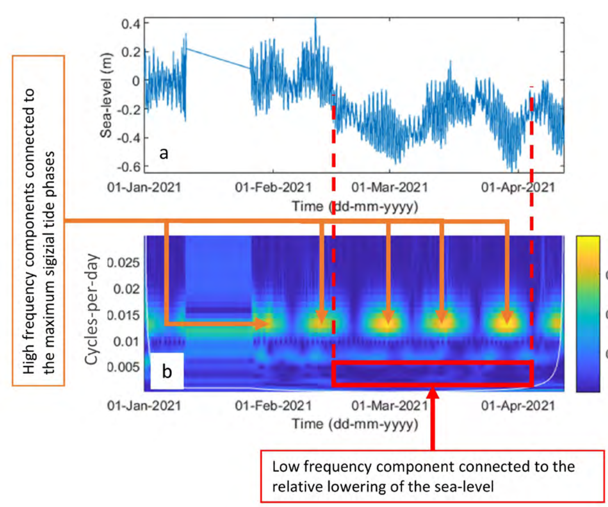



Figure 9 - CWT spectral analysis of the tidal record of the Bari station (property of ISPRA); a) the raw recordings are shown at the top, highlighting the time of negative pressure anomaly (red dashed lines); b) the scalogram of the coefficients of the CWT transform is at the bottom with the low frequency components.

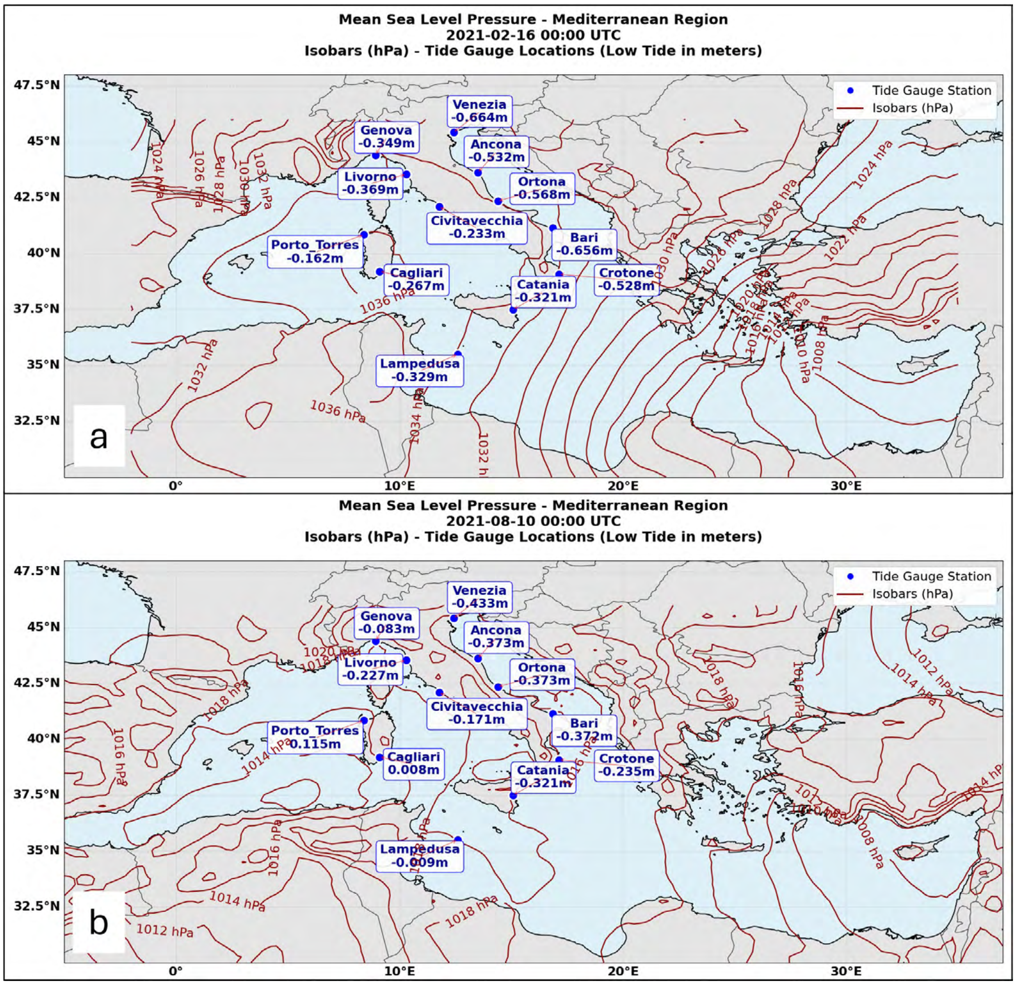



Figure 10 - Extreme low tide values observed at tide gauge stations (blue points) in the Mediterranean Sea, MSLP isobars derived from the ERA5 reanalysis dataset; a) MSLP and extreme low tides measured on 16 February 2021; b) MSLP and extreme low tides measured on 10 August 2021.

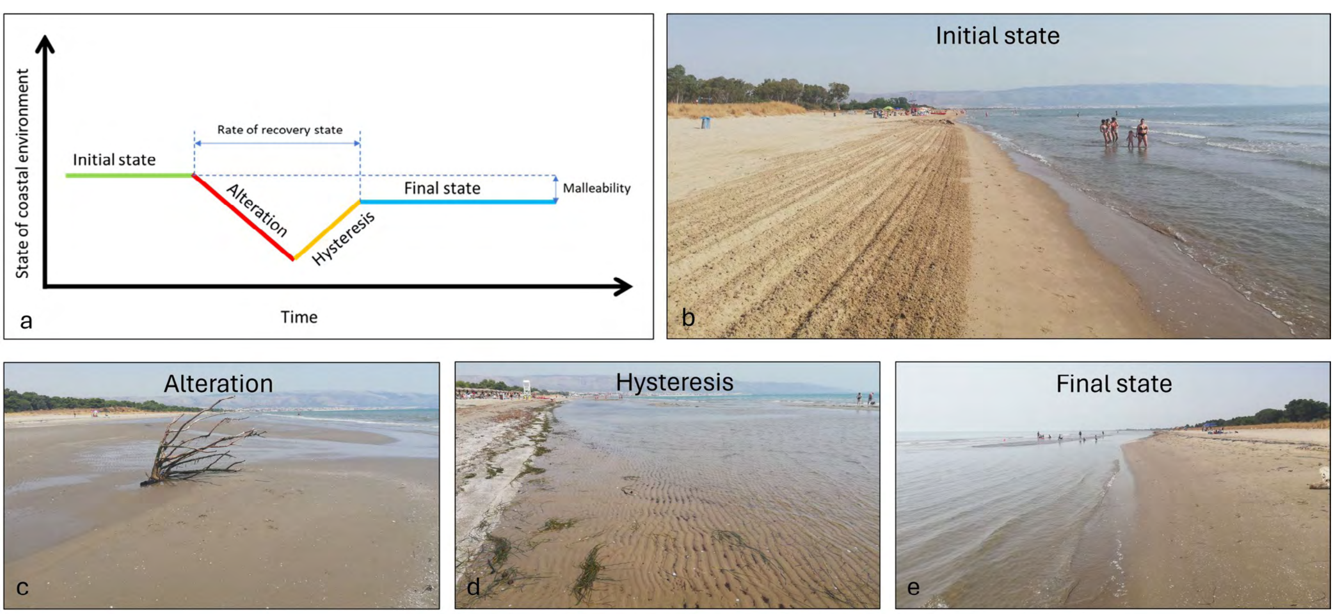



Figure 11 - The resilience model, modified by Westman (Westman, 1978), applied to coastal systems. a) The characteristics of resilience in a coastal system are the same as defined (Orians, 1975; Westman, 1978, 1986) for ecosystems: inertia, elasticity, amplitude, hysteresis, and malleability; b) Initial state of the coastal plain in Tavoliere delle Puglie (10/08/2021 07:00 UTC); c) Alteration phase of coastal system due to the extreme low tide onset (10/08/2021 08:00 UTC); d) Hysteresis phase during the persistence of low tide phase (10/08/2021 09:30 UTC); e) Final state of the coast after the extreme low tide (10/08/2021 12:00 UTC).

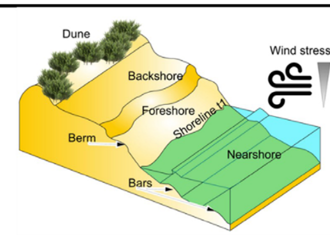
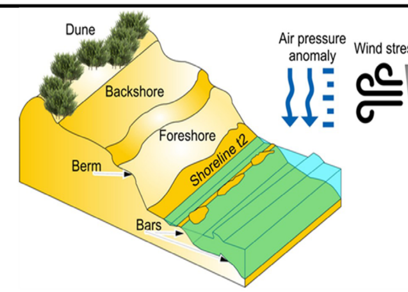
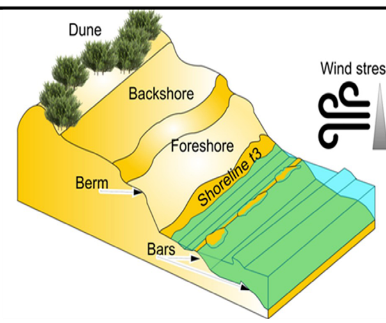
| Resilience characteristics | Interpretation | State of a mobile coastal system and shoreline position at different times |
|---|---|---|
| Inertia | Ability to withstand stress or variation in the sedimentary balance |  |
| Amplitude | Difference between the state of alteration and the final state of the coastal system |  |
| Hysteresis | Time interval between alteration and final state of a coastal system | |
| Malleability | Difference between the initial and final state of a coastal system |  |
| Flexibility | Ability to restore the original state of the coastal system following a solicitation or variation of the sedimentary balance | |

Figure 12 - Characteristics of the resilience model for a coastal system during an extreme low tide phase.

The concept of resilience, applied to the coasts, represents the ability of the coastal system to adapt or resist a certain alteration of its original state. As illustrated in fig. 11, an alteration of the state of a coastal system determines the passage from an initial state to a final state, which could not necessarily correspond to the original configuration of the coast. The rate at which this process occurs is defined as the "recovery rate," which consists of an initial alteration phase followed by a hysteresis phase. During the initial alteration phase, changes in sedimentary budgets and structures are observed over relatively long periods, ranging from weeks to months. This is followed by the hysteresis phase, in which the coastal system attempts to return to its original state, restoring both morpho-topographical conditions and the initial sedimentary balance (fig. 12). If the system's final state matched its initial state, it would indicate perfectly elastic behavior. In the observed case from February-March 2021, the alteration of the coastal system was triggered by high atmospheric pressure in the Mediterranean Sea, coupled with extreme low tides. These conditions particularly affected the beaches, causing a seaward shoreline migration. However, starting in mid-March 2021, following the end of the pressure anomaly, the coastal system began recovering its initial conditions.

The effect of the positive pressure anomaly on MSLP was one of the most intense observed since the last century. Gomis *et al.* (2008) showed that the components of atmospheric forcing at sea level from 1958 to 2001 (such as air and wind pressure variations) had an insignificant contribution in amplitude, of the order of 2 cm, significantly lower than the low tide observed in the months of February-March 2021. However, in this last case, the pressure anomaly had a temporary duration, culminating in the middle of March 2021 and allowing the coastal system to restore its initial state with an elastic response.

If permanent external alterations occur, as, in the case of sea-level rise, the coasts would not be able to respond elastically and could undergo irreversible changes, such as permanent submersion and the retreat of the coastal system (Antonioli *et al.*, 2020; Rizzo *et al.*, 2020; Anzidei *et* *al.*, 2021). Some permanent changes can be observed today, as in the plain of Metaponto, where there is a continuous erosion of the beach and the dune belt (Sabato *et al.*, 2012; Longhitano, 2015; Scardino *et al.*, 2020). Other types of permanent changes in the coastal system are directly related to anthropogenic activity, which causes irreversible changes, as already occurring along the plain of Manfredonia and the Molise coasts (Caldara *et al.*, 1998, 2006, 2014; Aucelli *et al.*, 2009, 2018; Rosskopf *et al.*, 2018; Scardino *et al.*, 2022; Petio *et al.*, 2024), where the defence interventions have altered the shoreline drift, the extraction of wells has determined the sediments compaction and localized subsidence phenomena, and the drainage of river basins has reduced the solid flow of rivers.

The adaptive response of the coasts to climate variations and anthropogenic impacts is one of the topics of great interest for international institutions, administrators, and policymakers as most of the world's residential and productive activities are concentrated along the coastal areas (Ericson *et al.*, 2006; Church *et al.*, 2013; IPCC, 2019; López-Dóriga and Jiménez, 2020).

## CONCLUSIONS

The adaptive responses of coastal systems are closely linked to the type of disturbance that causes changes in their physical and ecological state. If a coastal system cannot respond elastically, these disturbances may result in a final state that is entirely different from the initial one. Permanent disturbances, such as sea-level rise and anthropogenic pressure, are the primary factors that prevent elastic adaptive responses in coastal systems. In this study, we analyzed a non-permanent disturbance associated with positive atmospheric pressure anomalies that occurred in the Mediterranean basin in February-March 2021. Extreme low tides in February-March 2021 caused substantial seaward shoreline migration along Mediterranean coasts, exposing typically submerged features such as the Pizzomunno sea stack (Apulia, Italy) and an incipient isthmus at Kavouri Island (Greece). Tide gauge measurements below -0.6 m, projected across low-lying areas, highlighted shoreline displacements exceeding 40 m seaward, like in Torre Canne (Apulia, Italy) and Pozzuoli (Campania, Italy) in February 2021. Although this positive atmospheric pressure anomaly did not compromise the overall resilience capacity of the coastal system, some damage was observed in urban settlements, including the withdrawal of canals in Venice (Italy).

Multiple Mediterranean coastal sites exhibited a rapid and extensive adaptive response to this event, characterized by seaward shoreline migration and the exposure of typically submerged areas. Once the disturbance ended, the original coastal conditions were fully restored.

However, this elastic response does not always occur. In cases of sea-level rise or anthropogenic activity, coastal systems face irreversible changes, preventing an elastic recovery. Such disturbances lead to critical future scenarios, including substantial land loss, damage to socio-economic activities, and the decline of coastal ecosystem services.

## AUTHOR CONTRIBUTIONS

Conceptualization: G.S, A.R., G.M., V.D. Methodology: G.S, A.R., V.D. Formal analysis: G.S, A.R., G.M. Investigation: G.S, A.R. Resources: G.S., G.M. Data curation: G.S, A.R., V.D. Writing – original draft preparation: G.S, A.R. Writing – review and editing: G.S, A.R., G.M., V.D. All authors have read and agreed to the current version of the manuscript.

## DATA AVAILABILITY

Datasets related to the tide gauge for the sea-level station are freely available at https://www.mareografico.it/ (accessed on 08 August 2021) and http://www.ioc-sealevelmonitoring.org/ (accessed on 08 August 2021). Datasets related to sea-level projection are freely available at https://www.cen.uni-hamburg.de/icdc/data/ocean/ar5-slr.html (accessed on 08 August 2021).

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## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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