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Sea level rise and extreme events along the Mediterranean coasts: the case of Venice and the awareness of local population, stakeholders and policy makers

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Abstract
Sea level rise (SLR) is among the major climate change effects threating the coasts of the Mediterranean basin, which are increasingly exposed to coastal flooding, especially along the low lying coastal plains, river deltas, lagoons and reclamation areas. Coastal erosion, beach retreat and marine flooding are already causing unprecedented environmental and socio-economic impacts on coastal populations. According to the Intergovernmental Panel on Climate Change (IPCC) these effects are expected to worsen by 2100 and beyond with a projected global SLR up to about 1 m above the current level. This study provides an overview of the Mediterranean basin, focusing on the vulnerable city of Venice, which is particularly exposed to marine flooding due to SLR and land subsidence. We show the current and future sea level trend as well as a flooding scenarios in the absence of the Experimental Electromechanical Module (MoSE), which is protecting the city of Venice since 2020. To understand the awareness of citizens in Venice to address SLR, we have engaged a group of stakeholders through a structured participatory process to develop solution-oriented, case-specific and site-specific Policy Tools. Our results show that the Policy Tools contain relevant, effective and implementable actions stemming from stakeholder interaction and consensus building, identifying relevant issues that should be considered for SLR adaptation policies. A more extensive participation in public processes is required to materialize the Policy Tools into concrete actions to help vulnerable areas adapt to the expected SLR by the end of this century.

Keywords Mediterranean Sea · Sea level rise · Extreme events · Stakeholder · Policy makers · Venice · Acqua alta

Abbreviations

AR6	Sixth assessment report
DSM	Digital surface model
DTM	Digital terrain model
ESL	Extreme sea level
GIA	Glacial isostatic adjustment
GNSS	Global Navigation Satellite System
GSL	Global sea level
GSLR	Global sea level rise
IGS	International GPS Service

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IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light detection and ranging
LGM	Last glacial maximum
MoSE	Experimental electromechanical module
RSLR	Relative sea level rise
SLR	Sea level rise
SSP	Shared socioeconomic pathway
VLM	Vertical land movement

1 Introduction

Global sea level (GSL) data from tide gauge networks, radar altimeters and ground observations show that the sea level is rising at an unprecedented rate since the mid-nineteenth century. The current rate is about 4 mm/year, more than twice that observed in the twentieth century (Fox-Kemper et al. 2021; Palmer et al. 2021). The sea level rise (SLR) has been induced by the global warming due to the ever-increasing concentration of greenhouse gases in the atmosphere caused by human activities since around 1800, the beginning of the industrial era. This process is triggering the melting of ice caps and glaciers and the thermal expansion of the oceans, leading to a continuous rise of the levels (Oppenheimer et al. 2019). Global Sea Level Rise (GSLR) projections by 2100 AD predict a likely rise in the range of 0.28–0.55 m to 0.63–1.02 m, relative to the period 1995–2014, for very low and very high emission scenarios, respectively (66% confidence SSP1-1.9 and SSP5-8.5) (Fox-Kemper et al. 2021). In addition, a possible faster melting of the ice of West Antarctic and Greenland could trigger a SLR rise up to 2.3 m by 2100 and up to 5.4 m by 2150 (Bakker et al. 2017; Kopp et al. 2017; DeConto et al. 2021). Besides the eustatic factor, vertical land movements (VLM) due to the Glacial Isostatic Adjustment (GIA) and tectonics or volcanic activity can exacerbate the local SLR in subsiding coastal areas (Anzidei et al. 2014; Lambeck et al. 2010). The combination of the above phenomena is a dramatic factor of hazard for about one billion people living along the worldwide coasts. Enclosed basins, like the Mediterranean Sea, are sensitive to the effects of SLR, especially along the low elevated coasts, river deltas, lagoons and reclamation areas that are highly exposed to SLR. These coastal zones are further experiencing dramatic beach retreat, coastal erosion, marine flooding and salinization of the water tables that is causing 85% of the estimated damage costs. Natural and anthropogenic land subsidence is increasing the risk of flooding along the Mediterranean coasts (Anzidei et al. 2021; Vecchio et al. 2023), causing the relatively slow submergence of ancient coastal settlements of the Roman or pre-Roman age (Benjamin et al. 2017 and references therein), historical cities like Venice (Vecchio et al. 2019), and small islands (Anzidei et al. 2017).

The projected economic loss due to the retreat of coastlines in natural and cultural heritage sites in Southern Europe is estimated at 18 billion euros for the period 1908–2080 (Karagiannis et al. 2019). Since many Mediterranean countries are heavily dependent on tourism and other coastal activities (e.g. agriculture, farming, and maritime industry), the social and economic impacts of SLR are very significant. For example, in Catalonia (Spain) the SLR is projected to lead to a decline of 20% in the area's tourism-related GDP (Garola et al. 2022), whereas rice production in the Ebro River Delta is expected to decrease significantly, reducing farmers' profits by up to 300 euros per hectare (Genua-Olmedo et al. 2016). Even though the risks associated with SLR are important, they are not well understood by the population yet (Loizidou et al. 2023; Solarino et al. 2023). Adequate awareness-raising is needed to enable the public to identify risks, advocate for appropriate mitigation and adaptation policies, and participate in their implementation. To achieve this, it is necessary to present scientific data in a way that is understandable to the general public and to strengthen the relationship between science and policy. Decision-makers and stakeholders involved in managing the impacts of climate change and SLR, need to understand the importance of involving local people during the decision-making process, as their knowledge of the environmental and socio-economic assets of their areas is pivotal to the design and implementation of mitigation and adaptation measures.

Here we show the state of the art of the Relative SLR (RSLR) projections along the Mediterranean coast. In particular, we focus on the case study of Venice, where the combination of SLR, VLM and extreme meteorological events, are putting this vulnerable city at very high risk in the future (Loizidou et al. 2023).

2 The Mediterranean basin

The Mediterranean basin is one of the most complex tectonic areas of our planet. Its current shape results from the evolution of the long-lasting convergence between the major African and Eurasian plates across a roughly east–west boundary running across the Mediterranean Sea from the Azores Islands to the Himalayan mountain belt, active since the Late Cretaceous (Dewey et al. 1973; Le Pichon et al. 1988; Jolivet and Faccenna 2000; Faccenna et al. 2014). Geodetic data from regional GNSS networks, show that these major plates are still moving against each other at a velocity of a few millimetres per year (Devoti et al. 2017; Serpelloni et al. 2022), while seismicity is occurring along well-defined seismic belts underlining the boundaries of minor plates and a complex pattern of crustal deformations (Anzidei et al. 2014 and references therein) that include active and quiescent volcanoes (http://www.volcano.si.edu/).

In this complex tectonic framework, geological and geodynamic processes are causing crustal deformations, also along the coastal areas (Anzidei et al. 2014; Ferranti et al. 2010). At the same time, the Mediterranean region has also been affected by relevant sea level changes driven by the astronomical factors that caused the periodic growth and decay of the large ice sheets. The last cold period culminated in the Last Glacial Maximum (LGM) about 20,000 years ago, with associated isostatic effect due to the changing surface loads of ice and water (Lambeck and Purcell 2005; Spada 2017; Peltier 2001). Currently, the coasts of the Mediterranean are exposed to multiple coastal hazards that include slow and rapid events. Among the first are those due to SLR and land subsidence in response to climate changes and tectonics, respectively (Vecchio et al. 2023). The latter are related to the effects of storm surges, tsunamis and extreme meteorological events (Lionello et al. 2021).

The Mediterranean region is also experiencing a rise in the severity of extreme weather events such as heatwaves, droughts, and Medicanes. Rising temperatures in the Mediterranean contribute to warmer sea water, SLR and to intensified heat waves, impacting both human health and agriculture (Fig. 1a, b). Medicanes refer to a meteorological phenomenon characterized by the development of tropical cyclone-like systems in the Mediterranean (Flaounas et al. 2023; Borzì et al. 2023). While the Mediterranean is not typically associated with the formation of hurricanes, certain atmospheric conditions can lead to the creation of these rare and devastating weather events (warm sea surface temperatures, typically above 26.5 °C with a combination of atmospheric instability and the presence of a low-pressure system). These storms can bring intense rainfall, strong winds, and even storm surges to coastal areas around the Mediterranean that are particularly severe for the Venice lagoon.

3 The Venice lagoon: an iconic case study

The UNESCO world heritage site of the Venice lagoon is located in the north Adriatic Sea (Italy), covering an area of approximately 550 km^2. About 255,000 people live in the city boundary lagoon and 50,000 in the historical city of Venice (data from the City of Venice 2021). Around 30 million tourists visit Venice every year putting intense pressure on infrastructures and services (City of Venice 2021). This coastal city is affected by the combined effects of SLR, natural and anthropogenic land subsidence, as well as frequent events of "acqua alta" (extreme high-water levels due to the combined effect of astronomic and meteorological tides) and by a general sea level anomaly (with respect to the baseline

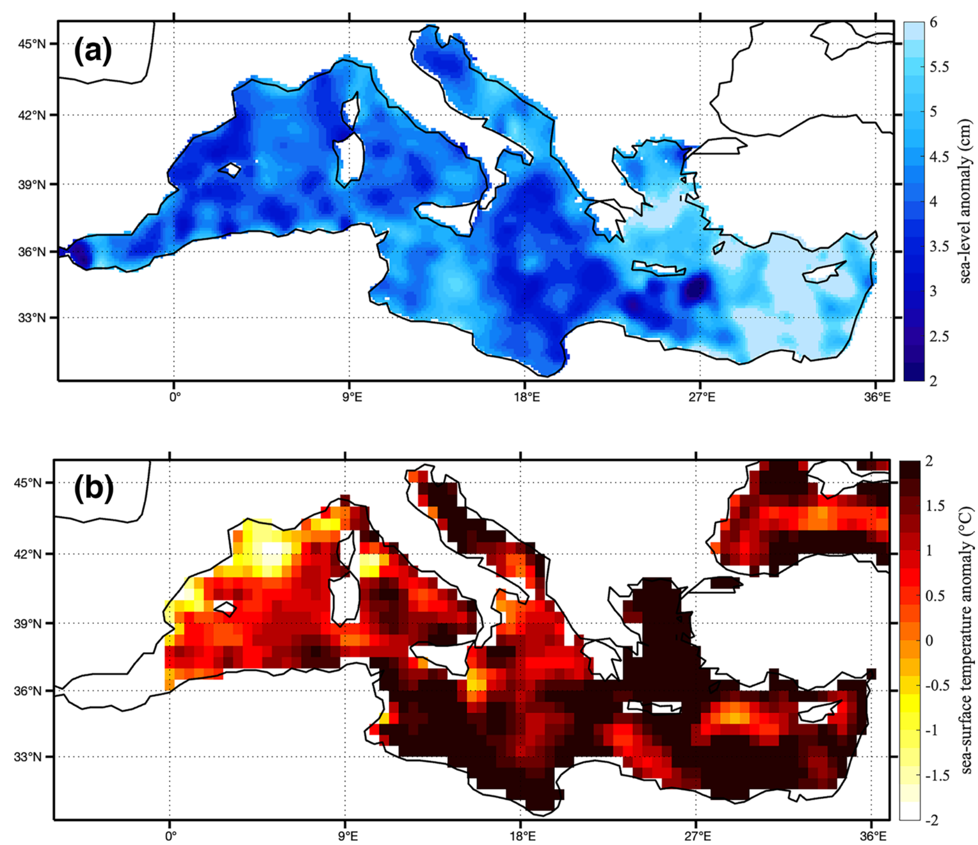

Fig. 1 **a** Sea level anomaly in the Mediterranean Sea averaged over the period 1993–2020 (value in cm; data from https://climate.copernicus.eu/). **b** Sea-surface temperature anomaly in the Mediterranean Sea averaged over the period 1993–2020 (value in °C; data from https://climate.copernicus.eu/)

period 1993–2020, Fig. 2). The frequency of extreme high water events has increased in the last few decades due to progressive SLR caused by global warming (Città di Venezia 2022b). When the high tide reaches the frequent level of 110 cm, about 12% of the historic city is flooded, while in a smaller cases, when the sea level reaches a height of 140 cm, 59% of the city is submerged. Between 2019 and 2023, about 58 events with tide amplitudes higher than 110 cm were recorded, compared to the 24 events recorded during a 4-year period (2009–2013) of the preceding decade (Città di Venezia, Tidal Forecast and Early Warning Centre 2022a). In recent decades, the phenomenon has been steadily increasing due to the natural and anthropic land subsidence caused by the extraction of groundwater and fluids, which affected the area between 1930 and 1970. Since the early 1900s, the mean sea level in Venice has risen by about 35 cm, higher than the average SLR of the Mediterranean Sea over the same period of 18 cm (Zanchettin et al. 2009, 2021; Anzidei et al. 2014; Wöppelmann and Marcos 2012), thus putting the lagoon at increasing risk of flooding by 2100 due to SLR (Vecchio et al. 2019; Lionello et al. 2021).

The Venice lagoon is an emblematic example of coastal zones' vulnerability to rising sea levels, standing out as one of the most affected regions, with projections indicating an increase in the magnitude, duration, and frequency of extreme sea levels in the future (Tebaldi et al. 2021). The repercussions of Extreme Sea Level (ESL) events in Venice are substantial, leading to significant damage to the city's cultural and economic heritage. The inundation of streets and buildings, along with the widespread destruction of artworks and landmarks, such as the historic St. Mark's Basilica, emphasizes the critical need for proactive measures (Ferrarin et al. 2021). The complex interplay of astronomical tides, seiches, and atmospheric forcings, including strong winds, depressions, storm surges, and meteotsunamis, contributes to the genesis of ESLs and flooding in Venice. The combined effects of these factors increase the likelihood

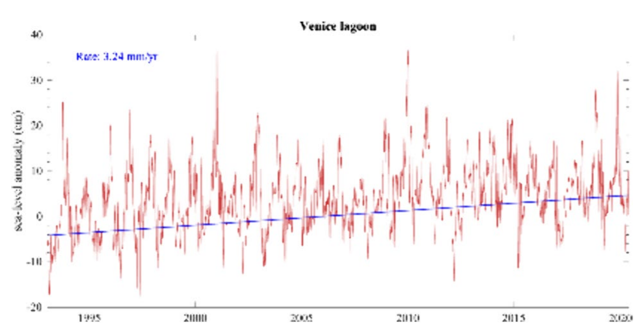

Fig. 2 The sea-level anomaly in the Venice lagoon over the period 1993–2020 with respect to the reference period 1993–2012 (value in cm) as observed from the Copernicus service. The mean SL anomaly in the lagoon is rising at 3.24 mm/year in the reference period

of extreme events occurring, necessitating a comprehensive understanding of their interactions (Lionello et al. 2021).

Notably, the highest sea levels and storm surges in Venice align closely with southeasterly winds, specifically the sirocco, prevalent from November to March. While extratropical cyclones in the Alpine region contribute to surges, the most intense events are associated with phenomena in the Western Mediterranean, around the Gulf of Genoa. Additionally, a minority of events is influenced by atmospheric circulation patterns related to Euro-Atlantic sector variability (Lionello et al. 2021).

Despite advancements in understanding the primary causes of extreme sea levels, the inherent complexity of the climate system and its ongoing perturbation by climate change render reliable forecasts elusive. This underscores the pressing need for novel efforts to evaluate and anticipate incipient transitions in the dynamics of the Venice lagoon. Developing innovative strategies to support and inform on extreme sea levels is imperative in navigating the intricacies of the evolving climate system (Zanchettin et al. 2021; Umgiesser et al. 2021).

Recently, a novel approach to detect, diagnose, and classify extreme sea levels (ESLs) in the Venice lagoon has been proposed in the context of extreme value theory (Alberti et al. 2023) by using a time-dependent, dynamic diagnostic of lagoon conditions based on two metrics: the instantaneous dimension d, marking the number of active feedback in an ESL, and the extremal index θ, informing on the persistence of an ESL. A close connection between ESL occurrences and extremal index θ, coupled with an increasing instantaneous dimension d as the severity of the ESL, has been highlighted, underscoring the potential of the extremal index θ to locate ESL events relative to sea level fluctuations around the astronomical tide, while d informs on the constructive interference of external forcing components. In a more recent pioneering effort, Faranda et al. (2023) adopted a methodology that combines the analysis of analogue atmospheric patterns with statistical techniques to attribute the severity of "acqua alta" events in Venice to climate change. Specifically, by examining atmospheric circulation patterns from the three most impactful "acqua alta" events in the lagoon (04/11/1966—194 cm; 29/10/2018—156 cm; and 12/11/2019—187 cm) and a comparable yet less severe event (01/12/2008—156 cm), they assessed the likelihood of the observed increase in "acqua alta" events being a result of natural variability or climate change. To gauge the effectiveness of the MoSE protection, they also analysed analogues of the most extreme events, estimating the potential flood damage that would have occurred without MoSE activation, as well as a comprehensive cost–benefit analysis to evaluate the economic implications of deploying MoSE during "acqua alta" events. Their results reveal significant protection from MoSE for events resembling 1966, 2008, 2018 and 2019. This study holds significant implications for the management of "acqua alta" events in Venice. While refraining from attributing observed changes to a single factor, the alterations in atmospheric circulation patterns, influenced by both natural and anthropogenic forces, are already profoundly impacting the Venice lagoon. However, while the MoSE system has been proven to be effective in mitigating events with historical analogues, additional measures may be required to address potential damages from unprecedented events. The impact of extreme events in the Venice Lagoon highlights the importance of adaptation and resilience strategies in the face of climate change. Effective disaster preparedness, early warning systems, sustainable water management practices, and infrastructure resilience are crucial components in mitigating the impacts of these events on both human and natural systems.

4 Land subsidence and relative sea level rise projections up to 2150 A.D. for Venice

Vertical land movements (VLM), associated with natural and anthropogenic processes, may cause subsidence and uplift along the coastal zones that can accelerate or slow down the local SLR (Fig. 3). Estimating the rates of these movements is a crucial task for the calculation of local SLR projections and marine flooding scenarios for the next decades. In order to achieve this task, vertical GNSS velocities for the area of Venice have been obtained following the workflow described in Serpelloni et al. (2022). Absolute vertical velocities have been obtained by minimizing coordinates and velocities of the International GPS Service (IGS) global core stations, while estimating a seven-parameter transformation with respect to the IGS realization of

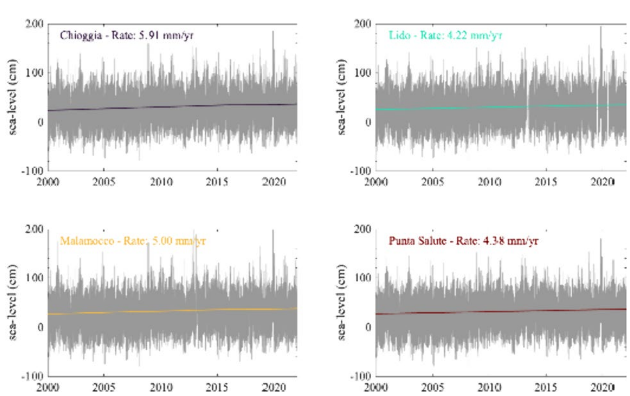

Fig. 3 Sea level trends in the Venice Lagoon at MoSE inlets (Chioggia, Lido, and Malamocco) and Punta della Salute (Canal Grande) tide gauge stations managed by Centro Previsione e Segnalazione Maree (2000–2022). Rates of SLR are ranging between 4.38 mm/year at Punta della Salute and 5.91 mm/year at Chioggia due to the spatial variability of the land subsidence in the lagoon

the ITRF2014 reference frame (Altamimi et al. 2016). A maximum likelihood estimation method (Bos et al. 2013) has been used to identify the nature of the stochastic noise in the time series. The median spectral indexes close to -1 are suggestive of a white noise plus flicker noise stochastic error model. Additional details on the data analysis can be found in Serpelloni et al. (2022). In the Venice lagoon, the GNSS stations belonging to different agencies (including those from Consorzio Venezia Nuova, CNR) have been operational since the last twenty years, providing reliable, accurate and precise estimates of vertical ground velocities.

The relative sea-level rise (RSLR) projections up to 2150 A.D. presented in this study are based on the most updated projections released by the IPCC in the 6th Assessment Report (Fox-Kemper et al. 2021) combined with the local land subsidence estimated by geodetic data from the available GNSS stations, assuming they will continue at the same rates up to 2150 A.D. For Venice, we chose to estimate the current rate of land subsidence at the PSAL station, which is the closest station to the Punta della Salute tide gauge station used by the IPCC for the projection. The vertical velocity has been estimated as -1.08 ± 0.60 mm/year and incorporated in the RSLR analysis. In Fig. 4, the RSLR projections relative to 2020 for Venice Punta della Salute are shown. Full lines correspond to the SSP1-2.6 (blue line, where global CO_2 emissions are cut severely, but not as fast, reaching net-zero after 2050), SSP3-7.0 (green line, where global CO_2 emissions are kept regularly increasing) and SSP5-8.5 (red line, CO_2 emissions double by 2050, driven by rapid economic growth fueled by fossil fuels and energy-intensive lifestyles, resulting in a scorching 4.4 °C rise in the average global temperature by 2100) scenarios and the coloured bands highlight the uncertainty. The latter is estimated as the sum of the squared uncertainties from the AR6 IPCC projections without VLM (as the distribution spread estimated from the 32nd and 68th percentiles) and the squared errors from the VLM measurements. Dashed lines correspond to the original AR6 projections, when the measured VLM is not included in the analysis.

To map the flooding scenarios due to RSLR, in the absence of a protective system such as the MoSE, we used the available high-resolution topography obtained from LiDAR (light detection and ranging) surveys, which allowed the calculation of digital surface models (DSM) and digital terrain models (DTM). For Venice, LiDAR data and derived DSM and DTM datasets, were provided by the Ministero delle Infrastrutture e dei Trasporti—"Provveditorato Interregionale per le Opere Pubbliche del Veneto -Trentino Alto Adige—Friuli Venezia Giulia", former Magistrato alle Acque di Venezia, through the dealer Consorzio Venezia Nuova (Fig. 5).

A simple "bathtub" approach was applied to assess the permanent flooding scenarios for different RCPs, where

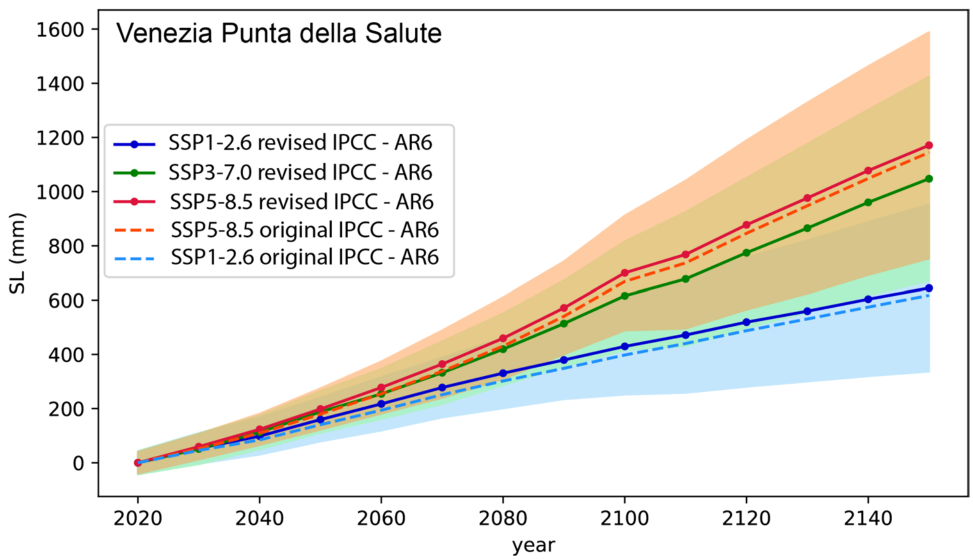

Fig. 4 Relative sea level rise projections for 2150 estimated at the tide gauge station of Venice Punta della Salute for SSP5-8.5 (red), SSP-7.0 (green) and SSP1-2.6 (blue) IPCC AR6 climatic scenarios. SLR projections include the rates of land subsidence estimated by GNSS data collected at VEN1 station in the time span 2008–2023

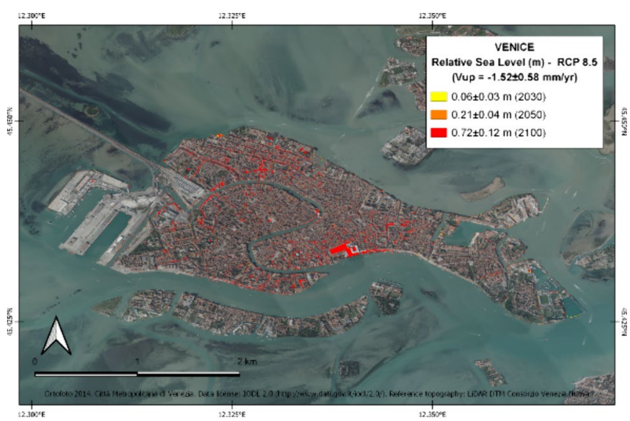

Fig. 5 Multi-temporal sea level rise scenario for Venice (RCP8.5). Colours show the extensions of the different areas exposed to flooding in 2030 (yellow), 2050 (orange) and 2100 (red). Scenarios are provided with respect to the mean sea level at 2016, thus not including tides that in Venice represent a critical factor of flooding. Background layer: Ortofoto 2014. Città Metropolitana di Venezia. Reference topography: LiDAR DTM ex Consorzio Venezia Nuova (from Falciano et al. 2023, www.savemedcoasts2.eu)

areas that fall below a target water level, which are not necessarily hydraulically connected to the sea, are considered as inundated. The quality of the flood scenario maps is dependent on the vertical accuracy of the DSM/DTM products used to calculate the inundation extent (in the order of a decimetre), the assumptions of invariance of the reference topography and VLM rates in the time horizons considered and, finally, the method used to assess the spatial extent of the potential inundation areas (Falciano et al. 2023). Despite the degree of uncertainty of the parameters involved, such maps may represent a first attempt to support policy makers and land planners in the preparation of climate change adaptation plans to address the SLR issue, which is exacerbated by VLM, and changes during extreme meteorological events and storm surge activity.

5 RSLR and stakeholders, gaps, needs, suggestions and the policy tool for Venice

In the frame of the European project SAVEMEDCOASTS2 (www.savemedcoasts2.eu) in 2021 a total of 24 stakeholders representing the Venice City Administration, port managers, water management authorities, non-governmental organizations, academia, researchers, the tourism industry, and small and medium businesses operating in Venice were engaged in a participatory process for developing a solution-oriented policy tool for SLR in the Venice lagoon.

The stakeholders were initially supported towards the assessment of the SLR vulnerability of Venice, which resulted to be high, pointing at the main areas of focus for reducing the city's vulnerability (Loizidou et al. 2023). Stakeholders were then facilitated towards recording the main gaps and needs of Venice with regard to SLR and climate change and identifying the most effective and appropriate solutions. The resulting Policy Tool for Venice builds an Action Plan for adapting and mitigating the impacts of SLR in the short (completion within 1 year), medium (completion within 1–3 years) and long term (completion within 3–5 years) (Table 1). The Policy Tool focuses on actions across five main categories: awareness-raising, more coordinated emergency response procedures, protection of vulnerable areas and infrastructure, quicker and more flexible management of MoSE, and building climate change resilience.

The need of a new Civil Protection for Emergency plan with more information, education and training about how

Table 1 Action plan for addressing SLR in Venice, as developed by the engaged stakeholders

Need 1: More coordinated emergency response procedures		
A1.1 Regular flooding emergency drills at schools	This was identified as a priority action by the stakeholders at the workshop. It involves the implementation of regular drills at schools to ensure that children are aware of how to react in case of flooding events. The stakeholders believed that this knowledge will then be transferred by the children to their parents/other adults	Short-term
A1.2 Training of residents on emergency procedures	The training should include actions that must be taken upon sounding of the flood alarms, but also actions that must be taken once the flooding event has ceased. This latter was identified as a gap during the workshop	Medium-term
A1.3 Targeted emergency awareness-raising for tourists	Tourists were identified by the stakeholders as one target group that is not particularly aware of either the meaning of the various alarms that sound during flooding events, or of the procedures that need to be implemented. As such, it is important to provide training, or at least information, to all tourists arriving in Venice. This could be done in various ways, including through information provided in accommodation rooms, or through a dedicated app or site managed by the City of Venice	Short-term
A1.4 Strategy for the management of alarm systems	There are various alarms that sound in the City of Venice depending on the intensity of the predicted flooding event. However, the stakeholders noted that there are no alarms for more intense events. Therefore, the alarms system must be reassessed to accommodate for higher than usual tidal events	Medium-term
Need 2: Greater awareness-raising		
A2.1 Provision of educational and awareness-raising activities at schools	School children are a key target audience for the awareness-raising activities. Awareness should be raised on the issue of climate change (its causes, impacts and how to mitigate it) as well as specifically on the topic of SLR. This can be achieved through targeted presentations and related activities at schools. Importantly, after the awareness-raising activities children should feel empowered to act against climate change	Short-term
A2.2 Awareness-raising for the public	Awareness-raising for the public can take be through various means including social media, public service announcements, promotional campaigns and so on. The aim of this awareness-raising should be primarily to inform the public about climate change and its link to SLR, and what they can do personally and collectively to mitigate it	Short-term
A2.3 Improve scientific communication to all stakeholders	This involves the communication of scientific data and information in a way that is comprehensible by the various target audiences, including the public, media, and decision-makers. It requires specialized personnel that can 'translate' and effectively communicate the scientific information	Short-term
Need 3: Protection of vulnerable areas and infrastructure		
A3.1 Mapping of vulnerable areas	Mapping of areas that are currently vulnerable to erosion, storm surges, SLR and those that will likely become vulnerable in the future, to design a prioritized plan of action for the protection of these areas	Short-term
A3.2 Maintenance and reinforcement of natural protection systems	Natural systems, including sand dunes, salt marshes, and littorals, protect coastal areas from flooding and erosion. These natural systems should be maintained, and where necessary, reinforced to ensure they remain functional	Short-term
A3.3 Identification and implementation of new nature-based solutions	Additional nature-based solutions should be implemented on vulnerable coastal areas to enhance the protection offered to them	Medium-term

Table 1 (continued)

Need 3: Protection of vulnerable areas and infrastructure		
A3.4 Ensure that urban buildings are resilient and protected	This relates to ensuring that buildings, including schools and businesses, remain safe and functional. This could be done through a series of measures that are implemented in Venice, including flood protection measures, water pumping, sacrificing the ground floor, etc.	Medium-term
A3.5 Maintain city infrastructure	This includes the proper maintenance of the canals through dredging and the continued raising of pedestrian areas to make the city more resilient to high tide events	Medium-term
A3.6 Identification and implementation of best practices to address the issue of water shortages	Water shortage is an important issue that Venice needs to address. This action concerns the identification of best practices to address this issue and their implementation. These practices could range from awareness-raising about water conservation, to technical studies on water recirculation	Medium-term
A3.7 Continuous monitoring of the state of vulnerable areas and infrastructure, and implementation of corrective actions, as necessary	This should be an ongoing action that will ensure that vulnerable areas and infrastructure remain protected in changing climates	Long-term
Need 4: Quicker and more flexible management of MoSE		
A4.1 Better definition of the governance of the MoSE through improvement in the communication between interested parties	The responsibilities of each of the bodies involved in the management and deployment of the MoSE should be clarified. This should be done through the improved communication between the interested parties	Short-term
A4.2 Improvement of the deployment procedures	The deployment procedures for MoSE should be improved to ensure that all the parties are in agreement about when the MoSE will be deployed (at which high tide level), for how long, and how the deployment takes place	Medium-term
A4.3 Continuous monitoring and reporting	The MoSE and its operation (together with all relevant aspects of it, including cost) should be closely monitored and this information should be shared with interested parties	Long-term
Need 5: Build climate change resilience		
A5.1 Define a clear strategic direction with regard to climate change	This should be a direct result of Venice's Climate Adaptation Strategy and should stem from multi-sectoral collaboration	Short-term
A5.2 Increase resources and capacities in relevant research and data centres	Research and data centres are providing valuable information for Venice. It is important to ensure that these centres have enough resources and capacities to not only collect precise and relevant data, but to also be able to transfer these data to decision-makers, the public, the media, and other relevant stakeholders, effectively	Medium-term
A5.3 Greater international networking and transfer of best practices	This involves monitoring what is happening at the international level, especially where it concerns innovative adaptation and mitigation practices, and adapting and transferring them to Venice	Medium-term

to react in case of extreme high-water level emergencies was the most important need according to the stakeholders. This is despite the fact that the city of Venice is provided with a Tidal Forecasts and Early Warning Centre (https://www.comune.venezia.it/it/content/centro-previsioni-%C3%A9-segnalazioni-m%C3%A0ree) that releases detailed flooding prediction and warnings about critical events for the upcoming 24, 48 and 72 h. The Tidal Office uses different communication channels (mobile application, emails, SMS, Telegram, sirens, and musical notes with rising pitches that correspond to rising tidal heights; see https://www.comune.venezia.it/it/content/servizi-allertamento). Nonetheless, the stakeholders in Venice considered that more coordinated emergency response procedures are required and that the implementation of training, awareness-raising activities and emergency drills, particularly at schools, is the best way of ensuring that people, both residents and tourists, learn how to react in case of extreme high water-level events. The stakeholders also identified the need for more information and the implementation of diffuse awareness-raising campaigns to encourage people to implement best practices for adapting to climate change as a solution.

At the time of the interviews and the workshops with stakeholders, the MoSE was not yet fully operational. It had started working in October 2020 on a pilot basis, and had been activated several times in the interim year. The feelings about the MoSE among the stakeholders were sometimes conflicting, although they recognized its importance. In fact, stakeholders were concerned about the exaggerated cost of its construction (about 6.2 billion euros) and operation (up to about 300,000 euros for every activation during the first period of activity). Some of the stakeholders were also discontented because money was being diverted from other important public works that could protect Venice against extreme tide levels and SLR, such as the cleaning of canals that run across the city of Venice and the other islets of the lagoon. Another point of concern was that while the MoSE "*has allowed the City to breathe a sigh of relief it might also lead to a general 'relaxation' about the issue of flooding, and Venetians could think that it is no longer a threat"*. It is worth noting that due to misinformation which have characterized the entire MoSE history there is a certain widespread misconception among stakeholders because "*the MoSE has not been designed to address SLR and it is already mandatory to look ahead and think of the post MoSE"*. Furthermore, not knowing exactly the detailed environmental studies carried out during the MoSE design phase, they believe that *"it has been designed to protect the City from extreme high tides a few times a year and it cannot stay permanently closed—this would be catastrophic to the lagoon ecosystem and will affect the quality of life of the people*". Therefore, among the most important needs by Venetian stakeholders was to improve the management and operation of the MoSE. Better definition of the governance and optimized communication among the parties that must collaborate for its deployment would ensure a shorter activation timeframe and thus more immediate emergency response. It could potentially also help reduce the operational costs associated with its deployment.

Another important need identified by stakeholders in Venice was to protect the vulnerable areas of the lagoon through the proper maintenance and reinforcement of natural defences. These include the restoration of salt marshes and enhancing natural sand dune vegetation, as they are considered particularly effective. Stakeholders believed that this could be supported by the implementation of nature-based solutions which are capable of reducing the impacts of SLR and storm surges along the coastal zone. Stakeholders also advocated for the protection of vulnerable city infrastructure, as well as the maintenance of canals and pedestrian areas to ensure the city is more resilient to high tide events.

A relevant point emerging from the stakeholders was that climate change and SLR should be considered in the design of all new infrastructures that might affect the evolution of the coast, including those built inland. The stakeholders were also concerned about maintaining the functionality of existing coastal infrastructures with respect to updated and more accurate information about SLR projections. In fact, they were doubtful about whether updated scientific SLR information and data used for the completion of the MoSE. The mobile barrier was designed many years before it became operational, raising serious doubts about its functionality in view of the latest scientific findings on the recent SLR and climate projections for the next decades and the intensification of meteorological extreme events (Lionello et al. 2021).

On the basis of the population's still little knowledge of the functionality and effectiveness of the MoSE, we therefore take the opportunity here to clarify some relevant information on the design and construction phases of the mobile barriers (see also https://www.mosevenezia.eu/?lang=en). The most important dates start in 1984 when a special law of the Italian government defined the objectives to safeguard Venice and its lagoon from sea level rise and "acqua alta" events. In 1994 the Consorzio Venezia Nuova (CVN) received the mandate of planning, designing and constructing a system of mobile barriers across the three main inlets to control the water flow between the lagoon and the open sea. In 1995 a team of international experts recommended the best technical solution that was later approved by the Italian government. Therefore, in 1998 the actual technical design of MoSE started and in 2003 the first worksite was opened at Lido inlet. It is worth noting that about in the same years, in 1994, the IPCC published its first report projecting a global SLR of about 20 cm by 2100. This value was initially considered in the design of MoSE until 2007, when the engineering project was improved to support up to 3 m in sea level difference between the open sea and the lagoon and a mean SLR of 60 cm in 2100.

Apart from the above technical aspects, environmental studies of the lagoon and its ecosystems examined the potential effects of the number and duration of barrier raising periods to optimize closures. Finally, since June 30, 2020 the MoSE system become fully operational. Till now the barriers have already been raised 78 times (at February 22, 2024), almost eliminating the detrimental and dangerous effects of "acqua alta" events on the precious city of Venice, the lagoon and the local population.

An important result from the stakeholder engagement is the need for specific local-scale scientific information and data on the expected impacts of SLR, coupled with the "translation" of the scientific data into comprehensive and comprehensible information for citizens and stakeholders. Local stakeholders believe that scientific information on SLR vulnerability and risks is too general and refers mainly to regional or global areas instead of describing the expected scenarios on their local zones of interest. The disconnection from scientific data causes significant gaps in awareness and even major misconceptions. To overcome this problem, the use of visualization tools capable to show the

SLR projections and detailed maps of multitemporal flooding scenarios for 2030, 2050, 2100 and beyond in the lagoon and its external limits, is the best way to let citizens understand the potential impacts of SLR. Maps for the different zones of the lagoon proved to be very useful visual means of transferring scientific knowledge.

An interesting point was that stakeholders noted that people tend to normalize the floods caused by extreme high-water levels and the phenomenon has been capitalized as a tourist attraction. Therefore, many tourists like to visit Venice during “acqua alta”. Finally, the reluctance to “retreat” to safer inner areas far from the lagoon and its dynamics, can be explained because people tend to accept the risk to live in an unsafe area, thinking that retreat from the area was not strictly urgent and necessary. This is similar to other high-risk areas such as active volcanic and seismic areas. “*I am aware of the risk but I will not move from here. This is my house, this is my land”*, most people living in dangerous areas say.

Finally, according to the stakeholders in Venice, the political will to act against climate change and SLR is still missing at all levels. Economic and political interests supersede environmental emergencies. The lack of political and public support and conflicting ecological and social priorities have been identified as major barriers associated with planning and decision-making relating to SLR (Stephens et al. 2020). Because adaptation requires important economic investments and longer-term strategies, the times are in contrast with the duration of the political mandate because politicians work in short time horizons (e.g. the duration of their political mandate). Then, political decision-making becomes a slow process, made even slower by bureaucracy and the required collaboration and coordination of multiple administrations and competing offices.

6 Conclusions

In this study, we have briefly shown the weakness of the Mediterranean coasts to the effects of SLR and extreme meteorological effects triggered by the recent global warming linked with human activities. Increasing extreme events are striking more and more frequently in this region, while sea level is rising at unprecedented rates putting at risk of flooding many thousands of square km of the Mediterranean coasts. In this complex framework that includes the dynamics of solid and fluid Earth, stakeholders are not adequately informed and are lacking relevant and easy to understand scientific information on the current impacts and evolution of climate change and SLR. Thus, it is important to investigate on the perceptions of stakeholders on SLR, site-specific mitigation and adaptation practices they can adopt in the vulnerable areas of the Mediterranean and, for this specific study, in the Venice lagoon to fill the gap in knowledge not only in the issue of climate change and SLR, but also of best-practice solutions of adaptation to face the climate challenge.

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Declarations

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