ARTICLE   OPEN

Check for updates

Attributing Venice Acqua Alta events to a changing climate and evaluating the efficacy of MoSE adaptation strategy

Davide Faranda [1,2,3 ✉], Mireia Ginesta[1], Tommaso Alberti [4], Erika Coppola[5] and Marco Anzidei[4]

We use analogues of atmospheric patterns to investigate changes in four devastating Acqua Alta (flooding) events in the lagoon of Venice associated with intense Mediterranean cyclones occurred in 1966, 2008, 2018 and 2019. Our results provide evidence that changes in atmospheric circulation, although not necessarily only anthropogenically driven, are linked to the severity of these events. We also evaluate the cost and benefit of the MoSE system, which was designed to protect against flooding. Our analysis shows that the MoSE has already provided protection against analogues of the most extreme event, which occurred in 1966. These findings have significant implications for the future of Venice and other coastal cities facing similar challenges from rising sea levels due to extreme events. This study also provides a pathway to evaluate the effectiveness of adaptation in a scenario more frequent and intense extreme events if higher global warming levels will be reached.

INTRODUCTION

The Acqua Alta events in Venice have caused significant damage to the cultural and economic heritage of the city over the years[1]. These events, which involve the flooding of the city's streets and buildings, have become increasingly frequent and severe in recent decades[2,3]. The three most devastating Acqua Alta events in terms of costs and damages occurred on 04/11/1966, 29/10/2018, and 12/11/2019, and have particularly impacted the city's cultural and economic heritage[4] and a forth one from a comparable sea levels high but less devastating occurred on 01/12/2008. The 1966 event[5], also known as the "Great Flood of Venice", caused widespread damage to buildings and artworks, including the historic St. Mark's Basilica. The 2018 and 2019 events, which occurred within a year of each other, caused significant damage to the city's cultural landmarks and businesses, including the iconic Caffè Florian and many of the city's historic shops[6]. Figure 1 provides a schematic representation of the hazards faced by the Venice lagoon due to rising sea levels. It shows the relationship between sea level, flooded area, and estimated damages. An empirical approach has been used to estimate the relation between the sea level reached within the lagoon and the economic damages based on data available for the four most devastating events. An analytical function was designed using an exponential law to link economic damage and observed sea level change. The parameters of the fit were estimated using the Levenberg-Marquardt algorithm and assessed for robustness using the Least Absolute Residuals method (see Methods). Figure 1 also highlights significant flooding levels, such as the level at which foodbridges are needed to walk across St. Mark's square and the level at which water enters the St. Mark's Basilica.

Acqua Alta events in Venice result from a complex interplay of various factors, as documented in literature[7,8]. These events involve high tides, which are influenced by natural phenomena such as the moon's position and phases, as well as the gravitational forces exerted by other celestial bodies. However, when strong winds blow across the Adriatic Sea towards the Venetian Lagoon, they can cause an increase in the water level, known as storm surge. This is because the winds push the water towards the city and the narrow entrance of the lagoon limits its ability to escape. The synoptic weather situation that causes these strong winds is typically a low-pressure system over the Tyrrhenian Sea, known as Genoa Low. If combined with high-pressure systems over central and northern Europe, this creates a strong pressure gradient and thus strong winds blowing towards Venice, causing potentially hazardous conditions. The impacts of the Genoa Low system as well as Mediterranean cyclones have been widely documented in literature[9–13], emphasising the importance of understanding this synoptic weather pattern in leading extreme events[14,15].

Climate change is widely considered to be a major contributing factor to the increased frequency and severity of extreme weather events, including storm surges and flooding[16]. The Intergovernmental Panel on Climate Change (IPCC) has stated that the increasing frequency and severity of extreme weather events are very likely caused by human activities, including the burning of fossil fuels and the resultant emissions of greenhouse gases[17]. These activities have led to changes in the Earth's climate, which have in turn altered storm patterns, increased sea levels, and caused more frequent and severe weather events[17]. Coastal zones, such as the historical city of Venice and its lagoon in the Northern Adriatic Sea, are particularly vulnerable to extreme sea levels, requiring a realistic approach to assess the risks and future projections of flooding, claiming for attribution studies of extreme weather events to climate change[18–24].

Given the peculiar landscape, Venice is expected to be particularly vulnerable to climate change. Sea levels in Venice have risen by approximately 26 centimeters over the past century, with projections indicating a change in extreme total water level between 20 and 40 cm for RCP4.5 (2100) and RCP8.5 (2050) and up to 80 cm for the RPC8.5 (2100)[25]. Nevertheless, the complexity of the climate system and the challenges of climate change make

¹Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay l'Orme des Merisiers, UMR 8212 CEA-CNRS-UVSQ, 91191 Gif-sur-Yvette, France. ²London Mathematical Laboratory, 8 Margravine Gardens, London W6 8RH, UK. ³Laboratoire de Météorologie Dynamique/IPSL, École Normale Supérieure, PSL Research University, Sorbonne Université, 75005 Paris, France. ⁴Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605, Rome 00143, Italy. ⁵International Centre for Theoretical Physics, Strada Costiera 11, Trieste 34100, Italy. ✉email: davide.faranda@lsce.ipsl.fr
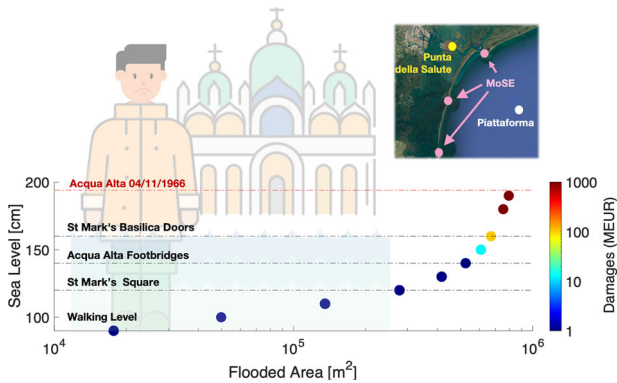
Fig. 1 Schematic representation of hazards for Venice lagoon. The relation between the sea level and the flooded area as a function of the estimated damages (filled coloured circles). The horizontal dashed-dotted black lines mark significant flooding levels corresponding to the sea level flooding St. Mark's square (120 cm), the level at which foodbridges are needed to walk across the square (140 cm), and the level at which water will enter the St. Mark's Basilica (160 cm). The red dashed-dotted line marks the level reached by the 04/11/1966 event known as "Great Flood of Venice" and studied in this work. The inset shows the location of the two tide gauge stations used to evaluate the sea levels within the lagoon (Punta della Salute, yellow circle) and outside (Piattaforma, white circle). The pink circles mark instead the position of the MoSE barriers at the three inlets (Diga Nord, Malamocco, and Diga Sud). Adapted from https://www.comune.venezia.it/it/content/venezia-e-lacqua-alta under the Creative Commons Licence 3.0 for non-commercial purposes.

difficult to evaluate the role of synoptic pattern changes in leading to Acqua Alta extreme events[2,4]. In the context of coastal floods in the city of Venice, there is a notable lack of studies that have attempted to attribute changes in atmospheric circulation over the Mediterranean region to specific causes. The complex and dynamic nature of the Mediterranean climate system in relation to Venice, affected by factors as local topography, ocean currents, and large-scale weather patterns, presents significant challenges in identifying and understanding the underlying mechanisms driving changes in atmospheric circulation. Despite the limited research in this area, it is widely acknowledged that changes in atmospheric circulation patterns can have significant impacts on the frequency and intensity of coastal floods in Venice, as well as on the city's infrastructure and economy[26].

Despite these difficulties, the Italian government has invested about 6.2 billion euros in the Experimental Electromechanical Module (MoSE) project, which includes a series of mobile barriers located in the three main channels that connect the lagoon with the north Adriatic Sea[27–29]. The MoSE project has faced some delays and controversies, but the barriers were successfully tested in 2020 and are expected to become fully operational soon. However, the issue of Acqua Alta in Venice is complex and multifaceted, requiring a coordinated and sustained effort to address. The MoSE project represents an important step forward, but further action is needed to mitigate the impacts of climate change and protect this unique and valuable cultural heritage site. The inset in Fig. 1 shows the location of the two tide gauge stations used to evaluate sea levels in this article (Punta della Salute and Piattaforma), while the pink circles indicate the position of the MoSE barriers at the three inlets.

In this paper, we employ a methodology that combines the use of analogue atmospheric patterns and statistical analysis [e.g. [30]] to attribute the increasing frequency and severity of Acqua Alta events in Venice to climate change. Specifically, we use atmospheric circulation patterns from the three most devastating Acqua Alta events in the lagoon (04/11/1966 - 194 cm; 29/10/2018

- 156 cm; and 12/11/2019 - 187 cm) and from a comparable (in terms of sea levels) but less devastating one (01/12/2008 - 156 cm) to identify analogues of these patterns in the recent past. By comparing the frequency of these analogues to the historical record, we assess the likelihood that the observed increase in Acqua Alta events is due to natural variability or climate change. To evaluate the effectiveness of MoSE (Experimental Electromechanical Module) protection, we analyse the analogues of the most extreme events and estimate the potential flood damage that would have occurred without MoSE activation. Finally, we perform a cost-benefit analysis to evaluate the economic implications of MoSE activation during Acqua Alta events.

RESULTS

Attribution of the 1966 event

We compare sea level pressure (slp), 2 meter temperature (t2m), total precipitation (pr), and the 10 m wind speed Scirocco-component (w) fields during Acqua Alta events in Venice from 1993 to 2022 (Factual Present) to the fields from 1950-1979 (Counterfactual Past), when human-driven climate change was just beginning. The choice of the variables is justified by the need of reflecting the airflows and weather conditions that characterise extreme events beyond floods. The method (see details below) ensures that comparisons are relevant, unlike purely statistical modeling techniques, which aim to simply analyse meteorological variables without tracing them back to the phenomena that produce them.

On November 4th, 1966, Venice experienced the highest Acqua Alta ever recorded since systematic measurements began. This was due to strong Scirocco winds, a strong depression, and a disastrous storm surge that breached the Murazzi (a hydraulic defense structure) in multiple locations. The high water persisted for 22 h above 110 cm and about 40 h above 50 cm, causing significant damage to the city, including power and gas outages, flooded streets and buildings, and destroyed boats and businesses. The island of Sant'Erasmo disappeared under waves up to 4 meters high, and Murano's glass factories were almost entirely destroyed (https://nuovavenezia.gelocal.it/venezia/cronaca/2016/10/17/news/la-cronaca-dell-aqua-granda-a-venezia-4-novembre-1966-1.14265973).

The meteorological contribution to the Acqua Alta was impressive, reaching 185 cm, while the maximum coincided with an astronomical tide of only 9 cm. The Scirocco winds prevented the outflow of water from the lagoon to the sea, and the minimum subsequent high tide was 116 cm. At 06:00 pm, the tide gauge at Punta della Salute reached 194 cm, the highest value ever recorded. Although other Italian cities were also severely affected by the storm, Venice was one of the most severely affected, and the city remained isolated for days.

Figure 2 displays the results of the attribution analysis for the 1966 Acqua Alta event in Venice. The study used the sea level pressure (slp), total precipitation (pr) and Scirocco 10m wind field (W) of the event (Fig. 2a) to search for analogues for both counterfactual (Fig. 2b) and factual (Fig. 2c) periods in the domain 10°E–15°E 42°N–47°N (Table 2). The slp field of the event consists of a deep Genoa Low depression. The analysis found that the slp field depicts negative anomalies on the southern flank of the cyclonic pattern in the factual period with respect to the counterfactual one (Fig. 2d). The temperature field does not depict significant changes between the two periods (Fig. 2e–h). The atmospheric pattern of the factual period is associated with higher precipitation over Lombardy and Veneto, which can enhance the contribution to Acqua Alta coming from the Adige and the Po Rivers (Fig. 2i–l). The maximum Scirocco winds were stronger over the Adriatic sea as well as over Veneto, which might contribute to an increase in storm surge (Fig. 2m–p).
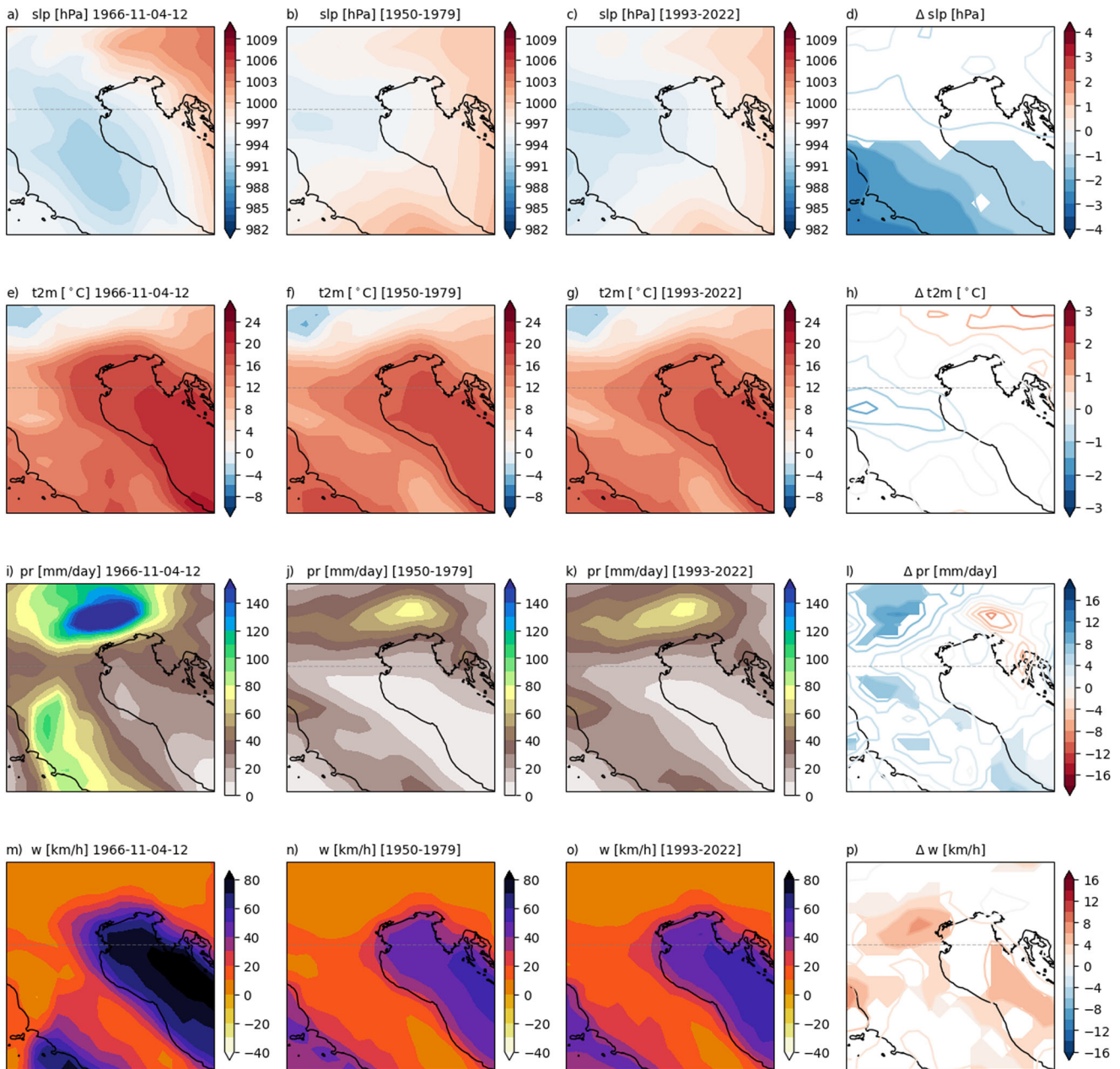
Fig. 2 Analogues Analysis for the 1966 Acqua Alta event in Venice. 6-hourly mean sea-level pressure, slp (**a**), 2-meter temperatures, t2m (**e**), total precipitation accumulated over 24 h, pr (**i**), maximum Scirocco wind component over 24 h, w (**m**), centered at the time of the event. Average of the 17 analogues found for the counterfactual [1950-1979] (**b**) and factual [1993-2022] (**c**) periods and corresponding 2-meter temperatures (**f**, **g**), total precipitation (**j**, **k**) and Scirocco wind speed (**n**, **o**). Δslp (**d**), Δt2m (**h**), Δpr (**l**) and Δw (**p**) between factual and counterfactual periods: coloured-filled areas refer to significant anomalies with respect to the bootstrap procedure (significance is defined as exceeding the 95th percentile in the bootstrap distribution).

Attribution of the 2008, 2018, and 2019 events

The Supplementary Information and Supplementary Fig. 1 describe the diagnostic of the analogues analysis for the 1966 event suggesting that the event is exceptional in both periods analysed. Supplementary Figs. 2–4 show the analogues analyses for the 2008, 2018, and 2019 events, respectively. The 2008 large scale circulation closely resembles that of the 1966 event but with a weaker depression. The 2018 event was associated to Vaia storm and was also characterised by an atmospheric river[31]. Such rivers are not very common in the Mediterranean basin and they could be important contributors to heavy precipitation. In this case, they have presumably influenced the deepening rate of Vaia (see also the huge signal in total precipitation reported in Supplementary

Fig. 3). The 2019 event was due to a small-sized, secondary cyclone over the Adriatic sea [32]. Although it is not unusual for local minima to form cyclonic circulations over the Adriatic Sea, often becoming part of a broader low-pressure system that extends east and west of the Italian peninsula, the small-scale cyclone played a significant role in the flooding of Venice. Exploring the potential enhancement of Acqua Alta events through atmospheric and oceanic variability, Supplementary Note 1.4 and Supplementary Fig. 8 shed light on this complex interaction. These materials investigate how four prominent sources of atmospheric and oceanic variability, namely the North Atlantic Oscillation (NAO), the El Nino Southern Oscillation (ENSO), the Pacific Decadal Oscilation (PDO) and the Atlantic Multidecadal Oscillation (AMO)

Table 1. Summary of sea-levels (SL [cm]) and damages [MEUR] during the four considered Acqua Alta events in Venice.

|	# MoSE	Variables	Event	[1950–1979] Counterfactual	[1993–2022] Factual (with MoSE)	[1993–2022] Counterfactual (no MoSE)
1966	11 (40%)	SL [cm][b]	194	122 (116,189)	111 (59, 156)	123 (107, 156)
		Damages [MEUR]	4.5	0.13 (0.09,1800)	0.25 (0.07, 28)	0.45 (0.06,28)
2008	09 (33%)	SL [cm][a]	156	119 (114,165)	113(63, 148)	116 (97, 149)
		Damages [MEUR]	28	0.20 (0.10,98)	0.25 (0.06, 11)	0.17 (0.06, 11)
2018	05 (17%)	SL [cm]	156	122 (114,155)	123 (75, 148)	124 (111, 148)
		Damages [MEUR]	28	0.32 (0.10, 27)	0.34 (0.07, 11)	0.38 (0.06, 11)
2019	08 (30%)	SL [cm][b]	187	116 (113,187)	111 (56, 141)	115 (102, 143)
		Damages [MEUR]	1.7	0.13 (0.08, 1800)	0.25 (0.07, 4)	0.12 (0.06, 5)

Mose indicates the number as well as the percentage of MoSE activations during the days anaologues of each event in the present period. Median values and 5-95 percentiles (brackets) of the distributions of analogues are reported for SL and damages during [1950–1979] (counterfactual past), [1993–2022] with MoSE activation (factual present), and [1993–2022] assuming no MoSE activation (counterfactual present).
[a]Indicates significant changes between counterfactual past and factual present (with MoSE activation).
[b]Indicates significant changes between factual present (MoSE activated) and counterfactual present (supposing the MoSE is not activated).
These changes are determined used a Cramer von Mises test at 0.05 significance level [48].

might modify frequency or intensity of Acqua Alta events in Venice. Our analysis suggests that while human-driven climate change remains the dominant driver behind most observed changes, the interplay of atmospheric and oceanic variability could contribute to the intensification of these events. Specifically, these natural factors could potentially exacerbate the conditions leading to 2018 and 2019 Acqua Alta events.

The main question we want to address in the remaining of the section is whether the MoSE is effective in reducing the damages caused by Acqua Alta events in Venice that are similar (analogous) to each of the four observed. To this aim we analyse the relationship between sea level (SL) and damages. In this case we extend the analogues search also one day before and one day after the dates identified as analogues to account for possible time lags. The period [1993–2022] is now partitioned into two different sub-periods: a factual present, corresponding to the actual scenario where the MoSE can be activated, and a counterfactual present, where we assume that the MoSE is not operative. To distinguish these two scenarios in terms of SL we make use of measurements at Punta della Salute (factual present), located within the lagoon (so, its measurements are affected by the MoSE activation), and Piattaforma, located outside the lagoon and being not affected by the MoSE. We retain the previously employed definition of counterfactual past for the period [1950–1979], however to avoid confusion we now rename it as counterfactual past. Potential damages are estimated using an exponential model with considering the daily operational cost of the MoSE, estimated at 0.025 MEUR (https://www.pagellapolitica.it/articoli/costo-mose-venezia), for the factual present. This analysis allows us to evaluate whether the MoSE has already functioned as an effective mitigation strategy. Results of this analysis are reported in Table 1. Figure 3 shows the details of the results for the 1966 event and Supplementary Figs. 9–11 for the other events analysed. First of all, we remark that the SL and the actual damages estimated during all events are larger than both the median values and even of the 95% percentiles of the SL and the damages distribution for all periods. This hints to the exceptionality of the events with respect to their analogues. For the 1966 event, we find 11 analogues where the MoSE has been operated (factual present). Our analysis finds that factual presents show significant reduction of SL with respect to both counteractual past and present periods. Damages for the counterfactual past are on average lower than factual and counterfactual presents with the MoSE system reducing damages from 0.45 MEUR to 0.25 MEUR.
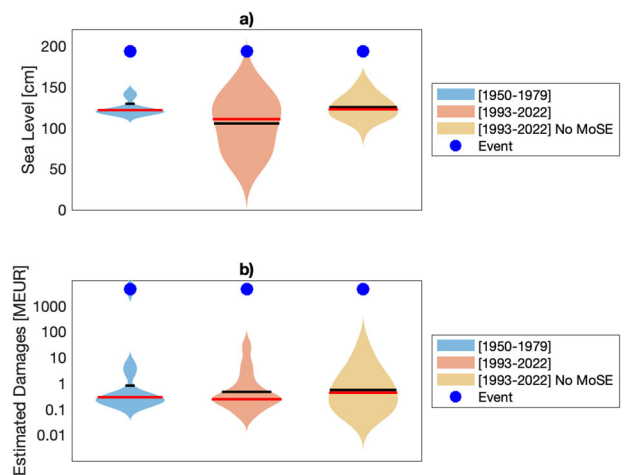
Fig. 3 Sea-levels SL during the analogues of the Acqua Alta 1966 event for past (blue), present (orange) and counterfactual worlds without MoSE (ocre). (a), and estimated damages of the flooding events associated (b). In the violin plots, red (black) lines represent average (median) values.

For the 2008 event, we find 9 analogues where MoSE has been activated and significantly lower sea-levels for the factual present both when compared to the conunterfactual past and counterfactual present. When looking at the damages, the MoSE appears as a non cost-effective measure with a median damage higher than both factual and counterfactual presents. For the 2018 event, there are only 5 analogues situations in the factual present and no significant changes are found. For the 2019 event, we find 8 analogues where the MoSE has been operated (factual present). As for 1966, factual present shows significant reduction of SL with respect to both counteractual past and present periods. When looking at the damages, the MoSE appears as a non cost-effective measure with a median damage higher than both factual and counterfactual presents.

By further inspecting the dates of the analogues (see Table 3 in the counterfactual world none of the 2008, 2018, and 2019 events is analogue to the 1966; conversely, in the factual world both the 2008 and 2018 events are analogues to the 1966 one. This allows us, on one side, to state that, although its uniqueness in terms of impacts, the 1966 is not unique, in a statistical sense; on the other

side, we confirm, instead, that the 2019 is an unprecedented event, also in a statistical view.

DISCUSSION

The analysis presented in this paper aimed at investigating the benefit and effectiveness of the MoSE system in reducing the damages caused by Acqua Alta events in Venice. To achieve this goal, the study used an empirical approach to estimate the relationship between sea level and economic damages, and evaluated the effectiveness of the MoSE system in mitigating the damages caused by events similar to four events in the past.

The results of the analysis show that, for events similar to the 1966, 2008 and 2019 events, the MoSE system has already produced significant protection in terms of number of times of activation of the system, compared to the counterfactual scenario where the MoSE system was not in place. However, our results also highlights the limitations of the MoSE system is used to mitigate damages caused by some specific events, such as the 2018 event.

While our study provides important insights into the relationship between sea level and damages caused by Acqua Alta events in Venice, there are several limitations that should be considered when interpreting our results. First, our analysis relies on identifying analogues based on the sea level pressure, winds and precipitation charts of the event, which may not fully capture all the relevant atmospheric and sea-related conditions that contribute to Acqua Alta. For example, our analysis does not explicitly include the contribution of the atmospheric river associated with the 2018 event [31] and the ERA5 reanalyses are not always adequate to represent mesoscale cyclones as those associated to the 2019 event [32]. Indeed a slight displacement or underestimation of the cyclone can cause errors of several centimeters in the prediction of sea level height in a small basin such as the Venice lagoon. Moreover, our database spans a limited time, and future studies may benefit from incorporating additional data sources and using more advanced machine learning techniques to improve the accuracy of the analogues identification process. Our analysis is based on empirical estimates of the relationship between sea level and damages, which may be subject to errors and biases. In particular, our model assumes an exponential relationship between sea level and damages, which may not hold under changing climatic conditions. Furthermore, our data on damages is limited to reported losses, which may not capture the full extent of the economic and social impacts of Acqua Alta events. Finally, our analysis does not incorporate information from climate models or other types of climate projections, which could help to assess the potential impacts of future climate change on Acqua Alta events in Venice. Incorporating such information would require additional data sources and modeling techniques, and may be subject to uncertainties and biases associated with the models themselves. The use of large ensemble simulations will also help in discriminating the role of anthropogenically driven changes of these patterns from the long term variability of the climate system.

In conclusion, the results of this study have important implications for the management of Acqua Alta events in Venice. While we cannot attribute the observed changes exclusively to one factor, the modifications of atmospheric circulation patterns due to both natural and anthropogenic forced variability leading to Acqua Alta events already greatly affect the city of Venice. Our findings suggest that the MoSE system can be an effective mitigation strategy for events with historical analogues, but additional measures may be needed to address the potential damages caused by unprecedented events[24]. Future research in this area should focus on improving the accuracy of analogues identification, incorporating more sophisticated modeling techniques, and expanding the range of data sources and variables used

to assess the impacts of Acqua Alta events. From the point of view of impacts, future research should focus to better understand the effectiveness of the MoSE system in mitigating damages caused by Acqua Alta events and to identify additional measures that can be implemented to reduce the impacts of these events on the city of Venice.

Our study represents one of the first examples that goes beyond identifying the circulation drivers of extreme events to quantifying the changes and their impacts. The framework we presented is general and can be applied to other case studies. However, our study also has limitations, like for example the limited database of sea-level for the past, the limited analogues used, and the fact that we did not use climate models. Despite these limitations, our study provides important insights into the attribution and impacts of extreme events, which are crucial for developing effective mitigation and adaptation strategies. We hope that our work will inspire future research and inform policymakers in their efforts to reduce the risks associated with extreme events.

METHODS

Data

We utilised the latest climate reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the implementation of the EU-funded Copernicus Climate Change Service (C3S). Specifically, we used the ERA5 dataset, which provides hourly data on atmospheric, land surface, and sea state parameters from 1950 to the present at a horizontal resolution of $0.25° \times 0.25°$[33]. The choice of using ERA5 data for this study was motivated by the dataset's consistency over a long period of time (73 years), which allowed us to detect changes in the large dynamics associated with Acqua Alta events. In addition, the global nature of the ERA5 dataset allowed us to avoid mixing data from different national weather services and ensured uniform spatial and temporal coverage. While other observational or reanalysis datasets were considered, such as E-OBS, MERRA, NCEP, and CFSR, these were discarded due to the lack of sea-point coverage or insufficient temporal and spatial resolutions. The Centro Previsioni e Segnalazioni Maree (Center for Tides Forecasting and Reporting) of the Venice Municipality provides tide gauge data that is essential for understanding the frequency and intensity of Acqua Alta events in Venice. The tide gauge data records the water levels in the Venetian Lagoon at 16 different locations, including the historical station of Punta della Salute. These measurements are taken every 1 h and are reported in centimeters above the mean sea level, referred to the tidal zero of Punta della Salute. The tide level data are freely available at https://www.comune.venezia.it/it/content/dati-dalle-stazioni-rilevamento.

Analogues methods

The attribution protocol described in Faranda et al.[30] has already been applied and validated for pressure maps leading up to series of extreme events in the year 2021, including floods in Westphalia[34], storm Alex[35], and wind-power changes[36].

Here we apply it for Acqua Alta events in Venice, as follows. Considering that most of the Acqua Alta events analysed were due to rapid, small-scale cyclones, we analyse hourly and 6–hourly data. We divide the ERA5 sea-level pressure data set into two periods: 1950–1979 and 1993–2022 each consisting of 30 years data. We consider the first period to represent a past world with a weaker anthropogenic influence on climate than the second period, which represents our factual world affected by anthropogenic climate change. Here, we assume that 30 years is a long enough period to average out high-frequency interannual variability of the atmospheric motions. This time period is also

recommended by the WMO for the computation of climate normals[37].

To account for the possible influence of low-frequency modes of natural variability in explaining the differences between the two periods, we also consider the possible roles of the El Niño-Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and the Pacific Decadal Oscillation, the main sources of natural variability.

Our methodology for identifying cyclonic event analogues relies on sea level pressure (slp), total precipitation (pr), and Scirocco wind speed (w) patterns. Scirocco wind represents the south-easterly wind component (135°), calculated using the 10m zonal (u) and meridional (v) wind components (see Eq. (1))

$$w = u_{10m} sin(135°) + v_{10m} cos(135°).\qquad(1)$$

To find the analogues we use 6–hourly data. Initially, we select the time step with the minimum sea level pressure from the event data and define the spatial domain covering the cyclonic low that caused the event (Table 2). To ensure comparability and equal weighting, we normalise each field $\phi = \{slp, pr, w\}$ using min-max normalisation, based on the minimum and maximum values observed throughout the 1950–2022 period (see, Eq. (2))

$$\phi_{scaled,i,j} = \frac{\phi(t)_{i,j} - \phi_{\min,i,j}}{\phi_{\max,i,j} - \phi_{\min,i,j}}.\qquad(2)$$

Table 2. Time and spatial domain used to find analogues.

TIME	Spatial Box
1966-11-04-12	[10E–15E, 42N–47N]
2018-10-29-18	[5E–16E, 40N–49N]
2019-11-12-18	[5E–16E, 32N–45N]
2008-12-01-00	[5E–16E, 39N–48N]

Table 3. Analogues listed as extreme water heights by[3] for counterfactual and factual periods.

COUNTERFACTUAL		FACTUAL	
1966		1966	
Date	SL (cm)	Date	SL (cm)
1951-11-12	151	2000-11-06	144
1968-11-03	144	2008-12-01[a]	156[a]
		2018-10-29[a]	156[a]
2008		2008	
Date	SL (cm)	Date	SL (cm)
1951-11-12	151	2009-12-24	145
1979-12-22	166	2019-11-15	154
2018		2018	
Date	SL (cm)	Date	SL (cm)
1951-11-12	151	2000-11-06	144
1968-11-03	144	2002-11-16	147
1979-12-22	166	2009-12-23	143
		2010-12-24	144
2019		2019	
Date	SL (cm)	Date	SL (cm)
		2010-12-24	144

[a]Highlights the correspondence between analogues of the 1966 events and other two events analysed in this study.

We then compute the Euclidean distances of the three scaled fields with respect to the event itself. The combined Euclidean distance is determined by aggregating the Euclidean distances of the dynamic field (slp) with that of the physical fields (pr and w) as

$$d(t) = \sqrt{d_{slp}(t)^2} + \sqrt{d_{pr}(t)^2 + d_w(t)^2}.\qquad(3)$$

Based on the combined Euclidean distances, we identify the best 17 analogues, corresponding to the records that minimise the combined distance. For the factual period, as is customary in attribution studies, the event itself is excluded. In addition, we prohibit the search for analogues within a 1-week window centered on the date of the event. Some of the analogues found were listed as extreme water heights by[3] for counterfactual and factual periods (Table 3), also reported as exceptional Acqua Alta events (https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali). Finally, once the dates of the analogues are found, we make use of ERA5 hourly data to compute the accumulated precipitation over 24 h and the maximum Scirocco wind speed in 24 h, centered at the time of the event. This approach provides a more comprehensive assessment of the impacts.

We examine the seasonality of the analogues during the relevant season and their association with NAO ENSO, PDO and AMO. We perform this last analysis using monthly indices from NOAA/ERSSTv5 data and retrieved from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. In particular, the ENSO index is version 3.4 as defined by Huang et al.[38], and the AMO, PDO index is calculated as described in Trenberth and Shea[39]. When the ENSO 3.4 index is positive, it corresponds to El Niño, and when it is negative, it corresponds to La Niña.

We define several quantities to support our interpretation of analogue-based assignment, including the analogue quality Q, which is the average Euclidean distance of a given day from its 17 closest analogues. If the value of Q for the extreme event belongs to the same distribution of its analogues, then the event is not unprecedented, and the attribution can be performed. If the value of Q is greater than those of its analogues, the event is unprecedented.

We also use dynamical systems theory to compute the local dimension D of each slp map, which is a proxy for the number of degrees of freedom of the field, and the persistence index Θ, which estimates the number of days we are likely to observe a map that is an analogue of the one under consideration[40]. We compute the values of persistence for the extreme event in the past, factual and counterfactual world and the corresponding distributions of the persistence for the analogues.

We count the number of analogues in each month of the extended Autumn season (September, October, November, December) to detect whether there has been a shift in circulation to months earlier or later in the season. This can have strong thermodynamic implications, for example, if a circulation leading to large positive temperature anomalies in early spring becomes more frequent later in the season when average temperatures are much higher.

Economic damage model vs. sea-level

We use an empirical approach to estimate the relation between sea level reached within the lagoon and economic damages to find an analytical function. We based our estimation on the reported damages associated with the four most devastating events (04/11/1966, 01/12/2008, 29/10/2018, and 12/11/2019) which costed 8000 MEUR, 20 MEUR, 47 MEUR, and 1000 MEUR, respectively (https://www.businessinsider.com/flooding-cost-1-billion-of-damage-to-venice-tourist-attractions-2019-12?r=US&IR=T, https://www.bbc.co.uk/newsround/50902267). Damage estimates are adjusted by the inflation (http://resolver.tudelft.nl/uuid:ea34a719-79c1-4c6e-b886-e0d92407bc9d). According to previous employed models for

estimating hazard functions for floods[41–44] we use an exponential law Damage $[MEUR] = a \exp b\, SL^*$, where $SL^* = SL/110$, to link the economic damage (in millions of euros) and the observed sea level change for extreme sea levels larger than 110 cm. The parameters of the fit are estimated by using the Levenberg-Marquardt algorithm whose robustness is assessed by the Least Absolute Residuals (LAR) method to minimise the absolute difference of the residuals. The best-fit parameters are $a = 5.05(3.06, 7.03) \times 10^{-3}$ MEUR and $b = 0.35(0.25, 0.45)$, where in brackets we report the 95% confidence levels, with an adjusted $R^2 = 0.99$ and a Root Mean Squared Error (RMSE = 27). We also used a power-law fit to model the economic damages as a function of the sea level, Damage $[MEUR] = a\, SL^{*b}$, with best-fit parameters $a = 8.97(4.07, 13.09) \times 10^{-3}$ MEUR and $b = 66.19(47.04, 85.34)$, where in brackets we report the 95% confidence levels, with an adjusted $R^2 = 0.84$ and RMSE = 46. However, the results are not statistically confident due to the under-estimation of damages for sea levels <160 cm. We are aware that only 3 events are not sufficient to provide a robust assessment of fitting procedures, however the use of exponential models to describe cost-benefit assessments and risk-hazard results has been widely documented in literature for different scenarios[41–43]. Furthermore, natural hazards are generally characterised by exponential laws in their occurrence as well as in their effects[45] or modeled as cascade processes (i.e. with a power-law model) where the resulting dynamics is a series of mutually interconnected phenomena (as in turbulence[46,47]).

DATA AVAILABILITY
ERA5 data are publicly available at climate explorer (http://climexp.knmi.nl/). Sea level data are made available at https://www.comune.venezia.it/it/content/centro-previsioni-e-segnalazioni-maree from the Centro Previsione e Segnalazione Maree - Protezione Civile, Venice, Italy, under the License Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Italy (CC BY-NC-SA 3.0 IT).

CODE AVAILABILITY
The code to perform the analogues dynamical analysis is available at https://fr.mathworks.com/matlabcentral/fileexchange/95768-attractor-local-dimension-and-local-persistence-computation.

REFERENCES

1. Tebaldi, C. et al. Extreme sea levels at different global warming levels. Nat. Clim. Chang. 11, 746–751 (2021).
2. Umgiesser, G. et al. The prediction of floods in Venice: methods, models and uncertainty (review article). Nat. Haz. Earth Sys. Sci. 21, 2679–2704 (2021).
3. Lionello, P. et al. Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article). Nat. Haz. Earth Sys. Sci. 21, 2705–2731 (2021).
4. Zanchettin, D. et al. Sea-level rise in Venice: historic and future trends (review article). Nat. Haz. Earth Sys. Sci. 21, 2643–2678 (2021).
5. Malguzzi, P., Grossi, G., Buzzi, A., Ranzi, R. & Buizza, R. The 1966 "century" flood in Italy: A meteorological and hydrological revisitation. J. Geophys. Res. Atmos. 111, D24106 (2006).
6. Ferrarin, C., Lionello, P., Orlić, M., Raicich, F. & Salvadori, G. Venice as a paradigm of coastal flooding under multiple compound drivers. Sci. Rep. 12, 5754 (2022).
7. Cavaleri, L. et al. The 2019 flooding of venice and its implications for future predictions. Oceanography 33, 42–49 (2020).
8. Ferrarin, C. et al. Local and large-scale controls of the exceptional Venice floods of November 2019. Progress Oceanogr. 197, 102628 (2021).
9. Miglietta, M. M., Carnevale, D., Levizzani, V. & Rotunno, R. Role of moist and dry air advection in the development of Mediterranean tropical-like cyclones (medicanes). Quart. J. Roy. Met. Soc. 147, 876–899 (2021).
10. Luppichini, M., Bini, M., Barsanti, M., Giannecchini, R. & Zanchetta, G. Seasonal rainfall trends of a key Mediterranean area in relation to large-scale atmospheric circulation: How does current global change affect the rainfall regime? J. Hydr. 612, 128233 (2022).
11. Flaounas, E. et al. Mediterranean cyclones: current knowledge and open questions on dynamics, prediction, climatology and impacts. Weath. Clim. Dyn. 3, 173–208 (2022).
12. Davolio, S., Silvestro, F. & Gastaldo, T. Impact of Rainfall Assimilation on High-Resolution Hydrometeorological Forecasts over Liguria, Italy. J. Hydromet. 18, 2659–2680 (2017).
13. Davolio, S., Miglietta, M. M., Diomede, T., Marsigli, C. & Montani, A. A flood episode in northern Italy: multi-model and single-model mesoscale meteorological ensembles for hydrological predictions. Hydr. Earth Sys. Sci. 17, 2107–2120 (2013).
14. Otto, F. E. L. Extreme events: The art of attribution. Nat. Clim. Chang. 6, 342–343 (2016).
15. Otto, F. Attribution of extreme weather events: how does climate change affect weather? Weather 74, 325–326 (2019).
16. IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).
17. Masson-Delmotte, V. et al. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 2 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021).
18. Van Oldenborgh, G. J. et al. Attributing and Projecting Heatwaves Is Hard: We Can Do Better. Earth's Future 10, e2021EF002271 (2022).
19. Vautard, R. et al. Evaluation of the Large EURO-CORDEX Regional Climate Model Ensemble. J. Geophys. Res. Atmos. 126, e2019JD032344 (2021).
20. van Oldenborgh, G. J. et al. Pathways and pitfalls in extreme event attribution. Clim. Change 166, 13 (2021).
21. Reed, K. A., Wehner, M. F. & Zarzycki, C. M. Attribution of 2020 hurricane season extreme rainfall to human-induced climate change. Nat. Comm. 13, 1905 (2022).
22. Bellprat, O., Guemas, V., Doblas-Reyes, F. & Donat, M. G. Towards reliable extreme weather and climate event attribution. Nat. Comm. 10, 1732 (2019).
23. Strauss, B. H. et al. Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nat. Comm. 12, 2720 (2021).
24. Alberti, T. et al. Dynamical diagnostic of extreme events in Venice lagoon and their mitigation with the MoSE. Sci. Rep. 13, 10475 (2023).
25. Ranasinghe, R. et al. Climate Change Information for Regional Impact and for Risk Assessment. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2021).
26. Sperotto, A. et al. A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: The case study of the municipality of Venice (Italy). Sci. Tot. Env. 562, 1031–1043 (2016).
27. Leonardi, N. The barriers of Venice. Nat. Geosci. 14, 881–882 (2021).
28. Mel, R., Carniello, L. & D'Alpaos, L. Addressing the effect of the Mo.S.E. barriers closure on wind setup within the Venice lagoon. Est. Coast. Shelf Sci. 225, 106249 (2019).
29. Umgiesser, G. & Matticchio, B. Simulating the mobile barrier (MOSE) operation in the Venice Lagoon, Italy: global sea level rise and its implication for navigation. Ocean Dyn. 56, 320–332 (2006).
30. Faranda, D., Pascale, S. & Bulut, B. Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought. Envir. Res. Lett. 18, 034030 (2023).
31. Davolio, S., Della Fera, S., Laviola, S., Miglietta, M. M. & Levizzani, V. Heavy Precipitation over Italy from the Mediterranean Storm "Vaia" in October 2018: Assessing the Role of an Atmospheric River. Mont. Weat. Rev. 148, 3571–3588 (2020).
32. Miglietta, M. M. et al. A high-impact meso-beta vortex in the adriatic sea. Quat. J. Roy. Met. Soc. 149, 637–656 (2023).
33. Hersbach, H. et al. ERA5 hourly data on single levels from 1959 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS) 10.10.24381 (Accessed on 09-11-2022) (2018).
34. Faranda, D. et al. A climate-change attribution retrospective of some impactful weather extremes of 2021. Weat. Clim. Dyn. 3, 1311–1340 (2022).
35. Ginesta, M., Yiou, P., Messori, G. & Faranda, D. A methodology for attributing severe extratropical cyclones to climate change based on reanalysis data: the case study of storm Alex 2020. Clim. Dyn. 61, 229–253 (2023).
36. Rapella, L., Faranda, D., Gaetani, M., Drobinski, P. & Ginesta, M. Climate change on extreme winds already affects off-shore wind power availability in europe. Envir. Res. Lett. 18, 034040 (2023).
37. Arguez, A. & Vose, R. S. The Definition of the Standard WMO Climate Normal: The Key to Deriving Alternative Climate Normals. Bull. Amer. Met. Soc. 92, 699–704 (2011).
38. Huang, B. et al. Reforecasting the ENSO Events in the Past 57 Years (1958-2014). J. Clim. 30, 7669–7693 (2017).
39. Trenberth, K. E. & Shea, D. J. Atlantic hurricanes and natural variability in 2005. Geophys. Res. Lett. 33, L12704 (2006).

40. Faranda, D., Messori, G., Alvarez-Castro, M. C. & Yiou, P. Dynamical properties and extremes of Northern Hemisphere climate fields over the past 60 years. *Nonl. Proc. Geophy.* **24**, 713–725 (2017).

41. Amadio, M. et al. Testing empirical and synthetic flood damage models: the case of italy. *Nat. Haz. Earth Sys. Sci.* **19**, 661–678 (2019).

42. Gerl, T., Kreibich, H., Franco, G., Marechal, D. & Schröter, K. A review of flood loss models as basis for harmonization and benchmarking. *PLOS ONE* **11**, 1–22 (2016).

43. Read, L. K. & Vogel, R. M. Hazard function analysis for flood planning under nonstationarity. *Water Resourc. Res.* **52**, 4116–4131 (2016).

44. Guan, X. Flood risk analysis integrating of bayesian-based time-varying model and expected annual damage considering non-stationarity and uncertainty in the coastal city. *J. Hydr.* **617**, 129038 (2023).

45. Read, L. K. & Vogel, R. M. Hazard function theory for nonstationary natural hazards. *Nat. Haz. Earth Sys. Sci.* **16**, 915–925 (2016).

46. Frisch, U. & Sornette, D. Extreme Deviations and Applications. *J. de Physique I* **7**, 1155–1171 (1997).

47. Alberti, T. et al. Chameleon attractors in turbulent flows. *Chaos Sol. Fract.* **168**, 113195 (2023).

48. Anderson, T. W. On the distribution of the two-sample cramer-von mises criterion. *Ann. Math. Stat.* **33**, 1148–1159 (1962).

AUTHOR CONTRIBUTIONS

D.F. and T.A. devised the study, D.F. and M.G. performed the analogues analyses and T.A. devised the model of damage. All authors contributed to discussing and writing the paper.

COMPETING INTERESTS

The authors declare no competing interests. No human or animal data have been used in this study.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41612-023-00513-0.

Correspondence and requests for materials should be addressed to Davide Faranda.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.