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

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Abstract

We use analogues of atmospheric patterns to investigate changes in the three most devastating Acqua Alta (flooding) events in the lagoon of Venice associated with intense Mediterranean cyclones occurred in 1966, 2018 and 2019. Our results provide evidence that changes in atmospheric circulation, although not necessarily anthropogenically driven only, 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 events, which occurred in 1966, while for 2018 and 2019 events our analysis is non-conclusive because of the lack

of analogues situations of those events. 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 provide 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.

Keywords: Climate Change, Attribution, Sea Level, Adaptation, Mitigation

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

22 Acqua Alta events in Venice are primarily caused by a combination of two main
23 factors: the tides and the synoptic weather conditions. The high tides are a natural
24 occurrence that are affected by the position and phases of the moon and other celestial
25 bodies. However, when strong winds blow across the Adriatic Sea towards the Venetian
26 Lagoon, they can cause an increase in the water level, known as storm surge. This is
27 because the winds push the water towards the city and the narrow entrance of the
28 lagoon limits its ability to escape. When this storm surge coincides with high tides,
29 it can result in Acqua Alta events, where the water level rises above the level of
30 the city's streets and floods the low-lying areas. The synoptic weather situation that
31 causes these strong winds is typically a low-pressure system over the Tyrrhenian Sea
32 (Genoa Low) combined with high-pressure systems over central and northern Europe,
33 creating a strong pressure gradient and thus strong winds blowing towards Venice,
34 causing potentially hazardous conditions. The impacts of the Genoa Low system as
35 well as Mediterranean cyclones have been widely documented in literature [6–10],

36 emphasizing the importance of understanding this synoptic weather pattern in leading
 37 extreme events [11, 12].

38 Climate change is widely considered to be a major contributing factor to the
 39 increased frequency and severity of extreme weather events, including storm surges
 40 and flooding [13]. The Intergovernmental Panel on Climate Change (IPCC) has stated
 41 that the increasing frequency and severity of extreme weather events are very likely
 42 caused by human activities, including the burning of fossil fuels and the resultant emis-
 43 sions of greenhouse gases. These activities have led to changes in the Earth’s climate,
 44 which have in turn altered storm patterns, increased sea levels, and caused more fre-
 45 quent and severe weather events. Coastal zones, such as the historical city of Venice
 46 and its lagoon in the Northern Adriatic Sea, are particularly vulnerable to extreme
 47 sea levels, requiring a realistic approach to assess the risks and future projections of
 48 flooding, claiming for attribution studies of extreme weather events to climate change
 49 [14–19].

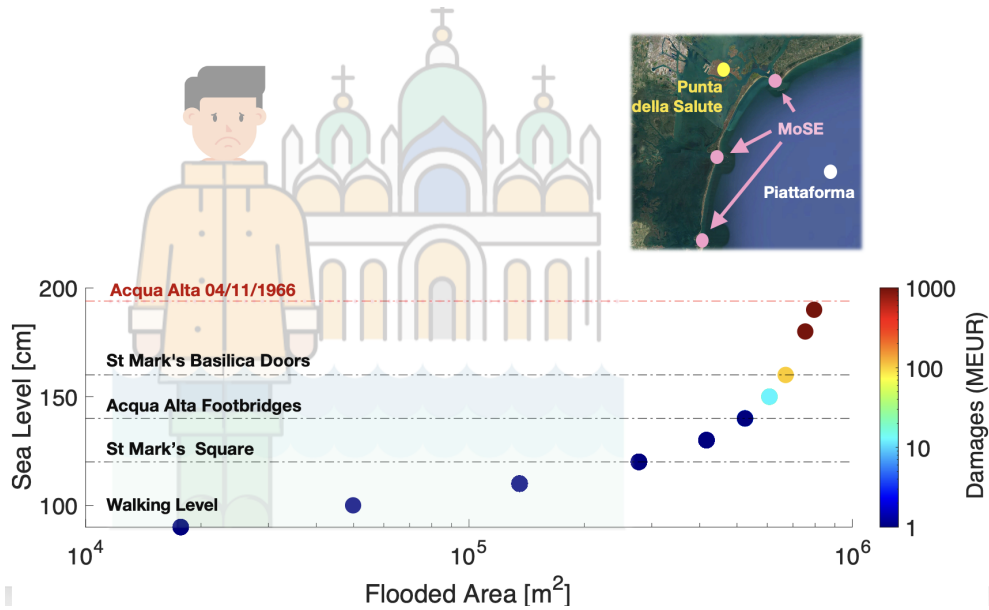


Fig. 1 Schematic representation of hazards for Venice lagoon. The relation between the sea level and the flooded area as a function of the estimated damages (filled colored circles). The horizontal dashed-dotted black lines mark significant flooding levels corresponding to the sea level flooding St. 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>.

50 Given the peculiarity the landscape, Venice is expected to be particularly vulnera-
51 ble to climate change. Sea levels in Venice have risen by approximately 26 centimeters
52 over the past century, with projections indicating a change in extreme total water
53 level between 20 and 40 cm for RCP4.5 (2100) and RCP8.5 (2050) and up to 80 cm
54 for the RCP8.5 (2100) [20]. Nevertheless, the complexity of the climate system and
55 the challenges of climate change make difficult to evaluate the role of synoptic pat-
56 tern changes in leading to Acqua Alta events [2, 4]. In the context of coastal floods in
57 the city of Venice, there is a notable lack of studies that have attempted to attribute
58 changes in atmospheric circulation over the Mediterranean region to specific causes.
59 While there has been some research on the topic, the complex and dynamic nature of
60 the Mediterranean climate system in relation to Venice, which is influenced by a range
61 of factors including local topography, ocean currents, and large-scale weather patterns,
62 presents significant challenges in identifying and understanding the underlying mech-
63 anisms driving changes in atmospheric circulation. Despite the limited research in this
64 area, it is widely acknowledged that changes in atmospheric circulation patterns can
65 have significant impacts on the frequency and intensity of coastal floods in Venice, as
66 well as on the city’s infrastructure and economy [21].

67 Despite these difficulties, the Italian government has invested about 6.2 billion
68 euros in the Experimental Electromechanical Module (MoSE) project, which includes
69 a series of mobile barriers located in the three main channels that connect the lagoon
70 with the north Adriatic Sea [22–24]. The MoSE project has faced some delays and
71 controversies, but the barriers were successfully tested in 2020 and are expected to
72 become fully operational soon. However, the issue of Acqua Alta in Venice is complex
73 and multifaceted, requiring a coordinated and sustained effort to address. The MoSE
74 project represents an important step forward, but further action is needed to mitigate
75 the impacts of climate change and protect this unique and valuable cultural heritage
76 site. The inset in Figure 1 shows the location of the two tide gauge stations used to
77 evaluate sea levels in this article (Punta della Salute and Piattaforma), while the pink
78 circles indicate the position of the MoSE barriers at the three inlets.

79 In this paper, we employ a methodology that combines the use of analogue atmo-
80 spheric patterns and statistical analysis [e.g., 25] to attribute the increasing frequency
81 and severity of Acqua Alta events in Venice to climate change. Specifically, we use
82 atmospheric circulation patterns from the three most devastating Acqua Alta events
83 in the lagoon (04/11/1966 - 194 cm; 29/10/2018 - 156 cm; and 12/11/2019 - 187 cm)
84 to identify analogues of these patterns in the recent past. By comparing the frequency
85 of these analogues to the historical record, we assess the likelihood that the observed
86 increase in Acqua Alta events is due to natural variability or climate change. To eval-
87 uate the effectiveness of MoSE (Experimental Electromechanical Module) protection,
88 we analyze the analogues of the most extreme events and estimate the potential flood
89 damage that would have occurred without MoSE activation. Finally, we perform a
90 cost-benefit analysis to evaluate the economic implications of MoSE activation during
91 Acqua Alta events.

92 Results

93 We compare the sea level pressure fields during Acqua Alta events in Venice from
94 1993-2022 to pressure from 1950-1979, when climate change was just beginning. The
95 choice of the variable is justified by the need of reflecting the large-scale airflows that
96 can drive extreme events such as floods. The method (see details below) ensures that
97 comparisons are relevant, unlike purely statistical modeling techniques, which aim to
98 simply analyze meteorological variables without tracing them back to the phenomena
99 that produce them.

100 On November 4th, 1966, Venice experienced the highest Acqua Alta ever
101 recorded since systematic measurements began. This was due to strong sirocco
102 winds, a strong depression, and a disastrous storm surge that breached the Murazzi
103 (a hydraulic defense structure) in multiple locations. The high water persisted
104 for 22 hours above 110 cm and about 40 hours above 50 cm, causing signifi-
105 cant damage to the city, including power and gas outages, flooded streets and
106 buildings, and destroyed boats and businesses. The island of Sant’Erasmus dis-
107 appeared under waves up to 4 meters high, and Murano’s glass factories were
108 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>).

109 The meteorological contribution to the Acqua Alta was impressive, reaching 185
110 cm, while the maximum coincided with an astronomical tide of only 9 cm. The sirocco
111 winds prevented the outflow of water from the lagoon to the sea, and the minimum
112 subsequent high tide was 116 cm. At 6:00 pm, the tide gauge at Punta della Salute
113 reached 194 cm, the highest value ever recorded. Although other Italian cities were
114 also severely affected by the storm, Venice was one of the most severely affected, and
115 the city remained isolated for days. The slow recovery was carried out physically by
116 the workers and technicians of ENEL as the power outages also had almost analogous
117 effects on the phone lines.
118

119 Figure 2 displays the results of the attribution analysis for the 1966 Acqua Alta
120 event in Venice. The study used the sea level pressure (SLP) field of the event (Figure
121 2a) to search for analogues for both counterfactual (Figure 2b) and factual (Figure
122 2c) periods in the domain 3°W-22°W 34°N-49°N. The SLP field of the event consists
123 of a deep Genoa Low depression. The analysis found that the SLP field did not differ
124 significantly between the two periods (Figure 2d) as well as temperature field (Figure
125 2e-h). The atmospheric pattern of the factual period is associated with higher pre-
126 cipitation over Lombardy, Veneto and Friuli which can enhance the contribution to
127 Acqua Alta coming from the Adige and the Po Rivers (Figure 2i-l). Winds were gen-
128 erally stronger on the coasts of Provence and the Tyrrhenian coasts of central Italy,
129 potentially contributing to orographic effects and increasing the amount of precipita-
130 tion over the Alps, but not producing any significant changes in the Adriatic (Figure
131 2m-p).

132 The Supplementary Information and Figure S1 describe the diagnostic of the ana-
133 logues analysis and the influence of interannual and interdecadal variability and shows
134 that the event is exceptional in both periods analysed. These analyses also show that
135 significant differences in the Pacific Decadal Oscillation (PDO) and Atlantic Multi-
136 decadal Oscillation (AMO) indices during the analogs day of the events are found

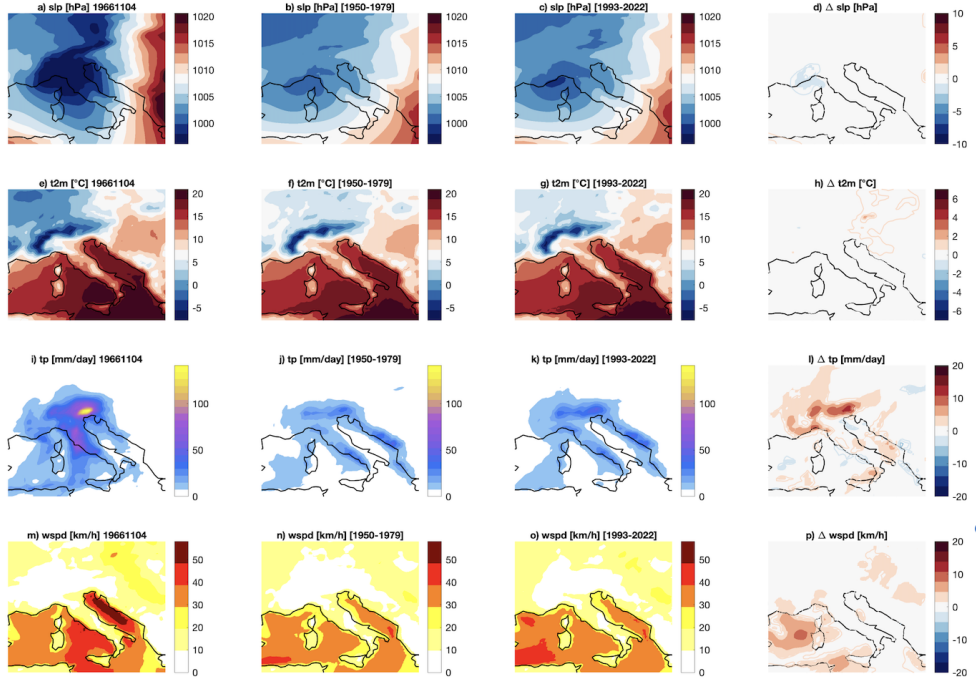


Fig. 2 Analogues Analysis for the 1966 Acqua Alta event in Venice. Daily mean sea-level pressure slp (a), 2-meter temperatures t2m (e), total precipitation tp (i), wind-speed wspd (m) on the day of the event. Average of the 17 sea-level pressure analogues found for the counterfactual [1950-1979] (b) and factual [1993-2022] (c) periods and corresponding 2-meter temperatures (f,g), daily precipitation rate (j,k) and wind speed (n,o). Δ slp (d), Δ t2m (h), Δ tp (i) and Δ wspd (p) between factual and counterfactual periods: colored-filled areas show significant anomalies with respect to the bootstrap procedure.

137 so that we cannot exclude a role of interdecadal variability in the changes of pat-
 138 terns identified in Figure 2. Figure S2-S3 shows the analysis for the 29/10/2018 and
 139 12/11/2019 events respectively. While the 2018 event large scale circulation closely
 140 resembles that of the 1966 events but with a weaker depression, the 2019 event is
 141 associated with a cyclone that propagates from Liguria to the southern Tyrrhenian
 142 sea but the Acqua Alta was reinforced by a secondary depression on the Adriatic sea
 143 causing sudden changes of winds. Therefore, while the results of the analysis for the
 144 2018 event (Figure S2) are similar to the ones described for the 1966 but with a less
 145 intense depression, for the 2019 event, we find that the event is unprecedented and no
 146 good-analogues can be found (Figure S3). Similarly to the 1966 event, for both 2018
 147 and 2019 events, we cannot exclude a role of interannual and interdecadal variability
 148 in the changes associated with synoptic patterns leading to Acqua Alta events.

149 We now analyze the relationship between sea level (SL) and damages and evaluate
 150 whether the MoSE (Modulo Sperimentale Elettromeccanico) is effective in reducing
 151 the damages caused by Acqua Alta events in Venice that are similar (analogous) to the

	# MoSE	Variables	Event	[1950-1979]	[1993-2022]	[1993-2022] no MoSE
04/11/1966	5 (30%)	SL	194	123	115	122
		[cm]		[116, 194]	[69, 150]*	[111, 150]
		Damages	8000	0.3	0.25	0.29
		[MEUR]		[0.1, 4000]	[0.01, 19]*	[0.07, 19]
29/10/2018	1 (6%)	SL [cm]	156	122	125	125
				[118, 144]	[96, 155]	[111, 155]
		Damages	47	0.3	0.5	0.5
		[MEUR]		[0.2, 5.6]	[0.07, 26]	[0.07, 26]
12/11/2019	3 (20%)	SL	187	113	112	118
		[cm]		[113, 114]	[62, 183]	[110, 183]
		Damages	1000	0.09	0.2	0.3
		[MEUR]		[0.09, 1000]	[0.06, 1600]	[0.06, 1600]

Table 1 The table shows a summary of sea-levels (SL [cm]) and damages [MEUR] during the three largest Acqua alta historical events in Venice. # MoSE indicates the number as well as the percentage of MoSE activations during the days analogues of each event in the present period, the estimation of changes for SL and damages (median values and 5,95 percentiles of the analogues distributions in square brackets) for [1950-1979], [1993-2022] with MoSE activation (factual present) and [1993-2022] period where we assume that the MoSE was not activated (counterfactual present). '*' indicates significant changes with respect to the past period, determined used a Cramer von Mises test at 0.05 significance level [26].

152 worst three observed. Using the measurements available at both Punta della Salute
153 and Piattaforma, we can construct two different statistics of SL and damages with
154 factual [1993-2022] Punta della Salute MoSE values and a counterfactual present peri-
155 ods where Piattaforma values are used instead of Punta della Salute, and potential
156 damages are estimated using the exponential model. For the statistics with the MoSE
157 activated, we substitute the damages with the daily operational cost of the MoSE, esti-
158 mated at 0.025 MEUR (<https://www.pagellapolitica.it/articoli/costo-mose-venezia>).
159 This analysis allows us to evaluate whether the MoSE has already functioned as an
160 effective mitigation strategy. Results of this analysis are reported in Table 1 and details
161 on the distribution in Figures S1 for all events. First of all, we remark that the SL
162 and the damages estimated during the three events are larger both of the median val-
163 ues and even of the 95% percentiles of the SL and the damages distribution. For the
164 1966 event, we find 5 analogues in the present periods that have activated the MoSE.
165 When we compare both present factual and counterfactual periods with the past for
166 the 1966 event, we notice a reduction of maximum damages, which is statistically sig-
167 nificant when comparing the factual present with the past. For the 2018 event, there
168 is only one analogue situation in the present period where MoSE has been activated.
169 Therefore the cost of the MoSE activation is equivalent to the estimated damages.
170 Finally, MoSE has been activated in three analogue situations of the 2019 event. The
171 damages in the factual present appears to be higher compared to the past, but still
172 lower when compared to the counterfactual present. As expected, these changes are
173 not significant due to the unprecedented nature of the 2019 event.

174 Discussion

175 The analysis presented in this paper aimed to investigate the effectiveness of the MoSE
176 system in reducing the damages caused by Acqua Alta events in Venice. To achieve

177 this goal, the study used an empirical approach to estimate the relationship between
178 sea level and economic damages, and evaluated the effectiveness of the MoSE system
179 in mitigating the damages caused by events similar to the three most devastating
180 events in the past.

181 The results of the analysis show that, for events similar to the 1966 event, the
182 MoSE system has already produced significant savings in terms of economic damages,
183 compared to the counterfactual scenario where the MoSE system was not in place.
184 For the 2018 event, there is a balance of cost/benefit but only one analogue event
185 that caused the MoSE activation has been observed so far. Finally, the results also
186 highlights the limitations of the analysis when MoSE system is used to mitigate the
187 damages caused by unprecedented events, such as the 2019 events. This is due to the
188 lack of analogues of such events in the near present and suggest that our analysis shall
189 be repeated in the future when disposing of a larger sample of events similar to 2018
190 and 2019.

191 While our study provides important insights into the relationship between sea level
192 and damages caused by Acqua Alta events in Venice, there are several limitations that
193 should be considered when interpreting our results.

194 First, our analysis relies on identifying analogues based on the sea level pressure
195 (SLP) field of the event, which may not fully capture all the relevant atmospheric and
196 oceanic conditions that contribute to Acqua Alta. Moreover, our database of historical
197 SLP fields is limited, and future studies may benefit from incorporating additional
198 data sources and using more advanced machine learning techniques to improve the
199 accuracy of the analogues identification process. Our analysis is based on empirical
200 estimates of the relationship between sea level and damages, which may be subject to
201 errors and biases. In particular, our model assumes a linear relationship between sea
202 level and damages, which may not hold for extreme events or under changing climatic
203 conditions. Furthermore, our data on damages is limited to reported losses, which
204 may not capture the full extent of the economic and social impacts of Acqua Alta
205 events. Finally, our analysis does not incorporate information from climate models or
206 other types of climate projections, which could help to assess the potential impacts of
207 future climate change on Acqua Alta events in Venice. Incorporating such information
208 would require additional data sources and modeling techniques, and may be subject
209 to uncertainties and biases associated with the models themselves. The use of large
210 ensemble simulations will also help in discriminating the role of anthropogenically
211 driven changes of these patterns from the long term variability of the climate system.

212 In conclusion, the results of this study have important implications for the man-
213 agement of Acqua Alta events in Venice. While we cannot attribute the observed
214 changes exclusively to one factor, the modifications of atmospheric circulation pat-
215 terns due to both natural and anthropogenic forced variability leading to Acqua Alta
216 events already greatly affect the city of Venice. Our findings suggest that the MoSE
217 system can be an effective mitigation strategy for events with historical analogues,
218 but additional measures may be needed to address the potential damages caused by
219 unprecedented events. Future research in this area should focus on improving the accu-
220 racy of analogues identification, incorporating more sophisticated modeling techniques,
221 and expanding the range of data sources and variables used to assess the impacts of

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

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

235 **Methods**

236 **Data**

237 We utilized the latest climate reanalysis data produced by the European Centre for
238 Medium-Range Weather Forecasts (ECMWF) as part of the implementation of the
239 EU-funded Copernicus Climate Change Service (C3S). Specifically, we used the ERA5
240 dataset, which provides hourly data on atmospheric, land surface, and sea state param-
241 eters from 1950 to the present at a horizontal resolution of $0.25^\circ \times 0.25^\circ$ [27]. The choice
242 of using ERA5 data for this study was motivated by the dataset’s consistency over a
243 long period of time (73 years), which allowed us to detect changes in the large dynam-
244 ics associated with Acqua Alta events. Additionally, the global nature of the ERA5
245 dataset allowed us to avoid mixing data from different national weather services and
246 ensured uniform spatial and temporal coverage. While other observational or reanaly-
247 sis datasets were considered, such as E-OBS, MERRA, NCEP, and CFSR, these were
248 discarded due to the lack of sea-point coverage or insufficient temporal and spatial
249 resolutions. The Centro Previsioni e Segnalazioni Maree (Center for Tides Forecasting
250 and Reporting) of the Venice Municipality provides tide gauge data that is essential
251 for understanding the frequency and intensity of Acqua Alta events in Venice. The
252 tide gauge data records the water levels in the Venetian Lagoon at 16 different loca-
253 tions, including the historical station of Punta della Salute. These measurements are
254 taken every 1 hour and are reported in centimeters above the mean sea level, referred
255 to the tidal zero of Punta della Salute. The tide level data are freely available at
256 <https://www.comune.venezia.it/it/content/dati-dalle-stazioni-rilevamento>.

257 **Analogues Methods**

258 The attribution protocol described in Faranda et al. [25] has already been applied and
259 validated for pressure maps leading up to series of extreme events in the year 2021,
260 including floods in Westphalia [28], storm Alex [29], and wind-power changes [30].

261 Here we apply it for Acqua Alta events in Venice, as follows. The typical time
262 scales of Acqua Alta events in Venice is two days so, before the analyse we perform a

263 grid-point by grid-point moving average of the atmospheric fields analysed in the day
264 of the event and the day before the event. Results do not change significantly if instead
265 of two days, we perform the moving average over three days. We divide the ERA5
266 sea-level pressure data set into two periods: 1950-1979 and 1993-2022 each consisting
267 of 30 years of daily data. We consider the first period to represent a past world with
268 a weaker anthropogenic influence on climate than the second period, which represents
269 our factual world affected by anthropogenic climate change. Here, we assume that 30
270 years is a long enough period to average out high-frequency interannual variability of
271 the atmospheric motions. This time period is also recommended by the WMO for the
272 computation of climate normals [31].

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

278 For each period, we examine all daily sea level pressure records and select the best
279 17 analogues, i.e. the records minimizing the Euclidean distance to the event record
280 itself. The number of 17 corresponds approximately to the smallest 1‰ Euclidean
281 distances in each subset of our data. We tested the extraction of 10 to 20 analogous
282 records, without finding qualitatively important differences in our results. For the
283 factual period, as is customary in attribution studies, the event itself is excluded. In
284 addition, we prohibit the search for analogues within a one-week window centered on
285 the date of the event. Finally, we examine the seasonality of the analogues during the
286 relevant season and their association with ENSO, PDO and AMO. We perform this
287 last analysis using monthly indices from NOAA/ERSSTv5 data and retrieved from the
288 Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. In particular,
289 the ENSO index is version 3.4 as defined by Huang et al. [32], and the AMO, PDO
290 index is calculated as described in Trenberth and Shea [33]. When the ENSO 3.4 index
291 is positive, it corresponds to El Niño, and when it is negative, it corresponds to La
292 Niña.

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

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

305 We count the number of analogues in each month of the extended Autumn season
306 (September, October, November, December) to detect whether there has been a shift

307 in circulation to months earlier or later in the season. This can have strong thermody-
308 namic implications, for example, if a circulation leading to large positive temperature
309 anomalies in early spring becomes more frequent later in the season when average
310 temperatures are much higher.

311 Economic Damage Model vs. sea-level

312 We use an empirical approach to estimate the relation between sea level reached
313 within the lagoon and economic damages to find an analytical function. We
314 based our estimation on the reported damages associated with the three most
315 devastating events (04/11/1966, 29/10/2018, and 12/11/2019) which were 8000
316 MEUR, 47 MEUR, and 1000 MEUR, respectively ([https://www.businessinsider.com/flooding-cost-1-billion-of-damage-to-venice-tourist-attractions-2019-12?](https://www.businessinsider.com/flooding-cost-1-billion-of-damage-to-venice-tourist-attractions-2019-12?r=US&IR=T)
317 [r=US&IR=T](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 esti-
318 mates are adjusted by the inflation ([http://resolver.tudelft.nl/uuid:](http://resolver.tudelft.nl/uuid:ea34a719-79c1-4c6e-b886-e0d92407bc9d)
319 [ea34a719-79c1-4c6e-b886-e0d92407bc9d](http://resolver.tudelft.nl/uuid:ea34a719-79c1-4c6e-b886-e0d92407bc9d)). According to previous employed mod-
320 els for estimating hazard functions for floods [34–37] we use an exponential law
321 $\text{Damage}[MEUR] = a \exp b SL^*$, where $SL^* = SL/110$, to link the economic dam-
322 age (in millions of euros) and the observed sea level change for extreme sea levels
323 larger than 110 cm. The parameters of the fit are estimated by using the Levenberg-
324 Marquardt algorithm whose robustness is assessed by the Least Absolute Residuals
325 (LAR) method to minimize the absolute difference of the residuals. The best-fit
326 parameters are $a = 5.05(3.06, 7.03) \times 10^{-3}$ MEUR and $b = 0.35(0.25, 0.45)$, where
327 in brackets we report the 95% confidence levels, with an adjusted $R^2 = 0.99$ and a
328 Root Mean Squared Error (RMSE = 27). We also used a power-law fit to model the
329 economic damages as a function of the sea level, $\text{Damage}[MEUR] = a SL^{*b}$, with
330 best-fit parameters $a = 8.97(4.07, 13.09) \times 10^{-3}$ MEUR and $b = 66.19(47.04, 85.34)$,
331 where in brackets we report the 95% confidence levels, with an adjusted $R^2 = 0.84$
332 and RMSE = 46. However, the results are not statistically confident due to the
333 under-estimation of damages for sea levels less than 160 cm. We are aware that only 3
334 events are not sufficient to provide a robust assessment of fitting procedures, however
335 the use of exponential models to describe cost-benefit assessments and risk-hazard
336 results has been widely documented in literature for different scenarios [34–36]. Fur-
337 thermore, natural hazards are generally characterized by exponential laws in their
338 occurrence as well as in their effects [38] or modeled as cascade processes (i.e., with a
339 power-law model) where the resulting dynamics is a series of mutually interconnected
340 phenomena (as in turbulence [39, 40]).

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507 Data Availability

508 ERA5 data are publicly available at climate explorer (<http://climexp.knmi.nl/>).
509 Sea level data are made available at [https://www.comune.venezia.it/it/content/](https://www.comune.venezia.it/it/content/centro-previsioni-e-segnalazioni-maree)
510 [centro-previsioni-e-segnalazioni-maree](https://www.comune.venezia.it/it/content/centro-previsioni-e-segnalazioni-maree) from the Centro Previsione e Segnalazione
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513 Code Availability

514 The code to perform the analogues dynamical analysis is
515 available at [https://fr.mathworks.com/matlabcentral/fileexchange/](https://fr.mathworks.com/matlabcentral/fileexchange/95768-attractor-local-dimension-and-local-persistence-computation)
516 [95768-attractor-local-dimension-and-local-persistence-computation](https://fr.mathworks.com/matlabcentral/fileexchange/95768-attractor-local-dimension-and-local-persistence-computation).

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526 Author Contributions

527 DF and TA devised the study, DF performed the analogues analyses and TA devised
528 the model of damage. All authors contributed to discussing and writing the paper.

529 Competing Interest

530 The authors declare no competing interests nor conflicts of interest. No human or
531 animal data have been used in this study.

532 **Declarations**

533 The authors declare no conflict of interests.

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

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Abstract

The supplementary material of this paper provides additional detailed analyses of the extreme flooding events that occurred in Venice in 1966, 2018 and 2019. The material includes detailed methodological element, explanation and figures that show the temporal evolution of sea-level pressures, temperatures, precipitations, wind speed of the three events analysed. Additionally, the material provides detailed information on the sea-level and the estimated damages caused by the

flooding, including the affected area for 2018 and 2019. The supplementary material also includes a comparison between the 2018 and 2019 events with the 1966 Great Flood of Venice, highlighting similarities and differences in terms of sea level, storm surge, and damage.

Keywords: Climate Change, Attribution, Sea Level, Adaptation

1 Supplementary Methods

1.1 Analogue quality Q

: Q 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 and therefore not attributable.

1.2 Predictability Index D

Using dynamical systems theory [1–3], we can compute the local dimension D of each slp map [4, 5]. The local dimension is a proxy for the number of degrees of freedom of the field, meaning that the higher D, the more unpredictable the temporal evolution of the slp maps will be [6–8]. If the dimension D of the derecho event analyzed is higher or lower than that of its analogues, then the extreme will be respectively less or more predictable than the closest dynamical situations identified in the data. The attractor of a dynamical system is a geometric object defined in the space hosting all the possible states of the system (phase-space). Each point ζ on the attractor can be characterized by two dynamical indicators: the local dimension D , which indicates the number of degrees of freedom active locally around ζ , and the persistence Θ , a measure of the mean residence time of the system around ζ [6, 9]. To determine D , we exploit recent results from the application of extreme value theory to Poincaré recurrences in dynamical systems. This approach considers long trajectories of a system — in our case successions of daily SLP latitude–longitude maps — corresponding to a sequence of states on the attractor. For a given point ζ in phase space (e.g., a given SLP map), we compute the probability that the system returns within a ball of radius ϵ centered on the point ζ . The Freitas et al. [10] theorem, modified by Lucarini et al. [11], states that logarithmic returns:

$$g(x(t)) = -\log(\text{dist}(x(t), \zeta)) \quad (1)$$

yield a probability distribution such that:

$$\Pr(z > s(q)) \simeq \exp \left[-\vartheta(\zeta) \left(\frac{z - \mu(\zeta)}{\sigma(\zeta)} \right) \right] \quad (2)$$

where $z = g(x(t))$ and s is a high threshold associated to a quantile q of the series $g(x(t))$. Requiring that the orbit falls within a ball of radius ϵ around the point ζ is

30 equivalent to asking that the series $g(x(t))$ is over the threshold s ; therefore, the ball
31 radius ϵ is simply $e^{-s(q)}$. The resulting distribution is the exponential member of the
32 Generalized Pareto Distribution family. The parameters μ and σ , namely the location
33 and the scale parameter of the distribution, depend on the point ζ in phase space. $\mu(\zeta)$
34 corresponds to the threshold $s(q)$ while the local dimension $D(\zeta)$ can be obtained via
35 the relation $\sigma = 1/D(\zeta)$. This is the metric of predictability introduced in Section ??.

36 When $x(t)$ contains all the variables of the system, the estimation of D based on
37 extreme value theory has a number of advantages over traditional methods (e.g. the
38 box counting algorithm [12, 13]). First, it does not require to estimate the volume
39 of different sets in scale-space: the selection of $s(q)$ based on the quantile provides a
40 selection of different scales s which depends on the recurrence rate around the point
41 ζ . Moreover, it does not require the a priori selection of the maximum embedding
42 dimension as the observable g is always a univariate time-series.

43 1.3 Persistence Index Θ

44 The persistence of the state ζ is measured via the extremal index $0 < \vartheta(\zeta) < 1$, an
45 dimensionless parameter, from which we extract $\Theta(\zeta) = \Delta t / \vartheta(\zeta)$. Here, Δt is the
46 timestep of the dataset being analysed. $\Theta(\zeta)$ is therefore the average residence time
47 of trajectories around ζ , namely the metric of persistence introduced in Section ??,
48 and it has unit of a time (in this study days). If ζ is a fixed point of the attractor,
49 then $\Theta(\zeta) = \infty$. For a trajectory that leaves the neighborhood of ζ at the next time
50 iteration, $\Theta = 1$. To estimate ϑ , we adopt the Süveges estimator [14]. For further
51 details on the the extremal index, see Moloney et al. [15].

52 2 Supplementary Analyses

53 2.1 Additional Analyses for the 1966 event

54 The quality of the analogues (Figure S1a) shows that this circulation is very uncommon
55 compared to the rest of the analogues with no significant changes in the two periods.
56 We detect visible changes in increase in predictability D (Figure S1b) while persistence
57 Θ is the same in present and past periods (Figure S1c). The seasonal occurrence of
58 analogues (Figure S1d) shows a shift towards the month of December in the present
59 period. This explain why we do not observe a warming signal in Figure S2; The
60 changes in ENSO (Figure S1e) are not statistically significant while AMO and PDO
61 distributions have a significant shift between the two periods (Figure S1f) and g),
62 suggesting a possible role of the inter-decadal variability of the Pacific and Atlantic
63 Circulation in the occurrence of these events. Finally, when computing analogues for
64 the whole period and counting their frequency per decade, we observe a non-significant
65 increase, leading to about one more event each decade (Figure S1h).

66 2.2 Analyses for the 2018 event

67 On Monday, October 29, 2018, at 2:40 pm, the tide reached a value of 156cm in
68 Punta Salute, Venice, causing significant flooding (<https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali#29ottobre>). The event was partly caused by an

70 Atlantic disturbance that remained stable between the Gulf of Lyon and the Gulf of
71 Genoa, but the effects were amplified by two blocking anticyclones positioned in East-
72 ern Europe and the Azores [16]. The anticyclones caused a strong acceleration of the
73 southerly winds along the Adriatic coast. On Monday, the atmospheric pressure in
74 Venice dropped by 12 hPa in 16 hours. The southerly wind had been blowing since
75 Sunday, reaching an average speed of around 60km/h and gusts of up to 95km/h.
76 The wind blew violently in the lagoon, especially when a convective thunderstorm
77 generated over Venice in the evening. The intense gusts raised internal waves in the
78 main canals of the city and islands, causing significant damage to the barriers, includ-
79 ing those protecting the tide center, residential buildings, and commercial activities.
80 The flooding covered 73% of the pedestrian areas and ranked fourth in importance,
81 equaled with the level reached on December 1, 2008. The lowest level was 119cm at
82 5:35 pm, the highest in history, except for the 1966 event, which registered 116cm.
83 In the evening, the maximum was 148cm at 8:25 pm, ranking seventh in height and
84 covering about 65% of the Venice’s walkable surface. The consecutive presence of the
85 sea level above 120cm was approximately 14 hours, equaling the 1966 record.

86 Figure S2 shows the results of the attribution of the synoptic configuration associ-
87 ated with the episode. The domain analyzed is 2°E-17°W 36°N-51°N. The slp field
88 of the event (Figure S2a) has been used for the search of 17 analogues for the past
89 and present periods. Their average is displayed respectively in Figure S3b,c). We
90 observe significant differences in the pressure field when subtracting present from past
91 analogues leading to more anticyclonic conditions in the present (Figure S2d). The
92 atmospheric pattern of the present period is further associated with higher temper-
93 atures over some Mediterranean region (Figure S2e-h) and higher precipitation over
94 Veneto and Friuli possibly enhancing the impact of these events compared to the past
95 (Figure S2i-l). Winds (Figure S2m-p) are generally stronger on the Tyrrhenian sea
96 but not on the Adriatic. The quality of the analogues (Figure S2q) shows that this
97 circulation is relatively rare compared to the rest of the analogues with no significant
98 changes in the two periods. Q for the events remain in the bulk of the distribution
99 of analogs quality for the past period but it is at the edge of the distribution for the
100 present period so that the slp pattern examined is not highlighted as dynamically
101 unprecedented by this analysis. We do not detect visible changes in predictability D
102 (Figure S2r) nor on the persistence Θ (Figure S2s) relative to the past world by half
103 of the day. The seasonal occurrence of analogues (Figure S2t) does not present any
104 significantly shifts from past to present period. The changes in ENSO (Figure S2u)
105 are not statistically significant while AMO and PDO distributions have a significant
106 shift between the two periods (Figure S2v,w), suggesting a possible role of the inter-
107 decadal variability of the Pacific and Atlantic Circulation in the occurrence of these
108 patterns. Finally, when computing analogues for the whole period and counting their
109 frequency per decade, we observe a non-significant decrease of events, leading to about
110 one less event each decade (Figure S2x).

111 2.3 Analyses for the 2019 event

112 To understand the causes of the Aqua Granda phenomenon that occurred on Novem-
113 ber 12th, we needed to reconstruct the meteorological situation of that day, which

114 developed within the framework of the particular meteorological situation of the
115 entire month ([https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali#](https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali#12novembre2019)
116 [12novembre2019](https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali#12novembre2019)). We have come to the conclusion that the exceptional levels of high
117 tide recorded on November 12, 2019, cannot be attributed solely to the Sirocco wind
118 blowing in the Adriatic Sea [16, 17]. A comparison with the Vaia storm that occurred
119 on October 29, 2018, shows that although the meteorological contribution in 2018 was
120 much greater, the maximum contribution occurred during a minimum astronomical
121 tide. On the other hand, in the case of the unfortunate coincidence of November 12th,
122 2019, the peak of the meteorological contribution coincided perfectly with the peak of
123 the astronomical tide [16, 18].

124 Moreover, the strength of the local wind was also unusual, due to an exceptional
125 meteorological situation [16, 19]. Our detailed analysis of the dynamics of atmospheric
126 circulation can help to understand what happened on the evening of November 12th.
127 From November 11th to 12th, the movement of the depression center towards the
128 southern Tyrrhenian Sea induced Sirocco winds along the Adriatic, but limited to the
129 central basin. Persistent winds from the north, northeast with average speeds of up
130 to 14 m/s were present in the northern Adriatic. On November 12, the movement
131 towards the northeast of the main pressure minimum present over the Tyrrhenian
132 Sea caused the formation of a secondary minimum on the Adriatic, downwind of the
133 Umbro-Marchigiano Apennines. This is an event similar, on a smaller scale, to the
134 much more common formation of a cyclone on the Gulf of Genoa as a result of the
135 interaction between a low pressure system coming from the west and the Alpine relief
136 (the so-called "Alpine cyclogenesis"): a meteorological phenomenon extremely rare in
137 the Upper Adriatic, both in terms of spatial and temporal dimensions, and with an
138 equally unusual evolution. In the afternoon, this local depression moved northwestward
139 to the Upper Adriatic, generating a reinforcement of winds from the Bora and Sirocco
140 during its ascent from Marche to Veneto.

141 Figure S3 shows the results of the attribution of the synoptic configuration associ-
142 ated with the 2019 episode. The domain analyzed is 3°W-22°W 36°N-51°N. The slp
143 field of the event (Figure S3a) has been used for the search of 17 analogues for the coun-
144 terfactual and factual periods. Their average is displayed respectively in Figure S3b,c).
145 We observe significant differences in the pressure field when subtracting present from
146 past analogues leading to more anticyclonic conditions in the present (Figure S3d).
147 The atmospheric pattern of the present period is further associated with higher tem-
148 peratures over Africa (Figure S3e-h) and lower precipitation over the Mediterranean
149 basin (Figure S3i-l). Winds (Figure S3m-p) are generally weaker on the Adriatic and
150 the Jonian sea. The quality of the analogues (Figure S3q) shows that this circulation is
151 extremely rare, compared to the rest of the analogues with no significant changes in the
152 two periods. The pattern of 2019 event is therefore unprecedented. We do not detect
153 visible changes in predictability D (Figure S3r) nor on the persistence Θ (Figure S3s)
154 relative to the counterfactual world by half of the day. The seasonal occurrence of
155 analogues (Figure S3t) does not present any significant shifts from past to present
156 period. The changes in ENSO (Figure S3u) are statistically significant while for AMO
157 changes are the limit of statistical significance and PDO distributions have a signif-
158 icant shift between the two periods (Figure S3v,w), suggesting a possible role of the

159 inter-decadal variability of the Pacific and Atlantic Circulation in the occurrence of
160 these patterns. Finally, when computing analogues for the whole period and counting
161 their frequency per decade, we observe a non-significant decrease of events, leading to
162 about one/two less event each decade (Figure S3x).

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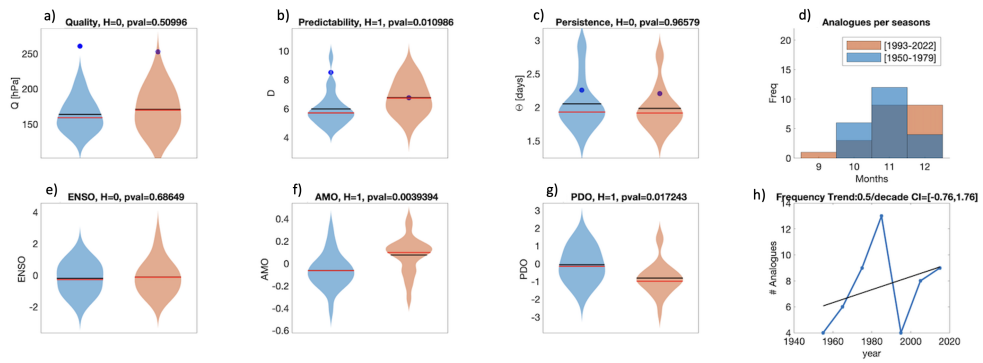


Fig. S1 Analogues Analysis for the 2018 Acqua Alta event in Venice. Violin plots for past (blue) and present (orange) periods for the analogues Quality Q (a) the Predictability index D (b), the Persistence index Θ (c) and the distribution of analogues in each month (d). Violin plots for past (blue) and present (orange) periods for ENSO (e), AMO (f), PDO (g). In the violin plots, red (black) lines represent average (median) values. The number of analogues per decade (blue) and its linear trend (black) in (h). Values for the peak day of the extreme event are marked by a dot. Titles in (a-h) report the results of the Cramer-von Mises test H and the pvalue $pval$. Title in panel (h) includes the value of the linear trend slope and its confidence interval CI in square brackets.

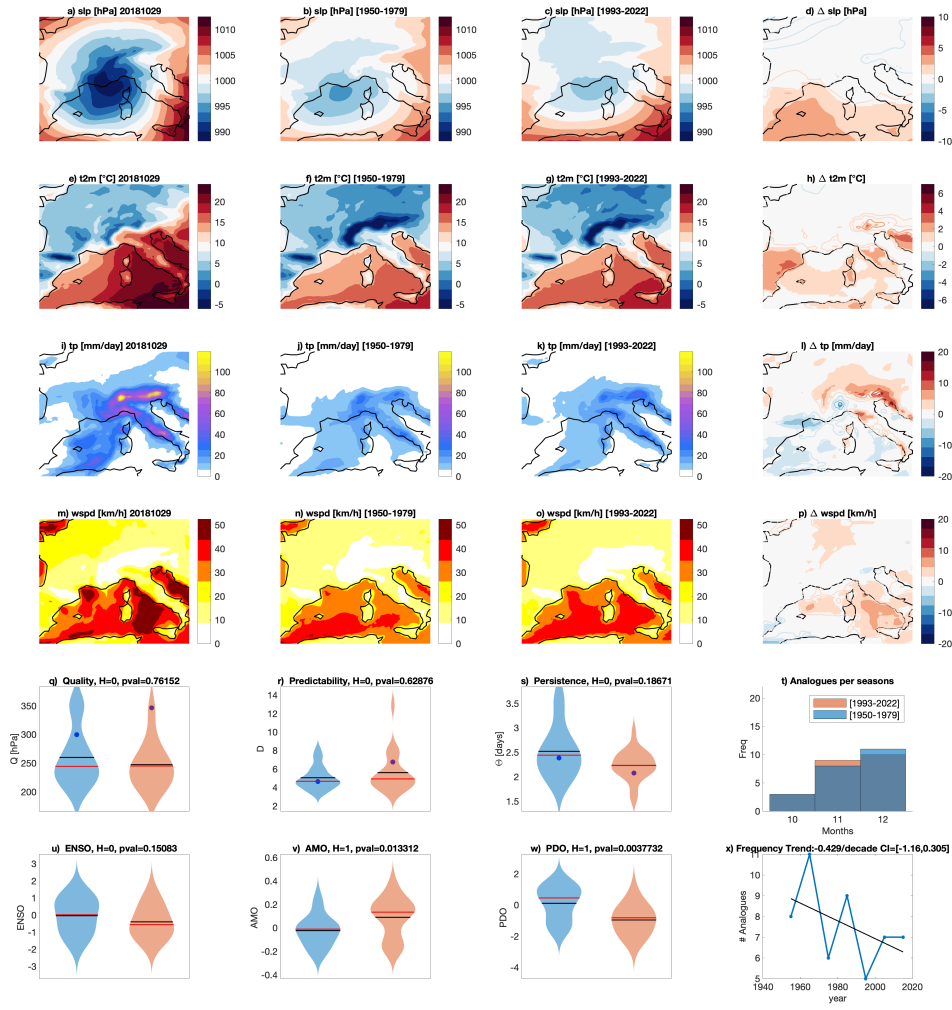


Fig. S2 Analogues Analysis for the 29/10/2018 Acqua Alta event in Venice. Daily mean sea-level pressure slp (a), 2-meter temperatures t2m (e), total precipitation tp (i), wind-speed wspd (m) on the day of the event. Average of the 17 sea-level pressure analogues found for the past [1950-1979] (b) and present [1993-2022] (c) periods and corresponding 2-meter temperatures (f,g), daily precipitation rate (j,k) and wind speed (n,o). Δ slp (d), Δ t2m (h), Δ tp (i) and Δ wspd (p) between present and past periods: colored-filled areas show significant anomalies with respect to the bootstrap procedure. Violin plots for past (blue) and present (orange) periods for the analogues Quality Q (q) the Predictability index D (r), the Persistence index Θ (s) and the distribution of analogues in each month (t). Violin plots for past (blue) and present (orange) periods for ENSO (u), AMO (v), PDO (w). The number of analogues per decade (blue) and its linear trend (black) in (x). Values for the peak day of the extreme event are marked by a dot. Titles in (q-v) report the results of the Cramer-von Mises test H and the pvalue pval. Title in panel (w) includes the value of the linear trend slope and its confidence interval CI in square brackets.

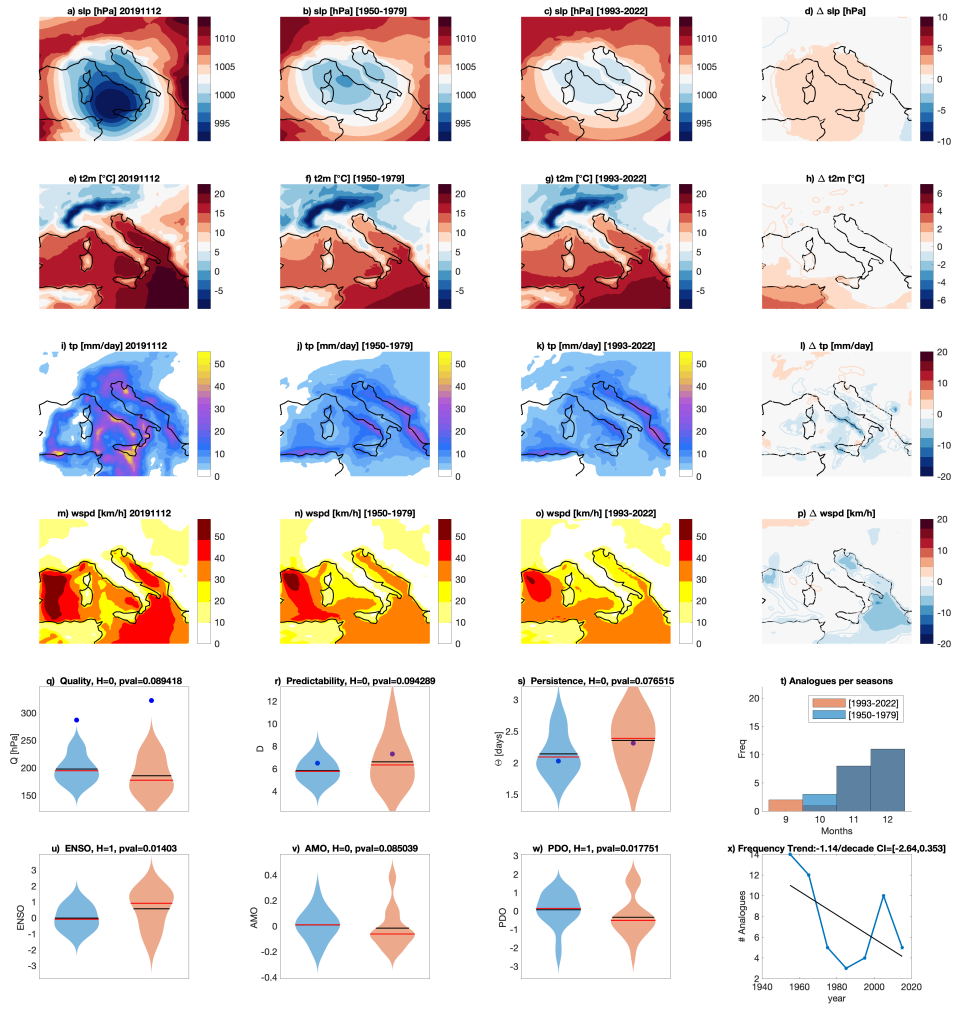


Fig. S3 Analogues Analysis for the 12/11/2019 Acqua Alta event in Venice. Daily mean sea-level pressure slp (a), 2-meter temperatures t2m (e), total precipitation tp (i), wind-speed wspd (m) on the day of the event. Average of the 17 sea-level pressure analogues found for the past [1950-1979] (b) and present [1993-2022] (c) periods and corresponding 2-meter temperatures (f,g), daily precipitation rate (j,k) and wind speed (n,o). Δ slp (d), Δ t2m (h), Δ tp (i) and Δ wspd (p) between past and present periods: colored-filled areas show significant anomalies with respect to the bootstrap procedure. Violin plots for past (blue) and present (orange) periods for the analogues Quality Q (q) the Predictability index D (r), the Persistence index Θ (s) and the distribution of analogues in each month (t). Violin plots for past (blue) and present (orange) periods for ENSO (u), AMO (v), PDO (w). The number of analogues per decade (blue) and its linear trend (black) in (x). Values for the peak day of the extreme event are marked by a dot. Titles in (q-v) report the results of the Cramer-von Mises test H and the pvalue pval. Title in panel (w) includes the value of the linear trend slope and its confidence interval CI in square brackets.

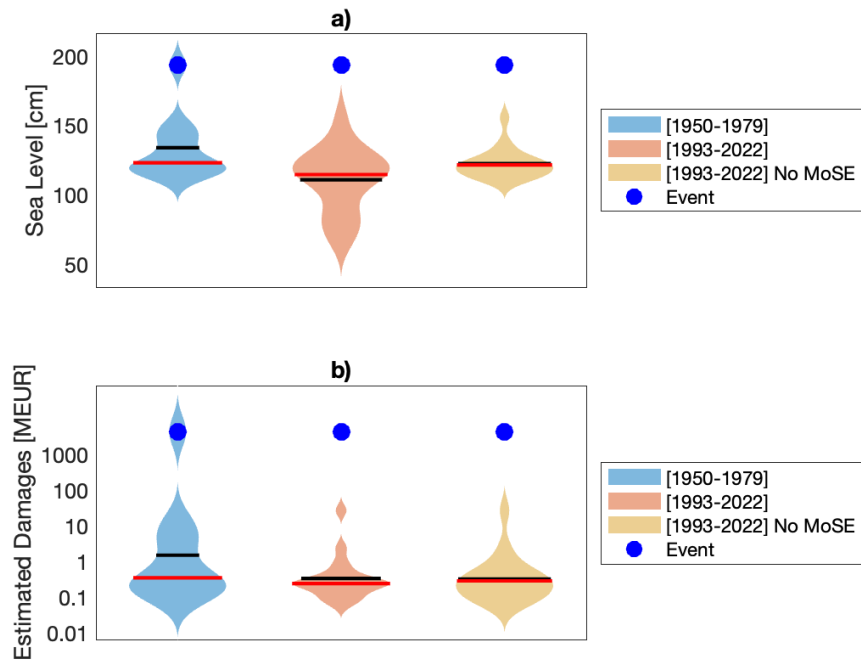


Fig. S4 Sea-levels SL during the analogues of the Acqua Alta 1966 event for past (blue), present (orange) and counterfactual worlds without MoSE (ocre) (a), and estimated damages of the flooding events associated (b). In the violin plots, red (black) lines represent average (median) values.

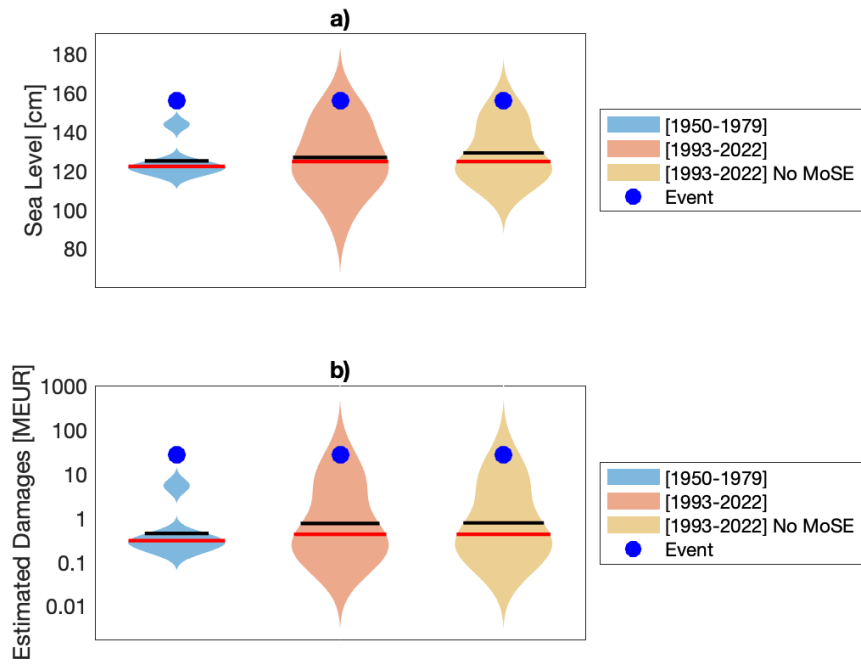


Fig. S5 Sea-levels SL during the analogues of the Acqua Alta 2018 event for past (blue), present (orange) and counterfactual worlds without MoSE (ocre) (a), and estimated damages of the flooding events associated (b). In the violin plots, red (black) lines represent average (median) values.

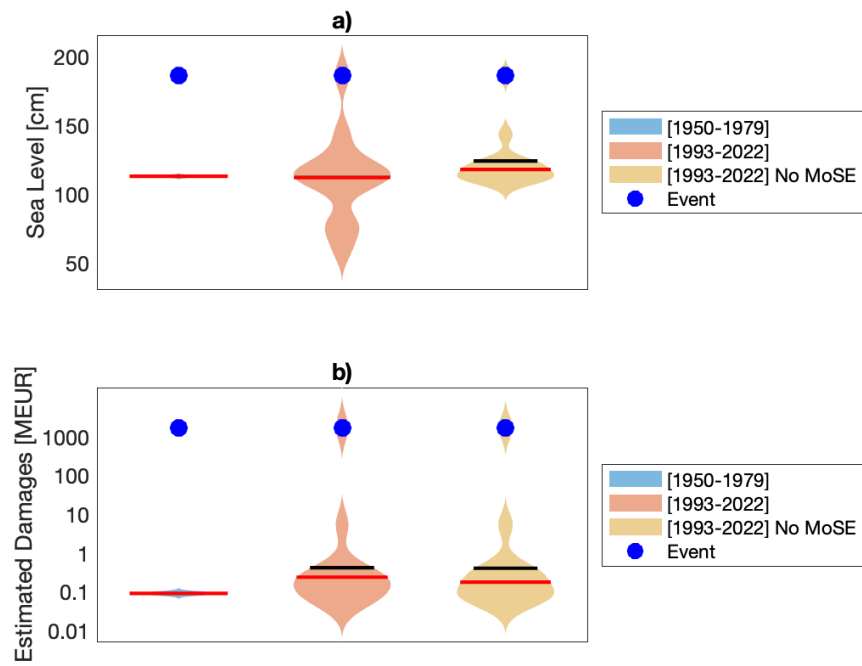


Fig. S6 Sea-levels SL during the analogues of the Acqua Alta 2019 event for past (blue), present (orange) and counterfactual worlds without MoSE (ocre) (a), and estimated damages of the flooding events associated (b). In the violin plots, red (black) lines represent average (median) values.