

# Cumulative impact of climate change and adaptation measures on Venice and its lagoon

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## Abstract

Adaptation measures to climate change can generate unintended environmental consequences, particularly in vulnerable coastal systems. In the Venice Lagoon, the Mose mobile barrier system was designed to protect the city from sea-level rise and storm surges, still ensuring the lagoon-sea exchange. However, under climate change the frequency and duration of Mose closures will increase and this might modify lagoon water renewal and affect ecosystem properties. Here, we apply a high-resolution hydrodynamic model forced by downscaled climate projections to analyse trade-offs of adaptation measures by projecting lagoon conditions under two emission scenarios (RCP-4.5 and RCP-8.5) at mid (2045–2049) and end-century (2095–2099), with and without Mose operation. Results show that Mose effectively limits sea-level rise inside the lagoon, but significantly increases water renewal time (WRT). Under RCP-8.5 closures would reach ~248 days/year and one-third of the lagoon would require more than 20 days to renew its water. Under this scenario, extreme warming would occur, with summer temperatures higher than 30 °C for over three months per year and frequent, long-lasting marine heatwaves. Under RCP-4.5 these impacts are about halved, highlighting the critical role of global mitigation. Our findings demonstrate that while Mose can safeguard Venice from flooding, it also intensifies hydrodynamic confinement, which would combine with temperature changes to produce a severe cumulative pressure on the lagoon system. These results highlight that only the combination of complementary local measures and effective greenhouse-gas mitigation can support viable long-term adaptation pathways for coastal systems.

**Keywords** Climate change · Coastal resilience · Marine heatwaves · Water renewal time (WRT) · Adaptation pathways · Mose barriers · Venice Lagoon

## Introduction

Climate change (CC) is unequivocal and expected to profoundly affect coastal marine ecosystems, with observable<sup>1</sup>, direct impacts ranging from sea-level rise (SLR) and ocean warming to acidification, and more frequent extreme events<sup>2</sup>. Projections indicate that future marine ecosystems will differ significantly from present conditions<sup>2,3</sup>, with the magnitude of change strongly dependent on global emission trajectories. The Mediterranean and the northern Adriatic Sea, are recognized as a climate change hotspot where physical drivers such as temperature

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and sea level are changing faster than the global average<sup>4,5</sup>. These direct alterations cascade through biogeochemical cycles<sup>2,6,7</sup>, biodiversity<sup>8</sup>, ecosystem functioning<sup>9</sup>, and the delivery of ecosystem services<sup>10–13</sup>. The challenges posed by these changes are particularly critical in densely populated coastal zones, where adaptation strategies must be designed within highly complex environmental and socio-economic contexts<sup>14,15</sup>.

Accurate projections of future changes are essential to guide both mitigation and adaptation policies. However, coastal and transitional systems such as lagoons are highly heterogeneous, requiring high-resolution, site-specific models able to capture fine-scale hydrodynamic processes and local variability. Importantly, such local-scale assessments are not only critical for managing site-specific vulnerabilities, but also provide essential insights to inform regional strategies and contribute to the development of robust climate policies<sup>15</sup>.

The Venice Lagoon is one of the largest lagoons (about 500 km<sup>2</sup>) in the Mediterranean Sea. It supports a unique interplay between natural habitats, biodiversity, urban infrastructures and economic activities, which has been shaped for centuries by both natural processes and deliberate human interventions aimed at stabilizing its morphology and preserving its ecological functions<sup>16</sup>. This delicate balance is now increasingly threatened not only by CC, but also by other anthropogenic pressures<sup>17</sup>, notably including adaptation measures themselves<sup>16</sup>. As a result, this lagoon is an interesting case study for assessing the combined impacts of global pressures and local adaptation.

Over the past century, relative sea-level in Venice has already increased by ~26 cm driven by both subsidence and global sea-level trends<sup>17</sup>.

To prevent extensive recurrent flooding events (“acqua alta”), the Mose (Modulo Sperimentale Elettromeccanico) system of mobile barriers was built to temporarily isolate the lagoon from the sea during high waters events<sup>18–20</sup>, thereby protecting the urban area when sea level is expected to exceed a predetermined threshold<sup>21</sup>. While effective in reducing flood risk, Mose closures are expected to become more frequent and prolonged with CC induced average sea level rises<sup>22</sup>, raising concerns about their ecological consequences<sup>16,17,23</sup>. Indeed, prolonged closures may alter water circulation and renewal time, with cascading impacts on the spatial and temporal variability of physical, biogeochemical and ecological properties of the lagoon<sup>24–28</sup>. Therefore a trade-off arises between the need of preventing the flooding vs. protecting the lagoon ecosystem<sup>25</sup>. As already experienced for other coastal cities worldwide<sup>29,30</sup>, adaptation measures often present contrasting needs among environmental quality, heritage preservation and social well-being.

However, so far only a few studies exist that provide site-specific projections of the state of the lagoon at the end of the century, even less considering the combined effect of CC and Mose closures. Notably, most of the studies focus on sea level rise<sup>20,22,23</sup>, few on changes in biogeochemical or biological properties related to changes in precipitation regimes and associated variation in timing of riverine loading<sup>6,31–33</sup>. A recent study<sup>34</sup> has explored CC and adaptation scenarios in the Venice Lagoon, but only up to 2050, and adopting the pseudo-global-warming approach<sup>35</sup> that applies estimates of climate anomalies assumed to be representative of climate scenarios to a control simulation. This method is indeed useful when long-term regional downscaled projections are unavailable but might suffer from the lack of coherence typical of time windows approaches. Notably, no study explicitly considers and quantify the impact of both CC and Mose operation on lagoon water properties, as temperature, salinity and water residence times, at the end of century scale horizon.

In this study, we adopt a full dynamical downscaling approach<sup>36</sup>, using regional climate projections over Italy produced by COSMO-CLM<sup>37,38</sup>, to drive the high-resolution hydrodynamic model SHYFEM<sup>39–42</sup> and project the future evolution of the Venice Lagoon under CC. Figure 1A illustrates the Lagoon of Venice, Fig. 1B illustrates the downscaling framework, where regional climate and Mediterranean Sea models provide the external forcings (meteorological, sea level, salinity, and temperature) for the lagoon model.

The model set-up allowed us to quantify the evolution of key hydrodynamic variables, including water temperature, salinity, renewal time (WRT), and marine heatwaves (MHW), under two emission scenarios, RCP-4.5 (low emission) and RCP-8.5 (high emission)<sup>43</sup>, and with and without Mose operations.

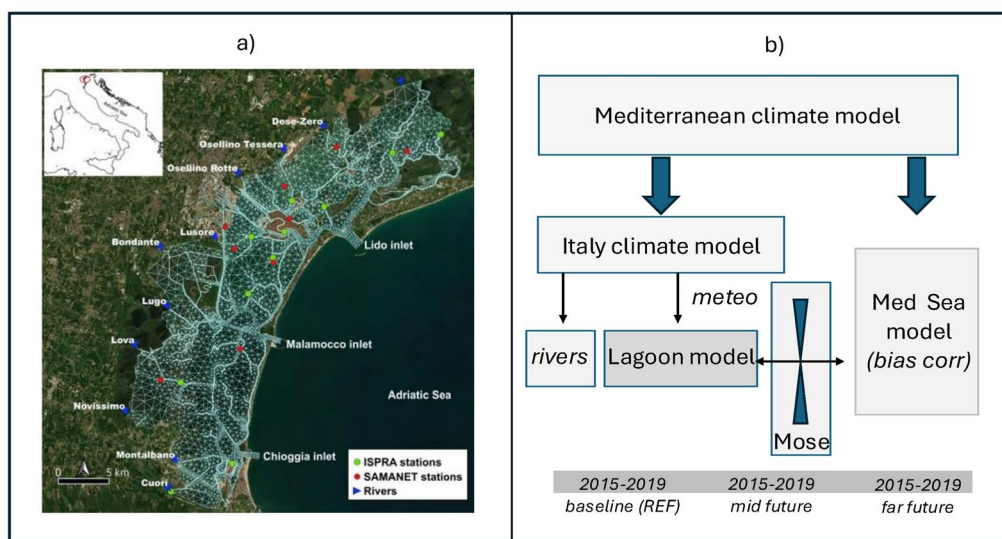


**Fig. 1** (a) Computational grid of the Venice lagoon model. Blue triangles show the rivers discharging into the lagoon. Red dots indicate the SAMANET monitoring stations, which provide continuous temperature and salinity observations. Green dots indicate the ISPRa monitoring stations, which provide continuous water-level observations. These observations were used for model calibration and validation. The three lagoon inlets are also indicated. The map was generated using QGIS version 3.40.8-Bratislava (QGIS Development Team; <http://qgis.osgeo.org>). Background satellite imagery is from the Sentinel-2 cloudless 2021 layer by EOX (<https://s2maps.eu/>; <https://esa.maps.eox.at/>), containing modified Copernicus Sentinel data [2021]. (b) Schematic representation of the downscaling modelling chain adopted for climate scenarios. Atmospheric forcing is provided by the high-resolution COSMO-CLM model downscaled over the Italian peninsula, while sea-level, temperature and salinity boundary conditions are derived from a Mediterranean Sea model after bias correction. River discharge is prescribed. The lagoon model includes Mose operation by closing the inlets when the tidal level exceeds the activation threshold. The framework is applied to the reference period (2015–2019) and to the mid-century and end-century scenario periods (2045–2049 and 2095–2099), with and without considering Mose closures.

Notably, WRT, an indicator that directly affects the ecological status of the lagoon by modulating nutrient cycling, oxygen dynamics, and pollutant dispersion, has not been previously quantified at high resolution for future scenarios in this system.

Statistical indicators of these variables were computed over representative multiyear periods, to characterize near-future (MID) and far-future (FAR) changes relative to present-day conditions (REF). This approach allowed us to capture interannual variability across present and future time slices, ensuring statistical robustness. By focusing on physical drivers as WRT, temperature and heatwaves, which are fundamental to shape in lagoon ecosystems<sup>26</sup>, our study complements previous work and contributes to a more comprehensive understanding of the cumulative impacts of climate and adaptation in coastal systems.

In this way, it also provides process-based information to inform long-term coastal adaptation<sup>14,15,24</sup>, by identifying when and where flood-protection measures substantially modify key water properties, and where complementary local measures may need to be considered.

## Results

### Model calibration and validation

The model was calibrated using observations from the year 2005, before the start of Mose operation, and 2020, the first year of active Mose closures. Validation was then performed against independent observations from 2008, 2019, and 2021. 2021, the second year of active Mose closures, was used specifically to validate the results on water levels. The calibration and validation procedures are described in the Methods, and additional details are provided in Supplementary Material section SM2 and in Fig. 13SM, and Table 4SM therein.

Overall, the model reproduces the observed physical conditions of the Venice lagoon with good accuracy in the three validation years (2008, 2019, 2021), as highlighted also in the Taylor diagram (Fig. 2). Comparisons with water-level observations from eleven ISPRA sampling stations (Figs. 1A and 2, Table 4SM, Figs. 4–7SM) showed a mean bias of  $\sim 0.01$  m and  $r$  values ranging from 0.97 to 0.98, RMSE 0.08. At the nine SAMANET sampling stations (Fig. 1A) temperature validation yielded  $r$  values above 0.98 and biases  $\sim 0.5$  °C, although winter temperatures were slightly underestimated at two sites. Agreement for salinity was weaker ( $r=0.67$ , bias  $\sim 1.5$ ) but still within acceptable ranges for lagoon-scale applications.

### Scenario analysis

Results are presented for four (two by two) combined climate and Mose-operation scenarios (see Methods). Comparisons are made across three representative periods: a reference baseline (2015–2019, REF), mid-century (2045–2049, MID), and end-of-century (2095–2099, FAR). The rationale of the choice for using a five-year-window is justified and explained in the Methods and in the Supplementary Material section SM3.

Results are presented and analysed one variable at a time using: Table 1 (mean values projected changes in closure frequency, mean water level, salinity, temperature, WRT, and MHW metrics across all scenarios and periods); Fig. 3 (frequency distributions of monthly salinity, temperature, and WRT, across all scenarios and periods); Fig. 4 (spatial distribution of water temperature anomalies); Fig. 5, and 6 (spatial distribution of WRT and their anomalies). In Fig. 3, each frequency distribution is the average of the 5 frequency distributions computed for each of the five years of a representative period, for the sake of readability of the differences among scenarios. The frequency distribution of each year and their averages for each representative periods is given in the Supplementary Materials (Figs. 14SM–16SM) which show a limited intra-period variability compared to the differences among scenarios.

We first examine projected changes in Mose closure frequency and lagoon water levels, as these define the physical and operational setting for the changes in salinity, temperature, WRT, and MHW described below.

### Projected changes in closure frequency and lagoon water levels

Given the current Mose operational rules, closures are projected to increase with SLR, and therefore in all climatic scenarios (Tables 1 and 9SM). Under RCP-8.5, closures rise from an average of 26 days/year (8% of annual time) at mid-century to 248 days/year (70%) by the end of the century. Under RCP-4.5, closures increase of 17 days/year (5%) and 138 days/year (40%) for MID and FAR, respectively.

Projected mean water level in the lagoon at the end of the century increases by 0.74 m under RCP-8.5 and by 0.55 m under RCP-4.5. When Mose operation is implemented, the corresponding simulated increase in mean lagoon water level is reduced to 0.51 m and 0.44 m, respectively, highlighting the role of Mose in mitigating, but not eliminating, lagoon water level rise.

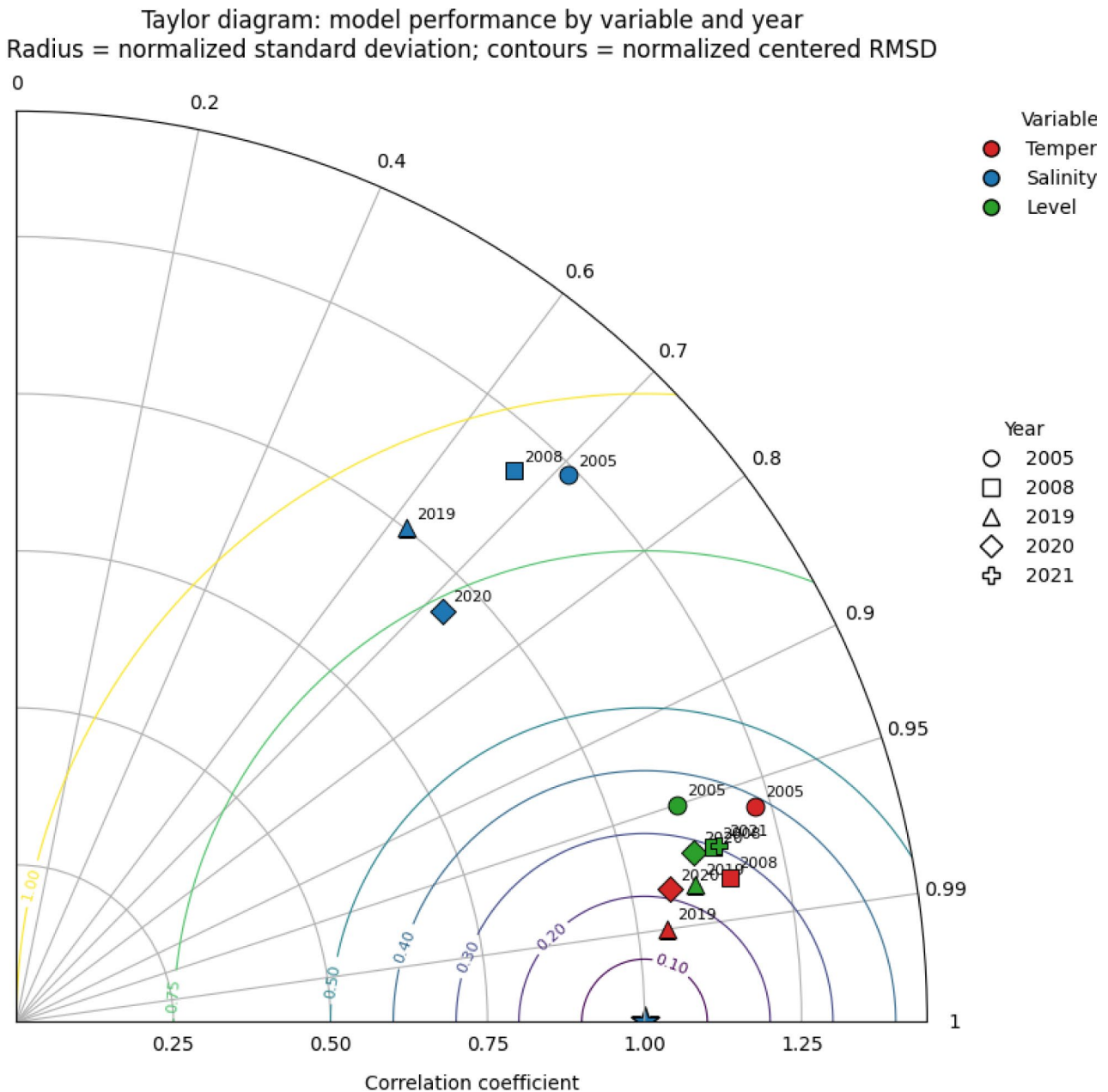


**Fig. 2** Taylor diagram summarizing model performance for water temperature, salinity and water level during the calibration-period and validation simulations. Radial distance represents the model standard deviation normalized by the observed standard deviation, the angular coordinate represents the Pearson correlation coefficient, and the contours indicate the normalized centered root mean square difference. The reference point corresponds to perfect agreement ( $r=1$ , normalized standard deviation=1 and centered RMSD=0). Colours identify the variables and symbols the simulation years.

### Projected changes in salinity

Salinity changes are small across scenarios (Table 1; Fig. 3a–b, Table 10SM). In MID, the distributions remain close to REF, with only a modest shift toward higher salinity values, most evident under RCP-8.5 and in the absence of Mose closures. In FAR, this shift increases, with the largest difference under RCP8.5-NoM. Mose operation partly dampens the increase, resulting in distributions closer to REF.

**Table 1** Comparison among indicators computed for the different scenarios: **Closures**: number of days per year in which the barriers have to be closed to keep the water levels below the threshold, Water level rise: increment of the average lagoon water level compared to the reference (2015-19), WRT: % of the lagoon area with yearly averaged residence time > 20 days or of > 30 days;  $T > 30^{\circ}\text{C}$ : % of the lagoon area with  $T > 30^{\circ}\text{C}$ ; MHW average number of days with  $T > T_i^{90th}$ , the 90th percentile climatology computed over 18 years for the SAMANET stations;  $\text{MHW} > 4^{\circ}$ : average number of days with  $T > T_i^{90th} + 4^{\circ}\text{C}$ ;  $\text{MHW} > 4^{\circ}\text{C} > 4\text{days}$ : maximum number of events, per station, of  $T > T_i^{90th} + 4^{\circ}\text{C}$  lasting 5 days or more (\*: computed on SAMANET stations).

| Indicator          | Unit            | REF  | Mid Future |      |      |      | Far Future |      |      |      |
|--------------------|-----------------|------|------------|------|------|------|------------|------|------|------|
|                    |                 |      | 2045-49    |      |      |      | 2095-99    |      |      |      |
|                    |                 |      | 4.5        |      | 8.5  |      | 4.5        |      | 8.5  |      |
|                    |                 |      | REF        | NoM  | Mose | NoM  | Mose       | NoM  | Mose | NoM  |
| Closures           | [days/years]    | 0    | 0          | 17   | 0    | 26   | 0          | 138  | 0    | 248  |
| Water level rise   | [m]             | 0    | 0.22       | 0.21 | 0.29 | 0.29 | 0.55       | 0.44 | 0.74 | 0.51 |
| Salinity           |                 | 31.1 | 0.3        | 0.2  | 0.4  | 0.2  | 0.2        | -0.4 | 0.8  | -0.3 |
| Temperature        | [°C]            | 16.7 | 1.4        | 1.4  | 1.3  | 1.2  | 2.3        | 2.2  | 4.9  | 4.6  |
| WRT                | [days]          | 9.5  | 10.0       | 10.4 | 10.1 | 10.4 | 11.0       | 13.5 | 11.9 | 17.7 |
| % res time>20 days | % lagoon area   | 1.5  | 2.3        | 2.9  | 2.5  | 3.3  | 5.8        | 16.8 | 10.7 | 33.9 |
| % res time>30 days | % lagoon area   | 0.4  | 0.4        | 0.4  | 0.4  | 0.5  | 0.5        | 2.5  | 1.0  | 11.2 |
| T>30 °C            | % lagoon area   | 1.0  | 5.8        | 5.8  | 2.6  | 2.6  | 11.8       | 11.4 | 23.4 | 22.6 |
| MHW                | [average, days] | 65   | 217        | 216  | 193  | 189  | 252        | 251  | 280  | 268  |
| MHW4>4 °C          | [average, days] | 3.7  | 11         | 10   | 8    | 8    | 17         | 16   | 93   | 85   |
| MHW4>4 °C>4days    | [# of events]   | 2    | 1          | 1    | 1    | 2    | 1          | 1    | 7    | 7    |
| MHW5>5 °C          | [average, days] | 1.2  | 5          | 5    | 5    | 5    | 8          | 8    | 57   | 52   |
| MHW5>5 °C>5days    | [# of events]   | 0    | 1          | 1    | 1    | 1    | 1          | 1    | 4    | 3    |

In FAR, basin-averaged mean salinity increases by 0.4 (RCP-4.5-NoM) and 0.8 (RCP-8.5-NoM), in the two simulations without Mose closures. Mose operation slightly reduced values under both scenarios.

### Projected changes in temperature

As shown in Table 1; Fig. 3c-d, temperature increases considerably, especially toward the end of the century. Basin-averaged annual mean temperature rises by 1.4 °C in MID and 2.3 °C in FAR under RCP-4.5, and by 1.5 °C in MID and 5.0 °C in FAR under RCP-8.5. In absolute term, basin-averaged annual mean temperature rises from 16.7 °C in the reference period to 19 °C under RCP-4.5 FAR and to 21.6 °C under RCP-8.5 FAR; with Mose operation, the corresponding values are 18.9 °C and 21.3 °C.

In all future scenarios temperature frequency distributions are shifted toward higher values relative to REF (Fig. 3c-d, Table 11SM). In FAR, such shifts increase, especially under RCP-8.5, with a significative fraction of values at temperature larger than 30 °C. (Table 1, and Fig. 3c-d). Overall, the distributions indicate a substantial increase in lagoon temperature across the annual cycle. Differences between Mose and NoM simulations performed under the same climatic scenario are small, and negligible if compared to differences between climatic scenarios.

Figure 3 presents the evolution of temperature changes, described by the monthly anomalies of the FAR RCP-4.5 and RCP-8.5 scenarios in respect to REF. Results show a consistent warming across scenarios, stronger under RCP-8.5 and particularly in specific moments and areas, especially from late spring to early autumn and in the inner lagoon, where monthly anomalies locally exceed 6 °C in wide areas. It is worth stressing that, under RCP-8.5, for more than three months (June to August), the absolute temperature remains continuously above 29,7 °C and reaches 32,9 °C in August. Under RCP-4.5 these values stay within 27,6 and 30 °C in the same months. Table 11SM provides additional data on temperature seasonal evolution under the different scenarios.

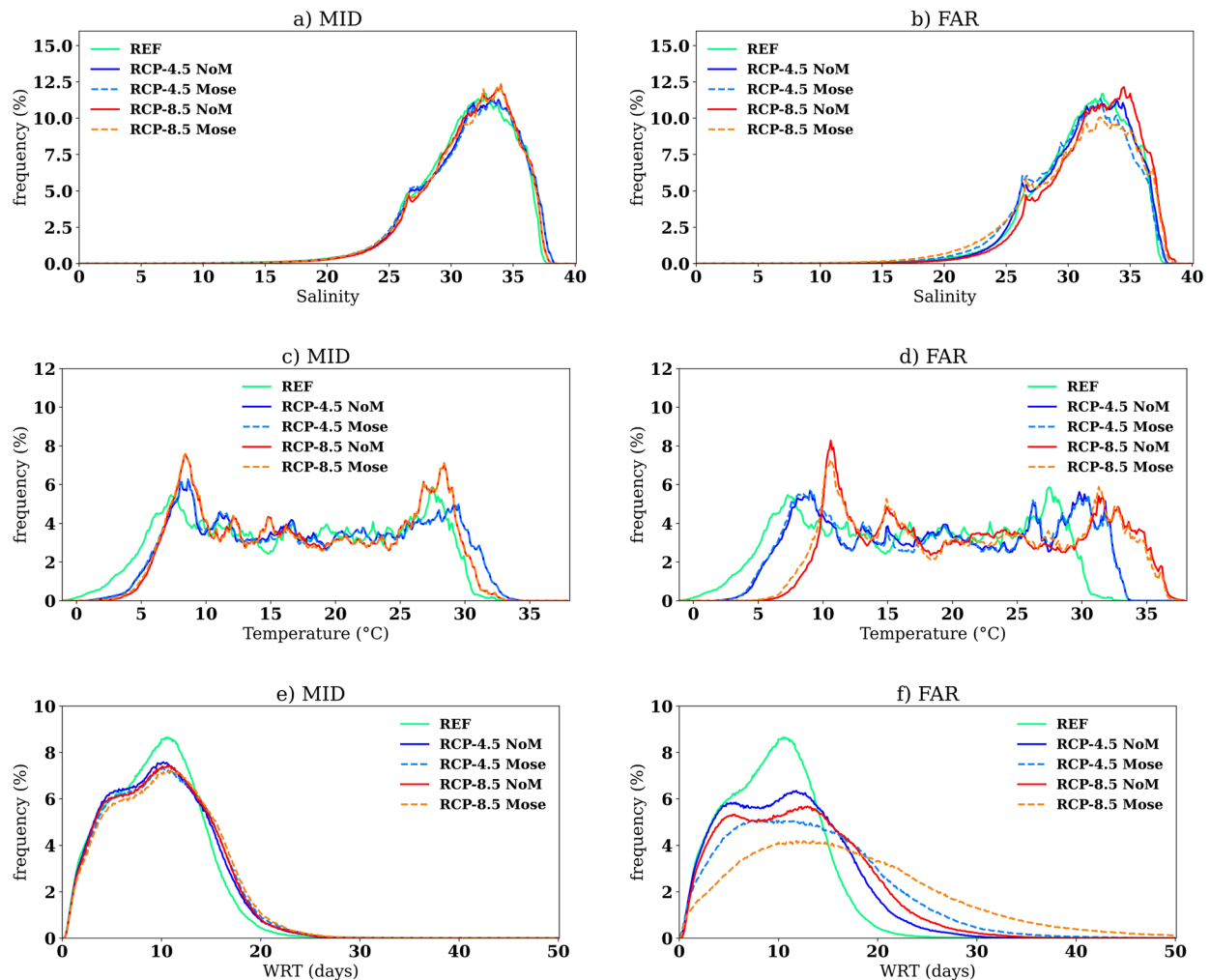


**Fig. 3** Comparison of yearly averaged frequency distributions (%) of monthly salinity (a, b), temperature (c, d), and WRT (e, f) in the MID (left column) and FAR (right column). Results are shown for REF and for the four climate and management scenarios: RCP4.5-NoM, RCP4.5-Mose, RCP8.5-NoM, and RCP8.5-Mose. For each scenario and period, frequency distributions were computed from the full set of simulated monthly values across all lagoon grid elements, weighting each element by its surface area. Each curve represents the average of the five yearly frequency distributions calculated within the corresponding 5-year representative period.

## Projected changes in WRT

WRT shows substantial projected changes under future climate and management scenarios.

Figure 3e–f, and Table 1 show that the present-day mean monthly WRT is ~9 days, with less than 1.5% of the model grid points above 20 days. Under RCP-8.5-FAR-NoM scenario, ~11% of values exceed 20 days and 1% exceed 30 days (Table 1). With Mose operation, these proportions rise to 34% of the lagoon over 20 days, 11% over 30 days (Table 1), and almost 4% above 40 days (Fig. 3f).

More generally, all distributions are shifted toward longer renewal times relative to REF (Fig. 3e–f). At mid-century, changes are modest but systematic: RCP-8.5-MID WRT values are slightly higher than those of RCP-4.5, both exceeding present conditions. In the FAR however, the differences become extremely relevant, the peak at short renewal times weakens, the distributions further broaden, and the high-WRT tail extends toward much

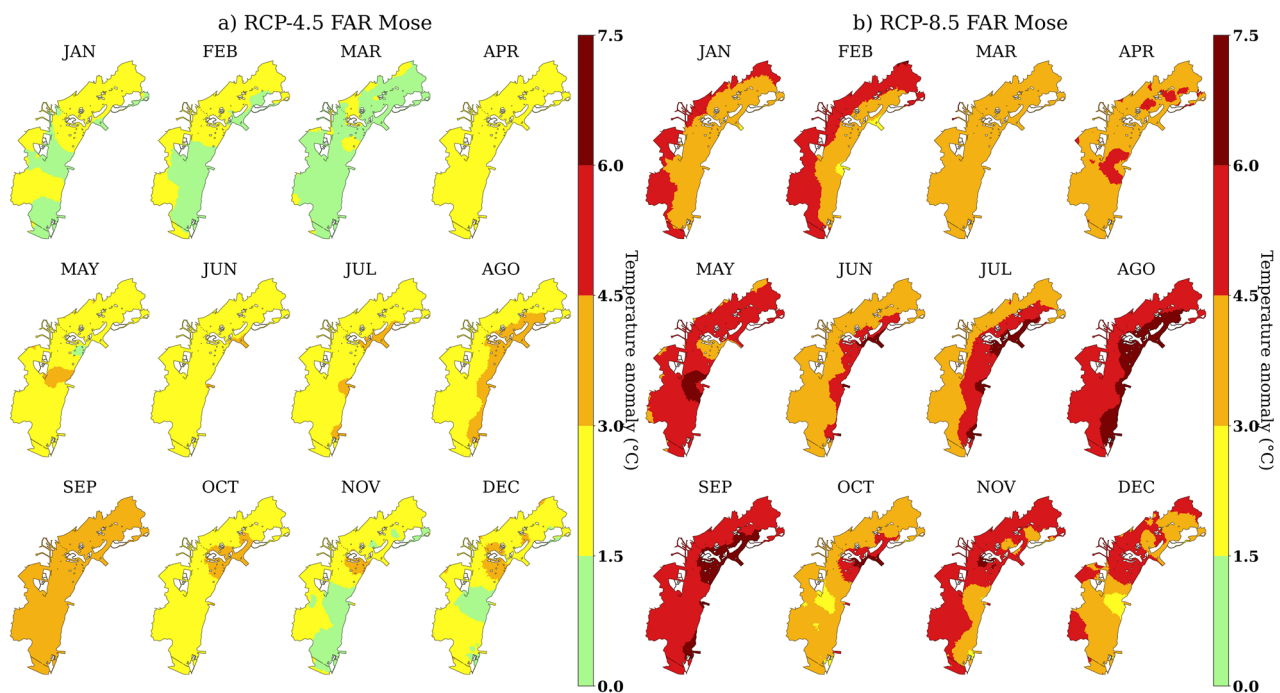


**Fig. 4** Lagoon monthly water temperature anomalies in respect to REF under RCP-4.5-FAR-Mose and RCP-8.5-FAR-Mose scenarios.

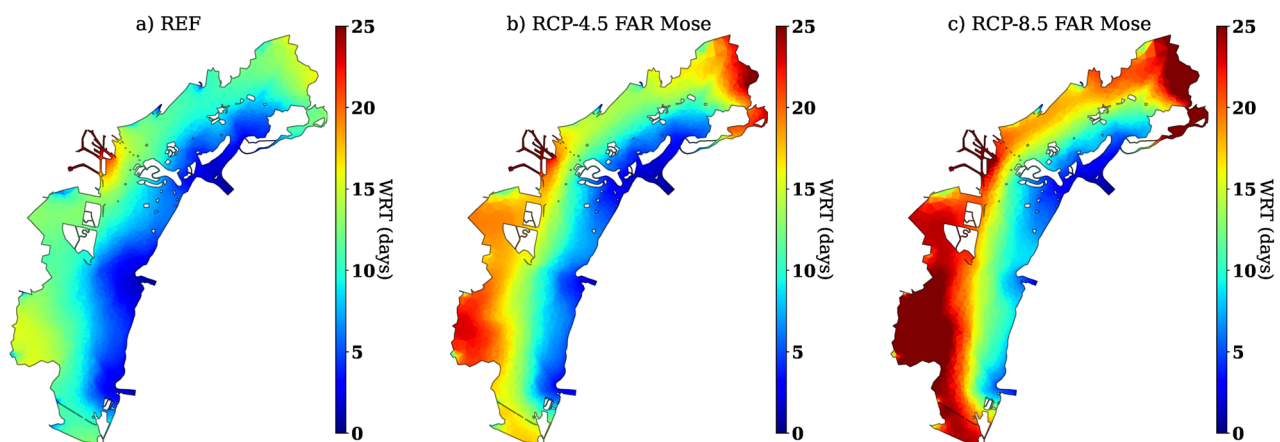


**Fig. 5** Maps of the 5-years averaged WRT for (A) REF, (B) RCP-4.5-MID-Mose (B), and (C) RCP-8.5-FAR-Mose.

larger values, indicating a globally reduced water exchange. The largest difference from REF occurs under RCP-8.5-Mose, which shows the highest frequency of very long renewal times.

WRT projected changes retain a clear spatial structure across the lagoon. Spatial patterns of WRT (Figs. 5 and 6) indicate a strengthening of internal gradients in climate scenarios: future conditions near the inlets resemble present-day values in the intermediate zone, while the inner lagoon reaches unprecedented renewal times, especially during several months of the year (Fig. 5). At the same time, future projections indicate an overall increase in WRT across the lagoon, particularly under the more severe climate scenario and Mose operation. Under RCP-4.5, increases are less extreme, yet the combination with Mose produces WRT distributions comparable to those of RCP-8.5-Mose. Figure 6 further shows that WRT anomalies vary both in space and time and are not spatially uniform over the annual cycle. Under RCP-8.5-FAR-Mose WRT anomalies are highest in October, where they

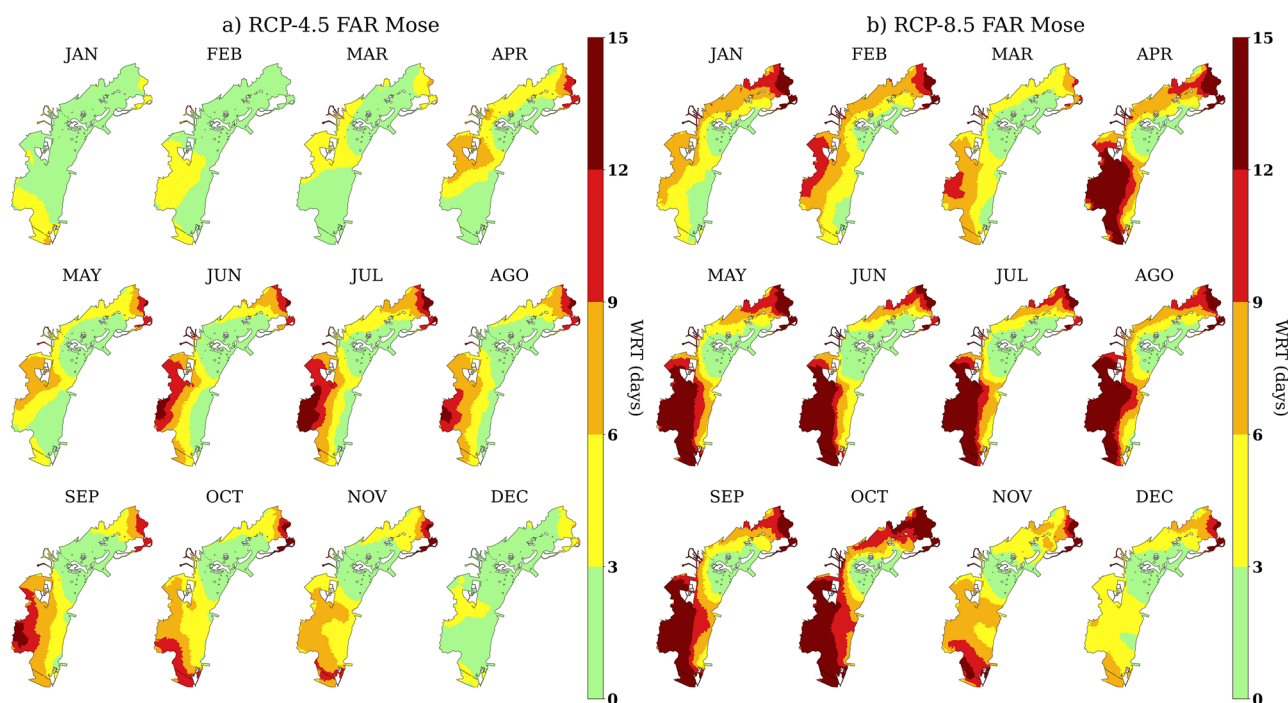


**Fig. 6** Lagoon monthly WRT anomalies in respect to REF under the RCP-4.5-FAR-Mose and RCP-8.5-FAR-Mose scenarios.

exceed nine days in Northern half of the Lagoon and 12 days in very relevant areas. And minimum in December, when the spatial heterogeneity is also less marked. The WRT in the Southern part of the lagoon exceed 12 days for 7 months per year. Similar situation occurs also in the most inner Northern part.

### Projected changes in Marine Heat Waves

MHW were computed from modelled daily temperatures extracted at the 10 SAMANET stations distributed across the lagoon, using site- and day-specific climatological thresholds. Site-specific results are provided in the Supplementary Material (Figs. 19SM-20SM) while the aggregated MHW metrics are summarized in Table 1. The analysis indicates a marked increase in the frequency, duration and intensity of MHW<sup>45</sup> across the lagoon over the course of the century. Mid-century projections show moderate increases across scenarios, whereas FAR diverge much more strongly, with more severe changes under RCP-8.5 and with only limited mitigation from Mose operation.

In the RCP-8.5-FAR scenario the 90th percentile of present-day climatology ( $T^{90th}$ ) is exceeded on average for ~270 days/year across the 10 SAMANET stations. Moreover, more than 90 days per year exceed  $T^{90th}+4$  °C, and over 50 days/year will exceed  $T^{90th}+5$  °C. These translate to an average of 7 MHW of type MHW4×4 and 3 of type MHW5×5 per year per station (see Methods for definitions).

### Statistical comparison across scenarios

Statistical analyses support the robustness of the comparison between variables across scenarios. Pairwise Mann–Whitney U tests, adjusted with Holm correction for multiple testing, indicated significant differences in temperature across all scenario combinations, and in salinity across most comparisons, confirming the sensitivity of the lagoon system to changes in both climate forcing and management regime. Differences in WRT are significant for most scenario combinations. However, three comparisons were not significant after Holm correction (REF/RCP-4.5-MID-NoM, RCP-4.5-MID/ECP-8.5-MID both with and without Mose).

Complete pairwise statistical results are reported in the Supplementary Material, Table 13SM.

## Discussion

The interpretation of the projected future changes should be framed in light of model performance and the main limitations of the modelling framework. Here, an extensive validation against independent observations showed high skill for water level and temperature, whereas salinity agreement was weaker, although still acceptable for lagoon-scale applications. This difference is plausible in a system like the Venice Lagoon, where salinity is strongly affected by local freshwater inputs, which are only partially known, and when known not always monitored at high enough time resolution. By contrast, water level and temperature are more directly constrained by atmospheric and marine forcings, which are much better known and monitored. Temperature and sea level exhibit excellent agreement with observations ( $r > 0.95$ ), whereas salinity shows lower but still acceptable correlations (0.62–0.72), reflecting the higher complexity of estuarine salinity dynamics. For 2020, the station-averaged annual RMSE at Punta della Salute is 0.07 m, matching the value at the same station/year reported by a previous 3D SHYFEM application<sup>46</sup>. Earlier 2D applications<sup>39</sup> yielded slightly better condition (RMSEs of 0.024 m under calm conditions and 0.052 m during a storm-surge event,) although these values were obtained from two targeted five-day simulations, and are therefore not directly comparable with the present annual-long basin-wide assessment. For salinity, the closest quantitative benchmark is a 2D application for the year 2005<sup>47</sup> which provides RMSE of 3.05, bias of 1.17,  $r$  of 0.6, comparable to the values obtained here, and identified freshwater forcing as a major source of uncertainty. The same limitation applies to our simulations, because some local freshwater inputs are only partly quantified and, where monitored, are not always available at sufficient temporal resolution. Further improvements in model skill could therefore be achieved through more detailed representation of river discharge and distributed freshwater inputs. However, these aspects are especially relevant for improving salinity skill – which is not central in the conclusion of our study – and less relevant for the robustness of our projection on temperature and water renewal time. Therefore, validation results support the use of the modelling framework for our scenario-based assessment, even if suggesting caution in interpreting fine-scale salinity patterns.

CC is expected to alter key water properties of the Venice lagoon, with potential consequences to its ecosystems. A careful, site-specific assessment of the cumulative impacts of CC and adaptation measures is particularly relevant for the Venice Lagoon, where multiple pressures overlap and where environmental changes can unfold rapidly due to the semi-enclosed nature of the system. This relevance is reinforced by the lagoon's historical, cultural, environmental, and socio-economic value and vulnerability, as well as by its centuries-long tradition of environmental management. In this context, the Mose system has become emblematic of the trade-offs between flood protection, ecosystem functioning, and the preservation of a highly vulnerable coastal heritage<sup>16,17</sup>. In fact, it has been widely and hotly debated, attracting global attention for decades.

Two climate scenarios (RCP-4.5 and RCP-8.5) were selected to represent a plausible range of future climate conditions and to assess how strongly lagoon responses depend on the emissions trajectory<sup>43,44</sup>. This comparison is particularly relevant in Mediterranean coastal lagoons, which lie within a recognised climate-change hotspot<sup>4,5</sup>. In this context RCP-8.5 provides a useful upper-bound reference for climate risk assessment<sup>43</sup>.

In this study, we applied a coherent hierarchy of state-of-the-art models to estimate the future evolution of the Venice Lagoon under two climate scenarios, explicitly accounting for the cumulative effects of Mose closures.

Previous downscaling studies for the Venice Lagoon mainly focused on changes in precipitation regime and seasonality and their implications for biogeochemical properties, without explicitly representing water circulation, temperature, or renewal time, nor the effects of repeated Mose closures over a century-scale horizon<sup>31,32,42</sup>. More recently, a study investigated future temperature and sea level extremes up to 2050 by imposing predefined climatic trends on meteorological and hydrological forcings rather than applying a fully dynamical downscaling<sup>34</sup>. While that approach provided valuable insights into large-scale responses, it did not explicitly address the effects of Mose operation on salinity or WRT. By contrast, we used a fully coherent dynamic downscaling

framework, and our study is the first -to our knowledge- to quantify the combined effects of CC and Mose operation on physical properties and WRT in the Venice Lagoon over a century-scale timespan.

Our results are relevant for impact assessment and also for longer-term adaptation planning. Recent work on Venice has highlighted the importance of mapping how adaptation pathways evolve to understand how the space of available responses progressively narrows with sea-level rise and which objectives may still be preserved under alternative long-term strategies<sup>25</sup>. More broadly, evidence from coastal cities worldwide suggests that adaptation is often still incremental, narrow in scope, and strongly centered on infrastructural protection, while complementary and alternative responses remain less explored<sup>14</sup> and long enough time horizon and trajectories often ignored. In this context, the present study does not define adaptation pathways directly, but provides quantitative information on when and where the current open-lagoon protection strategy may substantially modify key water properties. It can therefore support the evaluation of complementary responses within longer-term adaptation pathways.

The projected changes concern key physical indicators such as salinity, water temperature, MHW and WRT, all of which are relevant for assessing potential environmental pressures on lagoon habitats and ecosystems functioning<sup>48–53</sup>.

Among these, WRT is a key descriptor of lagoon hydrodynamics, as it is the time required for a basin to renew its waters. It is also relevant to the spatial organisation of biological communities, since areas characterized by shorter renewal times host communities more similar to marine ones, while inner, more confined areas with longer renewal times support distinct assemblages<sup>27,28</sup>. In addition, WRT is also important for water quality and related processes, as it influences the rate at which pollutants and nutrients are exported out of the system and replaced by new water. Although several related indicators can be used to assess water exchange, such as renewal time, residence time, confinement, or water age, in all cases renewal rate depend on inlet geometry, tidal range, wind regime, and river discharge<sup>48–51</sup>. For the Venice Lagoon, previous studies<sup>48,50,51</sup> showed that confinement varies considerably among lagoon sectors and seasons and is particularly sensitive to wind forcing, river inputs and the representation of water exchange at the inlets. Mose operation introduces an additional control by periodically interrupting the sea-lagoon exchange.

The projected increase in WRT under future scenarios is primarily attributable to SLR, as shown in previous studies<sup>46</sup>. Higher mean sea level increases the volume of lagoon water that must be renewed, while the water exchange through the inlets is insufficient to compensate for the larger volume. Mose closures further increase WRT by temporarily suppressing inlet fluxes during high-water events, thereby limiting tide- and wind-driven lagoon–sea exchange. Repeated Mose closures further exacerbate this trend, strengthening internal gradients in WRT, in particular under the far-future RCP8.5 scenario. From an ecological perspective, this indicates that area with physical conditions associated with confined inner lagoon environment would expand, while areas characterized by stronger marine exchanges will shrink, in partial contrast with the recent tendency toward more marine-like conditions observed in the last decade in the lagoon<sup>54</sup>.

Salinity shows only modest changes across the different scenarios, despite the substantial changes in both temperature and WRT. Salinity is influenced by multiple interacting drivers, including climatic factors such as precipitation and temperature (through their effect on evaporation), as well as exchanges with the sea and fresh-water inputs from rivers, which also influence WRT. Evidently, the combined effects of increased WRT (reflecting reduced water exchange with the sea) and climate change are not sufficient to produce major alterations in the overall salinity distribution.

Mose closures also have only a limited impact on salinity. Although statistical tests may detect significant differences in some cases, the magnitude of these changes remains small and is likely to be of limited relevance.

This result is consistent with the well-established view that WRT and salinity describe different aspects of lagoon functioning and may become partially decoupled. This has been demonstrated both by the theoretical framework on the paralic ecosystems<sup>27</sup> and by previous studies in the Venice Lagoon<sup>47,50</sup>, which showed that salinity and WRT exhibit distinct spatial patterns.

Our results therefore suggest that future environmental conditions may lead to an even stronger decoupling between hydrodynamic confinement and salinity, with areas characterized by substantially longer residence times while maintaining salinity levels comparable to those observed today.

Such conditions would expose lagoon organisms to longer residence times and reduced water renewal without the corresponding decrease in salinity that currently accompanies hydrodynamic confinement.

Water temperature is projected to increase by about 2.5 to 5 °C by the end of the century, depending on the scenario, with marked spatial and seasonal variability. The response is primarily controlled by atmospheric forcing through the surface heat budget, including short-wave solar radiation, long-wave radiation, and sensible and latent heat fluxes, and by water circulation, that redistributes heat within the lagoon. Model skill is consistent with a reliable representation of these processes. In the shallow inner sectors, the shallower water column and weaker exchange with the coastal sea amplify the response to surface heating, producing the largest summer anomalies. Spatially averaged monthly increments can reach 6–7 °C in summer, leading to absolute temperatures above 30 °C and locally exceeding 35 °. Such conditions may be close, or even exceeding, the thermal tolerance limits of some species. As an example, previous work in the Venice Lagoon, indicated mass mortality for economically relevant species such as *Mytilus galloprovincialis* and *Ruditapes philippinarum* for temperature exceeding 30 °C for more than 3 days and 12 days, respectively<sup>55</sup>.

Furthermore, the increase of temperature would lower oxygen solubility, and may alter biogeochemical and oxygen dynamics, particularly in the most confined areas of the lagoon.

Our projections also indicate a marked intensification of MHW. Daily model outputs show that intense and prolonged heatwaves will become increasingly frequent, extending to nearly year-round conditions under the far-future scenario. This indicates that future change will involve not only higher mean temperatures, but also a strong amplification of thermal extremes with potentially important consequences for sensitive species<sup>55</sup>.

The Venice Lagoon responds to climate forcing through mechanisms shared with other coastal and estuarine systems. However, response magnitude and direction depend on site-specific hydrodynamic configuration and connectivity. In shallow semi-enclosed systems, thermal extremes are strongly controlled by local air-sea heat fluxes and weak offshore exchange, consistent with the pronounced warming and MHW intensification projected for Venice<sup>56</sup>.

Hydrographic responses are more locally driven and system dependent. In the Curonian Lagoon, climate-driven increases in river runoff enhance flushing, reducing both WRT and marine intrusion<sup>57</sup>. Under SLR increasing salinity and spatially contrasting WRT changes are projected for the Hudson-Raritan Estuary, driven by changes in circulation, stratification and mixing<sup>58</sup>. In Venice, SLR and increasingly frequent Mose closures, instead, lead to longer WRT, with minor response on salinity. Barrier operation itself may substantially alter estuarine dynamics: in the Hudson River Estuary, simulated surge-barrier closures suppress tidal mixing, enhance stratification and modify salt intrusion, with recovery depending on closure frequency and river flow<sup>59</sup>. Overall, these comparisons show that common climatic drivers produce different responses depending on freshwater forcing, circulation, morphology and regulation of sea/ocean exchange, highlighting the need for high-resolution, site-specific assessments to understand the mechanisms controlling future change in transitional coastal systems.

One limitation of our projections is that the model uses a fixed bathymetry. Consequently, the simulations do not account for future topo-bathymetric evolution and assume that the current lagoon morphology is artificially maintained. However, previous modelling studies of the Venice Lagoon<sup>46</sup> showed that the morphological evolution observed over the last century (1927–2002) had only a limited effect on lagoon-wide average WRT (about 2–3%), although local impacts could be much larger. Those effects were also smaller than those associated with sea-level rise of 0.3–0.5 m or with Mose operation. While this comparison suggests that, relative to the magnitude of the morphological changes considered in that study, SLR and barrier operation appear to exert a larger, and possibly dominant, influence on basin-scale WRT, direct quantitative comparisons remain limited because the response depends on the magnitude and spatial pattern of the morphological changes considered, as well as on differences in forcing conditions, temporal averaging, and experimental design.

Finotello et al. (2023)<sup>60</sup> similarly showed that salt-marsh loss produces spatially heterogeneous changes in mean high-water levels, further indicating that morphological effects may be relevant locally but limited at the basin scale. An exact quantification of the effects of alternative future morphological trajectories would nevertheless require dedicated simulations and analysis.

The contrast between RCP-4.5 and RCP-8.5 highlights that the future evolution of the lagoon depends strongly on the broader climate trajectory. By the end of the century, the divergence between the two scenarios becomes sufficiently large to indicate that global mitigation can substantially reduce the magnitude of future warming, water-level rise, and hydrodynamic alteration, in turn implying a less frequent use of Mose and less severe cumulative impact. The opposite is true for higher emission scenarios. In this respect, the comparison shows how strongly local adaptation outcomes are in this case conditioned by global emissions pathways.

In summary, the long-term evolution of the Venice lagoon emerges from the interaction between climate forcing and adaptation management. Within this framework, in the coming decades Mose can substantially buffer the impact of sea level rise and reduce flood exposure for Venice, but not those of warming, and this protection will come at the cost of a substantially reduced water renewal. Under the more mitigated climate scenario RCP-4.5, the projected changes in temperature, water levels and WRT are much less severe than under RCP-8.5, highlighting the importance of global mitigation for limiting the magnitude of future change. At the same time, identifying when and where these impacts emerge may help support the evaluation of complementary local measures to address specific critical conditions along the adaptation pathway.

Beyond the Venice case, these findings are relevant to other shallow, regulated coastal systems in which hard protection modifies water exchange with the sea. In this sense, quantitative framework developed here can support the evaluation of adaptation pathways by identifying when and where additional measures could support a more resilient adaptation to CC.

## Methods

### Hydrodynamic model and grid setting

We applied the SHYFEM model (System of Hydrodynamic Finite Element Modules), which solves the three-dimensional hydrodynamic and transport equations on an unstructured triangular mesh using a finite-element spatial discretization and a semi-implicit time-integration scheme. The model includes a hydrodynamic module for sea surface height and current velocities, a transport module for heat and salt advection and diffusion, and a surface radiation module for heat fluxes<sup>39,40</sup>.

The hydrodynamic module accounts for tidal, atmospheric, and density-driven forcing, and the bottom friction follows the Strickler formulation. Vertical turbulence was parameterized with GOTM closure schemes<sup>61</sup>, and horizontal sub-grid mixing follows the Smagorinsky approach<sup>62</sup>. The model uses z-level vertical discretization with partial bottom cells and includes wet-and-dry processes to represent the temporary emergence of the shallowest lagoon areas during low tide. A full description of the model equations and numerical solutions is given in Umgiesser et al. (2004)<sup>39</sup> and examples of model applications in the Venice Lagoon<sup>29,33,34,40,46–48,50,51</sup>.

Mose closures at the inlets were implemented following the approach of Melaku Canu et al. (2001)<sup>33</sup> and Umgiesser (2020)<sup>22</sup>.

The accuracy of finite element hydrodynamic simulations depends strongly on the precision and spatial resolution of the bathymetric data and grid design. These not only determine local water column depth, but also influence the representation of bed roughness, as well as the incorporation of specific structures and features that affect transport dynamics. Bottom conditions are inherently dynamic, changing due to both natural processes and human activities. In the Venice lagoon, bathymetry is frequently modified by channels dredging, natural erosion and sediment deposition, which affect not only the water depth but also the morphology and boundaries of the basin.

To account for the most recent morphological evolution, including modifications associated to Mose construction, we adopted an updated grid<sup>41</sup>. The grid (Fig. 1) was generated by merging recent bathymetric surveys<sup>63</sup> with previous versions<sup>39,40</sup>. It is formed by ~6000 nodes and ~10,000 elements, with a spatial resolution ranging from 10 to 300 m, corresponding to an increase of about 32% in cell number compared to the earlier set-up. The updated grid includes the new channels, higher resolution in shallow areas, and revised coastline and element depths based on the latest available surveys. Future morphological evolution was not explicitly included in the scenario simulations; instead, all future runs assumed that the present-day configuration of channels and mudflats is maintained through ongoing management and maintenance interventions throughout the projection period.

## Calibration and validation

Observational data used for calibration and validation were obtained from local monitoring networks shown in Fig. 1. Water-levels observations were provided by the ISPRA Ambiente tide gauge network at 11 stations every 10 min (<https://www.venezia.isprambiente.it>). Salinity and temperature data were obtained from the SAMANET monitoring network, every 30 min. These datasets provided the reference basis for calibration and independent validation of the model for present-day also when Mose was activated.

The Venice lagoon model was calibrated with two one-year simulations (2005 and 2020), forced by observed meteorological conditions (wind, air temperature, precipitation, shortwave and longwave radiation), river inflows, and boundary conditions at the three inlets. Model outputs were compared with in-situ observations of water levels and temperature collected during the same years (see SM2 and Figs. 4SM and 6SM for water levels, Figs. 8SM and 9SM for temperature).

The selected calibration years represent contrasting conditions: 2005 corresponds to pre-Mose conditions, while 2020 includes the first active Mose closures, allowing model performance to be assessed under both unmanaged and managed hydrodynamic conditions. Calibration focused in particular on bottom-stress parameterization near the inlets and in areas affected by bathymetric updates. Additionally, calibration was refined for 2020, focusing on periods coinciding with actual Mose closures to improve the representation of closure dynamics.

Validation was performed with three additional one-year simulations (2008, 2019, 2021), using observed meteorological forcing, river inputs, and boundary conditions. These years were selected to cover different observed conditions; 2021 includes Mose operation, whereas 2008 and 2019 represent periods without active closures. Model results were compared with independent observations of temperature, salinity, and water levels (see SM2; Figs. 6SM and 7SM for water levels and Figs. 11SM and 12SM for temperature, 13SM for salinity).

A further model validation against observations from 2015 to 2019 was done for the downscaling modelling framework used to project the future state of the lagoon, described in the next section (Fig. 17SM).

## Downscaling modelling framework and scenario analysis

Future simulations were carried out using a downscaling modelling framework in which the lagoon model was externally forced by outputs from regional climate models (Fig. 1, right) following approaches adopted in previous downscaling experiments<sup>31,32</sup>. Our analysis relies on CMIP5-based forcing, since CMIP6 regional downscaling is not yet available for this area. CMIP5 therefore remains the most coherent basis for local-scale projections.

Meteorological forcing was provided by the COSMO-CLM regional climate<sup>37,38</sup> run at 8 km (0.0715°) resolution, over the Italian Peninsula, nested within the CMCC-CM model applied over the Mediterranean basin. Salinity and temperature at the lagoon inlets were derived from existing simulations of the CMCC-MFS16-NEMO Mediterranean Sea regional model<sup>64</sup> also forced by CMCC-CM, for both RCP-4.5 and RCP-8.5 scenarios. Inlet boundary values were bias-corrected against long-term field observations<sup>36,65,66</sup>. Sea-level rise was prescribed by linear interpolation between the present level and ensemble median projections reaching +0.71 m by 2100 for RC-8.5, and +0.52 m for RCP-4.5<sup>30,67–69</sup>. The COSMO-CLM regional model has been extensively validated

over Italy and provides temperature and precipitation projections consistent with the range of variability of the EURO-CORDEX ensemble<sup>37</sup>.

River inflows were estimated from projected rainfall trends, using linear regressions. The resulting discharge changes are consistent with previous lagoon-scale studies<sup>6,31,32</sup>, and with projections for rivers discharging in the Adriatic Sea<sup>70</sup> providing a ~35% reduction in river release for the mid-century Adriatic. This is comparable to the ~40% reduction derived from COSMO precipitation projections used here, supporting the plausibility of the assumed forcing. A sensitivity test varying river discharge by  $\pm 20\%$  around the baseline reduction showed only minor effects on lagoon conditions, with average changes of  $< 3\%$  in salinity and  $< 1\%$  in temperature, confirming the robustness of the applied hydrological forcing.

Mose operation was introduced according to the current operational guidelines: closures were activated whenever a tidal peak was forecast to exceed 1.10 m, preventing the sea level from rising above 0.90 m during the tidal cycle. Reopening was set as soon as the ebbing tide returned below the 0.90 m threshold.

A full technical description of the modeling system is provided in Supplementary Material (SM1).

The validated downscaled modelling system was used to represent two climate scenarios, (mid emission and high emission), with and without Mose operation, for the period 2006–2100. This resulted in four climate and management scenarios: RCP-4.5-NoM, RCP-4.5-Mose, RCP-8.5-NoM, RCP-8.5-Mose. The validated 5-year simulation for the period 2015–2019 was used as the reference baseline (REF).

For the analysis, three representative 5-years periods were considered: REF (2015–2019), MID (2045–2049), FAR (2095–2099). These 5-year windows were selected considering the characteristic temporal scales of the Venice Lagoon, where dominant hydrodynamic and renewal processes operate on time scales of days to weeks and typical WRT are on the order of weeks. In climate studies considering ocean or large basins, climatologies are often computed over periods of 20 or more years, in order to capture interannual variability on large-scale processes<sup>2</sup>. In the Venice Lagoon, however, the key indicators considered here reflect processes acting on much shorter timescales, while long averaging periods would be affected by the progressive non-stationarity introduced by climate forcing. We therefore compared temperature, salinity, and WRT statistics computed over periods of 1 to 5 years and we found that multi-year averages converged to quasi-stationary values for periods longer than three years, with changes below 0.1% (see SM3 and Tables 4SM–6SM therein). A 5-year window was therefore adopted as a conservative compromise that captures interannual variability while limiting contamination from long-term non-stationarity associated with the climate forcing. RCP-4.5 and RCP-8.5 were selected to represent a plausible range of low and high emission trajectories.

Overall differences among scenarios were assessed using pairwise Mann–Whitney U tests. P-values from the pairwise comparisons were adjusted for multiple testing using the Holm correction. Descriptive statistics (mean, standard deviation, median and interquartile range) were also calculated for each scenario. Complete pairwise statistical results are reported in the Supplementary Material Table SM13.

Anomalies of temperature, salinity, and WRT were then computed as differences between each scenario and the REF baseline.

## Derived indicators and analysis

### WRT, temperature and salinity

WRT were computed following previous studies<sup>48,49</sup>, using a passive tracer released inside the lagoon. To capture interannual variability and minimize the influence of tidal and meteorological conditions, we performed 365 simulations per year, each starting on a different day and lasting 60 days. This duration exceeds the present WRT of any lagoon sub-basin and ensures that the tracer method converges to a stationary value. Monthly means WRT values were then computed from these simulations.

WRT, temperature, and salinity, were analysed to assess their variability under different climate and management scenarios. For each lagoon grid point, daily values were extracted and weighted by surface area to compute

means, standard deviations and frequency distributions. Monthly values of salinity, temperature, and WRT were used to compute yearly frequency distributions across all lagoon grid elements; the five yearly distributions within each representative period were then averaged to obtain the corresponding MID and FAR frequency distributions. These indicators provide a consistent basis for comparing spatial patterns and scenario-dependent changes in lagoon hydrographic conditions.

### Marine heatwaves (MHW)

MHWs were identified following the approach proposed by Hobday et al.<sup>40</sup>, using site- and day-specific thresholds derived from in-situ temperature records. For each of the ten SAMANET monitoring stations distributed across the Venice Lagoon, we built an 18-year (2005–2022) hourly temperature climatology. From this dataset, we computed the 90th percentile of temperature for each day of the year and station,  $T^{90th}(day,site)$  which was used as the baseline threshold for detecting anomalous warming events.

Modelled daily temperature extracted at the same station locations were compared against these thresholds to detect MHWs for all scenarios, focusing on the MID (2045–2049) and FAR (2095–2099) periods. A MHW was defined as a period of at least 5 consecutive days with temperature exceeding the site- and day-specific threshold  $T^{90th}(day,site)$ . High-intensity events were further classified as MHW4 and MHW5, indicating temperature anomalies exceeding  $T^{90th}(day,site)$  by +4 °C and +5 °C, respectively. We also tracked their duration: MHW4 × 4 and MHW5 × 5 refer to events lasting four or five days above the corresponding +4 °C and +5 °C thresholds.

This framework enabled us to quantify both the frequency and severity of thermal extremes under projected climate conditions. Supplementary Fig. 19SM and Fig. 20SM provide site-specific visualizations of MHW metrics, while Table 12SM summarizes results aggregated by scenario and period.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-73719-w>.

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**Author contributions** DMC and CS conceived the study and established the experimental design. CL, DMC, GR, LA produced the model set-up, CL and LA, performed the simulations and the post-processing. All authors performed the analysis and discussed the results. DMC and CS wrote the ms with contributions from all co-authors.

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**Data availability** Data are accessible here: <https://drive.google.com/drive/folders/1Chl4iBOOoXdkFloET5MmGSTld2WNP63k?usp=sharing> The dataset includes Monthly averaged fields of temperature, salinity water levels, WRT for the reference simulation (2015–2019) and the years 2045–2049 and 2095–2099 of the 4 simulations of climate and regulation scenarios (RCP 4.5-NoMose, RCP-8.5-NoMose, RCP-4.5-MoseM, RCP-8.5-Mose) A Zenodo repository will be active after

publication.

## Declarations

**Competing interests** The authors declare no competing interests.

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