

Is the future given? Cumulative impact of Climate change and MOSE closures on Venice and its lagoon.

Donata Melaku Canu (✉ dcanu@ogs.it)

National Institute of Oceanography and Applied Geophysics - OGS

Leslie Aveytua-Alcazar

National Institute of Oceanography and Applied Geophysics - OGS

Celia Laurent

National Institute of Oceanography and Applied Geophysics - OGS

Ginevra Rosati

National Institute of Oceanography and Applied Geophysics - OGS

Cosimo Solidoro

National Institute of Oceanography and Applied Geophysics - OGS <https://orcid.org/0000-0003-2354-4302>

Physical Sciences - Article

Keywords:

Posted Date: December 22nd, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3731067/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Abstract

Measures to adapt to climate change (CC) might have secondary adverse effects. In Venice, the hotly debated MOSE system will prevent the flooding of the city, but also the water renewal of the lagoon, and since the frequency of the closures will increase with CC, concerns are raised on the fate of the lagoon ecosystem^{1,2,3}. Nonetheless, a systematic downscaling of the cumulative impact of CC on the Venice lagoon under multiple emission scenarios and with or without the associated MOSE closures was not presented yet. Here we show that the systematic implementation of MOSE closures will efficiently buffer the CC impact on sea level rise, but not on temperature, and in any case at the cost of a significant increment in the lagoon water renewal time. However, results also emphasize that the future is not given, and a combination of more conservative emission scenarios and MOSE might be able to save both Venice and its lagoon. Model projections suggest that at the end of the century, under the RCP8.5 scenario the lagoon will stay close for about 260 days/year, lagoon water will exceed 30°C for more than 4 months, marine heat waves will dramatically increase, the average water renewal time will triplicate and more than 35% of the lagoon will need more than 20 days to renew its water. Those impacts will be much less severe, and possibly much less challenging for marine organisms, under the RCP4.5 scenario. Results emphasize the necessity of combining global mitigation and local adaption but stress the need of site-specific carefully planned adaptation measures. They also show that the future is not written, and we are still in time to adopt choices able to protect our environment.

Introduction

The Venice Lagoon, its ecosystems, and its human socioeconomic activities are highly sensitive to the expected cumulative impacts of climate change and related adaptation measures. The lagoon has been inhabited for centuries, during which the Venetians grew into a major economic and maritime power and one of the longest-lived republics ever. During this time, the lagoon has been continuously subjected to natural and anthropogenic changes, and extensive efforts have been made to stabilize and preserve its morphological and ecological features⁴. The relationships between the city of Venice and its lagoon, and among man-land-and-sea have been at the heart of a carefully nurtured, delicate, and extremely fertile balance, which must now also consider the rapidly growing effects of a changing climate. This combination of factors makes the Venice Lagoon a relevant, particularly interesting, and highly appropriate site for analyzing the combined impacts of climate and adaptation measures.

Climate change is now unequivocal and is expected to trigger severe changes on any coastal marine ecosystems⁵. Direct impacts such as the increment in temperature, sea level, ocean acidification, and frequency of extreme events (including precipitation and heat waves) are already being observed, and model projections indicate that future marine ecosystems will differ significantly from the present ones, with the intensity of the divergence depending on the extent to which humanity will be able to choose and adhere to emissions scenarios less impacting than the business-as-usual one. The Mediterranean region, including the northern Adriatic Sea and its lagoons, will be particularly affected^{6,7} and several studies

show how direct impacts will cascade to biogeochemistry^{8,9,10}, biodiversity¹¹, ecosystem functioning¹², and associated ecosystem services^{13,14,15,16}.

Understanding and projecting the potential magnitude of changes is critical for supporting adaptation and mitigation strategies and identifying gaps in existing strategies. Tools to support the assessment of the climate related direct impacts on people and ecosystems are particularly needed in the areas where human activities are most concentrated, such as coastal and lagoon systems. However, the specificity of these coastal systems - along with the need to assess and address potential impacts that are also of economic interest – requires very high-resolution and site-specific models, capable of capturing local processes and of accounting for specific local inputs and spatial and temporal variability and heterogeneity.

The Venice Lagoon is one of the largest lagoons (about 500 km²) in the Mediterranean. It hosts a rich diversity of habitats and biological communities and a densely inhabited area, with many co-existing economic activities, often somehow related to the ecological state of the lagoon. In this lagoon, over the last century land subsidence and the effects of climate change have already resulted in a relative sea level rise of 26 cm¹⁷, which is expected to increase in the coming decades due to climate change.

Since the city of Venice was periodically inundated by seawater ("high tide phenomena"), mobile barriers (the "MOSE" system) have been built at the lagoon inlets, to interrupt the exchange between the lagoon and the sea when sea level is expected to exceed a predetermined threshold¹. However, due to climate change and associated sea level rise, the frequency and duration of closures is expected to increase in the coming decades¹⁷ and there are concerns about the potential ecological impacts of these repeated closures on the lagoon ecosystem^{2,3}. Indeed, changes in water circulation and residence time have relevant impacts on the spatial and temporal variability of physical and biogeochemical properties and contribute to (re)shape and change the different water bodies characteristics, states, and the associated ecosystem structures, functions and services^{18,19,20}.

However, and surprisingly enough, so far only few studies exist that provide site-specific projections of the state of the lagoon at the end of the century. Additionally, most of them focus only on sea level rise^{21,17}, few on changes in biogeochemical or biological properties related to changes in precipitation regimes and associated variation in timing of riverine loading^{10,22,23}, but none, to our knowledge, focus on base physical and hydrodynamical properties - such as water temperature, residence time, frequency of occurrence of extreme events- with the exception of a study²⁴ that report an estimate of averaged values of temperature, salinity, and residence time under a single climate scenario, as part of a comparative numerical experiment on 10 lagoons. None of the above studies, however, also consider the effects of the massive and already implemented adaptation measure, i.e., the repeated closure of the inlets.

Here, we updated, validated, and applied a finite element model for the Venice Lagoon in order to project changes in the hydrodynamic properties of the lagoon (sea level rise, salinity, temperature, water

residence time) expected at the end of the century (2100) under two different climate scenarios, and also considering the repeated closures of the barriers (MOSE) at the lagoon inlets to prevent city floodings.

The simulations were performed using the community finite element model SHYFEM²⁵, which is especially suited to reproduce the geometry and hydrodynamics of complex shallow water basins such as the Venice Lagoon, with its narrow channels and small islands. The model was developed starting from a previous application in the Venice Lagoon^{26,27} by updating the bathymetry in agreement with recent survey data and refining the computational grid accordingly. The lagoon model was validated against measurements and then integrated in a coherent modelling system in which the lagoon model is forced by meteorological and boundary conditions provided by other models, as commonly done in downscaling studies²⁸ (Fig. 1).

The modelling system was then validated against present data and, finally, used to project water levels, water temperature, salinity, and water residence times (WRT) at each vertex of the finite element mesh, for two future climate scenarios representing a high (RCP-8.5), and an intermediate (RCP-4.5) emissions scenario.

The analysis of the results focuses on the impacts of these scenarios and of the consequent MOSE closures on the key hydrodynamic properties of the Venice Lagoon that have potentially relevant cascading effects on ecosystem structures, functions, and services.

Model corroboration

The model responses show a good agreement with the observed physical and chemical values (0.6 and 0.7 for salinity, and 0.76 and 0.97 for water levels). The comparison against water level observations made at the 11 ISPRA monitoring stations is satisfactory in terms of both phase and intensity, with a bias of about 0.02 m, and R^2 values ranging between 0.97 and 0.98. The comparison with salinity and temperature in the 9 SAMANET stations is also good (R^2 between 0.6 and 0.7 for salinity and between 0.97 and 0.98 for temperature), and highlights the capability of the model to describe the main physical processes and water properties in all the different areas of the lagoon, but for a modest underestimation of winter temperature in two of the 9 stations. Globally the temperature bias is of about 0.5°C in the three years, and lower than that, if the two stations ve3 and ve5 are not considered. Figures 1SM, 2SM, 3SM, 4SM, and 5SM in the supplementary material depict the data model comparisons for each of the stations.

Climate projections

The climate projections were made for two climate scenarios, RCP-4.5 and RCP-8.5, with and without MOSE to assess the changes directly associated to climate and those induced by the consequent repeated closure of the lagoon inlets. A total of 5 simulations were run over a century: reference simulation Ref; RCP-45_No_Mose; RCP-4.5; RCP-8.5_No_Mose; RCP-85. Results are summarized in Fig. 2, which compares the frequency distributions of the monthly values of salinity, temperature and WRT for

the different scenarios, in Fig. 3, that shows the yearly averaged WRT maps, and in Fig. 4, giving the spatial distribution of far future monthly temperature anomalies, computed as differences between future and reference states.

The tables 3SM, 4SM and 5SM, show the basin averaged values of climate change anomalies. Table 6SM in the Supplementary Materials summarizes changes in number of closures, sea levels, residence time, temperature, and marine heat waves frequency and intensity for the different scenarios.

Closures. Adopting the procedures and sea level thresholds currently used for operating MOSE closures (see Supplementary Materials), under the RCP8.5 scenario the mobile gates are expected to be closed for 30 full days per year (8% of the total annual time) in the mid-future and 260 days (70% of the total) in the far future. Under the RCP4.5 scenario, the expected closure times are 19 days (5%) and 150 days (40%) for 2050 and 2100, respectively.

Water level in the lagoon rises in both scenarios according to the sea level rise at the inlets. The projected mean water level at the end of the century rises by 0.72 m in scenario RCP-8.5 and by 0.52 m in scenario RCP-4.5. The application of MOSE closures constrains the mean water level rise to 0.48 m in the RCP 8.5 scenario and to 0.42 m in the RCP 4.5 scenario. Note that these changes refer to the present level.

WRT WRT presents a spatial variability (Figs. 2 and 3), with lower values close to the marine boundaries and the main channels, and higher values toward the mainland. On average, water residence times will increase in the climate scenarios, in agreement with previous studies²⁴. Differences are well evident in the maps of yearly averaged WRT (Fig. 3), and in the frequency distributions of monthly WRT values computed at each grid site and month (Fig. 2). In the mid-future, the increase is not very large, but it is possible to see that WRT is slightly, but systematically, longer under RCP-8.5 than RCP-4.5, which in turn is higher than the present condition. In the far future, however, the differences become extremely large, and relevant. While in the present condition the WRT averages about 9 days, and virtually there are no monthly WRT greater than 20 days, in the RCP-8.5 far future, even without MOSE closures, about 10% of the monthly WRT are greater than 20 days and 1% exceed 30 days. However, the situation becomes even more extreme when MOSE closures are considered (red dotted line Figure D), with 37% and 12% of the monthly WRT values greater than 20 and 30 days, respectively, and almost 5% even larger than 40 days. Inspection of Fig. 3 highlights for the future a strengthening of the internal gradients between the mainland and the sea and an increase in extreme values. In the area closer to the inlets, the projected WRT future values are similar to those presently observed in the intermediate area, while the inner and more restricted area reach unprecedented values. Under the more conservative RCP-4.5 scenario the situation is less extreme, but the combination of RCP-4.5 and MOSE closures results in a situation similar to the RCP-8.5 scenarios without MOSE operations.

Salinity shows small absolute variations between present and future scenarios, in the range of few salinity points (-1.2/+ 2.4). As can be seen from Table 4SM and Figure, (A and B) the MOSE closures tend to buffer and further reduce the climate change effects on salinity.

Water temperature shows a mean increase of about 1.1°C (mid future) and 2.5°C (far future) in the RCP-4.5 scenario, but about 1.4°C (mid future) and over 5°C (far future) under RCP-8.5. The increments are even more extreme in the summer months, with spatially averaged monthly values of 8°C higher than present conditions, and even higher values in specific areas and times, and consequent significant thermal stress even for the most tolerant species. Figures 2 and 4 show a general increase of the temperature in all scenarios, higher in RCP-8.5 than RCP-4.5, but as already remarked the warming is particularly large in specific moments and areas. The MOSE closures have a limited effects on temperature, observable mainly in the areas closer to the freshwater inputs. It is worth to stress that for 4 months (June to September) the absolute value of temperature is larger than 30°C, and reaches 33°C in July and August.

Marine Heat Waves

The analysis also indicates that marine heat waves (MHW) will occur more frequently and last longer. Consistently with the definition in Hobday et al.²⁹ we identified MHW as prolonged episodes with temperatures above the 90° percentile of the climatological values ($T_{day,site}^{90th}$), defined as MHW4 events in which the temperature was larger than $T^{90th} + 4^{\circ}\text{C}$, and MHW4x4 the MHW4 lasting more than 4 days. Similarly, MHW5x5 are events 5°C warmer than T^{90th} for more than 5 days. Climatology was computed in 10 sites evenly distributed in the lagoon (the SAMANET stations), in which 18 years long time series of daily observations are available (Figs. 6SM and 7SM). Model projections for the same site are then compared to the climatologies.

The inspection of results show as the frequency and severity of heat waves is expected to dramatically increase. The four scenarios do not show large differences in projected value up to the mid future, but significantly diverge during the second half of the century, with projected changes much larger under RCP8.5 than RCP4.5, and only modest differences because of MOSE operations, which seems to lightly reduce warming.

Under the RCP8.5, at the end of the century water temperature will exceed the present day climatological 90th percentile T^{90th} in each of the 10 samanet station, for about 270 days/year (average value over the 10 stations), will be 4 degrees warmer than T^{90th} for 98 days/year, 5 degrees larger than T^{90th} for 60 days/year. Furthermore there will be an average of 10 MH4W4 and 6 MH5W5 heatwaves per year in each of the stations.

Discussion

Climate change will alter the functioning of ecosystems and significantly affect related human activities. In addition to global strategies to mitigate climate change, local adaptation measures are needed, especially along the coasts and where human activities are more concentrated. However, specific adaptation measures can be effective in mitigating impacts on some environmental features, while being less effective on others and may even have adverse cascading effects on others. Therefore, a careful and

site-specific assessment of the potential cumulative impacts of climate change and adaptation measures can be helpful in defining adaptation strategies. This is particularly true for coastal areas, as these systems often experience a range of concurrent and overlapping activities with multifaceted interdependencies on environmental properties, and for lagoons, as in semi-enclosed systems the effects of environmental changes unfold in a relatively short period of time.

Such an assessment could be even more interesting for the Venice lagoon, because of its historical, cultural, environmental, and socio-economic values and vulnerability, its century long tradition of careful environmental management, and also because the MOSE system is a relevant, much debated and first-of-its-kind adaptation measure, selected and implemented after very long and enflamed discussions.

Furthermore, coastal areas are exposed to multiple pressures and, in order to reduce the risks associated with marine hazards, sustained efforts must be made to set up observation and forecasting systems and provide stakeholders with scenario simulations to enable them to make more informed decisions.

Sharing environmental data, information and results from downscaled simulations of climate change scenarios has several advantages²⁸. First, they can help to improve our understanding of climate-related processes and complex features such as the spatial distribution of change and the temporal response of the lagoon system to change. Second, they can support the ecological and/or economic assessment of potential climate change-related hazards for specific objectives such as shellfish farming^{23,30,31}, or for conservation objectives and promote risk assessment studies³². In addition, they can provide information on adaptation strategies, such as the redefinition of uses in the lagoon, and support the definition of monitoring, regulation, and control measures³³. Finally, they can contribute to the growth of ocean literacy and promote innovative and sustainable applications for coastal solutions/services³⁴.

Here we used a coherent hierarchy of state-of-the-art models to estimate the future state of the Venice Lagoon under two climate scenarios, also considering the MOSE repeated closures specifically associated with each scenario. Downscaling experiments for the Venice Lagoon had already been conducted, but they focused mainly on the effects of changes in precipitation regime and seasonality on biogeochemical properties, without assessing the direct effects on water temperature or the consequences of sea level rise on water circulation and residence time. The lagoon model used for these studies^{22,23}, was not able to adequately account for changes in transport processes. In addition, none of the studies considered the cumulative effect of climate change and MOSE closures, i.e., the fact that climate change will also lead to an increase in the number and frequency of lagoon closures, with the corresponding consequences for physical properties. Conversely, we address these issue systematically, by conducting and analyzing the impacts of both a high and a medium climate scenario with and without MOSE. The novelty of this work therefore is that it provides the first dynamic downscaling of physical properties performed by coherently integrating a set of state-of-the-art models, validated specifically for this region, with respect to two alternative climate scenarios, and considering MOSE closures.

The model is used to calculate several variables from which we can derive environmental arrays for hazards, such as salinity, water temperature, and WRT, which are important for the characterization of lagoon habitats, their limitation, and their suitability for maintaining ecosystem structure and function, and their evolution under changing climatic forcings.

WRT is a measure that characterizes the time required for a basin to renew its waters and it is of paramount importance in shaping the characteristics of biological communities. Indeed, areas characterized by a shorter renewal time host biological communities closer to the marine communities and different from those normally found in the inner and more confined areas where the renewal time is longer¹⁹. *WRT* is also an important factor in assessing the health and sustainability of a lagoon ecosystem, as it determines the rate at which pollutants and nutrients are removed and replaced by new water. There are several slightly different indicators that can be used to assess these characteristics (e.g., residence time, renewal time, confinements, water age, see Monsen et al.³⁶ or Melaku Canu et al.³⁷ for a discussion on differences in interpretation and methodology), but in all cases the rate of water exchange is influenced by several factors, including inlet shape, tidal range, and wind regime, which all contribute to the velocity of water in the inlets and the rate of water exchange. In the case of the Venice Lagoon, also the artificial closure of the system due to MOSE operation can have a very relevant impact on *WRT*. Our results show that under the influence of climate change *WRT* in the lagoon will increase even without MOSE closures, especially in the inner area closer to the mainland. MOSE closures will exacerbate this trend and cause even higher internal gradients in *WRT*, especially in the far future RCP-8.5 scenario. From an ecological perspective, this would imply that the area classified as suitable for "inner/confined" communities will increase, while the habitat for "marine" communities will decrease, which is some ways in contrast with the process of marinization recently observed in the lagoon. However, these changes will not fully match with the expected changes in salinity, which shows little absolute variations. Furthermore, as the *WRT* changes have a seasonal component, the habitat suitability of the biological communities in the lagoon will also change with the seasons, possibly causing stress to low mobility organisms with life span longer than one season.

Water temperature shows an average increase ranging from about 2.5°C to 5°C at the end of century, depending on the climatic scenario considered, but with seasonal and spatial variability. Spatially average monthly increment for the basin can be as high as 7–8°C in the summer months, i.e temperature absolute values of 30°C and more, which already is a rather stressful conditions for even the most tolerant species, but some areas will reach even higher values, as high as 40°C. Conversely, winters will be less cold, which can also be stressful for the life cycle of some species. In general, we observe an increase in the frequency and magnitude of extreme conditions in the future scenarios. The analysis of daily model outputs for specific sites shows that intense and prolonged heat wave will occur everywhere and with increasing frequency, up to nearly year-round in the far future scenario.

The analysis of the model projections shows that the operation of the mobile barriers will lead to a further increase in *WRT* values, but to modest changes in salinity and temperature, which will be slightly higher and lower, respectively, than the values without MOSE operation.

In summary, the future of the Venice lagoon ecosystem is at risk, as in less than a century it might be exposed to unprecedented environmental condition. During the coming decades the MOSE system can buffer the effects of climate change on sea level rise, but not on temperature, and in any case at the cost of a very significant increase in the residence time of the lagoon water. MOSE can therefore protect the city of Venice from flooding for around 50 years, but not the lagoon ecosystem from global warming.

However, despite such negative outlook, it is important to emphasize that the future is not a foregone conclusion. Under the more conservative climate scenario RCP-4.5, the projected impacts in terms of temperature, sea level rise and residence time is much smaller, about half as large as under RCP-8.5. Systematic implementation of MOSE closures under RCP-4.5 will further increase water residence time, but globally the impacts appear to be much less severe than under RCP-8.5, indicating that the choice of a different emissions policy and system pathway is still possible and can be very effective.

A combination of local adaptation and global mitigation measures still seems to have the potential to save both Venice and its lagoon. But we need to be able to implement both efficiently.

The model results are freely available to enable further analysis and support a comparative ecological and/or economic assessment of the potential hazards related to climate change and water regulation.

Methods

The SHYFEM model

The SHYFEM numerical model solves the 3-D transport equations using a finite element approach for spatial discretization and a semi-implicit algorithm for temporal integration.

The model includes a hydrodynamic module for current computations, a transport module for advection and diffusion module of heat, salt, and the biogeochemically active tracers, and a radiation module for heat fluxes at the water surface. The atmospheric input data drive the computation of heat fluxes at the air-water interface, lagoon surface temperature, and wind stress. The hydrodynamic module accounts for tidal, atmospheric, and density-driven forcing, and the bottom friction follows the Strickler formulation. Vertical sub-grid turbulence effects are calculated in accordance with GOTM schemes³⁸, while the horizontal turbulent diffusion relies on the Smagorinsky (1993)³⁹ scheme. The model uses constant depth vertical levels with partial bottom cells and includes wet-and-dry processes to account for the low tides effects causing momentaneous drying of the shallowest elements of the grid. The model simulates heat and tracers transport and diffusion at each node of the high-resolution domain. More details on the model equations and their solution are given in²⁵ Umgiesser et al. (2004).

Inlet closures for the scenarios with MOSE was implemented using the approach of Melaku Canu et al. (2001)²⁶ and Umgiesser (2020)¹⁷.

The grid

The quality of the results of finite element hydrodynamic simulations is highly dependent on the precision and spatial resolution of the bathymetric information and grid design, which determines not only the local water column depth, but also information on bed roughness and the incorporation of specific structures and features that affect water and sediment transport dynamics. Bottom conditions are dynamic and can change due to natural processes and human activities. In fact, the bathymetry of the Venice lagoon is subject to constant modifications due to canals dredging, natural erosion and sediment deposition, changing not only the water depth but changing the borders of the basin as well.

The simulations were performed with a new and improved grid, to consider the recent evolution of the lagoon morphological properties, including those related to MOSE construction. The grid (Fig. 1) was built merging recent survey data ⁴⁰ and the bathymetries of previous versions ^{41, 25, 27}. It is formed by 6017 nodes and 10407 elements, with an increase of about 32% of the number of cells with respect to the previous version. It features the addition of few channels, increased resolution in relevant shallow areas, and the update of the element's depths and of the coastline. The spatial resolution varies from about 10 meters to 300 meters.

Validation and set up for the lagoon model and for the climate simulations

The Lagoon model was validated by performing 3 one year long simulations (2005, 2008, 2009) forced by observed values of meteorological forcing (wind, air temperature, precipitations, short and long term irradiance), rivers input, and boundary conditions at the 3 inlets, and comparing model output to observations of temperature, salinity and water level collected within the lagoon (Fig. 2, right).

The 3 years were chosen because they are representative of different observed conditions, and because for those years it was possible to reconstruct a coherent and complete model set up (i.e. set of forcing, boundary conditions, observed values). The comparison data set was obtained from the local monitoring agencies: water levels values are monitored by the ISPRA Ambiente (<https://www.venezia.isprambiente.it/>) at 11 tide gauge stations indicated in Fig. 1 at a frequency of 10 minutes. Salinity and water temperature measures of the years 2002–2019 are monitored by the SAMANET Network at high frequency (30 minutes) (<http://solve.corila.it/>).

The simulation for the future climate scenarios were performed -, as in all downscaling experiment^{22, 28} by a modelling system in which the lagoon model is forced by output from other models (Fig. 2, left).

In our application, meteorological forcings were obtained by a high resolution regional climate model, COSMO CLM ^{42,43} run at 8 km (0.0715°) resolution, for dynamical downscaling of global climate simulations over the Italian peninsula, in turn, nested in the regional climate model run over the Mediterranean basin CMCC-CM.

Salinity and temperature at the inlets were derived from existing runs of the regional model of the Mediterranean Sea, CMCC-MFS16-NEMO (<https://dds.cmcc.it/#/dataset/medsea-cmip5-projections-physics>, Lovato, 2022), forced by the same CMCC-CM Mediterranean model runs, for the two scenarios

RCP-4.5 and 8.5, after correcting for the bias computed by comparing model projection at the lagoon inlets for the 2019 with field observation^{28, 45, 46}. Sea level at the inlets was calculated by a linear interpolation between the present level and the median values of an ensembles of projections provided by an ensemble of models, namely an increase of 0.71 m for the year 2100 under the RCP-8.5 scenario²¹ and an increase of 0.52 m by 2100 for the RCP-4.5 scenario (AR6 IPCC ensemble⁴⁷).

River inputs were estimates as simple linear regression as a function of the projected rain volume, as in previous downscaling experiments for the lagoon^{8,22, 23, 28}.

Finally, the regulation strategy of MOSE closure was introduced following the procedure described in the MOSE operational guide and currently applied: every time that a tidal peak higher than 110 cm would have been reached, the closure was applied, by anticipating the incoming tide and preventing the sea level to rise above 90 cm during the considered tidal cycle. Reopening was set as soon as the decreasing tide would reach again the 90 cm threshold.

Figure 2 (left) illustrates the links among different models providing forcing to the lagoon model in the climate downscaling application to the Venice Lagoon.

The model setups for the validation and the climate simulations are summarized in Supplementary Material, Table 1SM, which lists the sources of the inputs and forcings used in the simulations, and in Table 2SM, which contains a list of the simulations.

Three reference simulations for the years 2005, 2008 and 2019, characterized by different meteorological forcing conditions, were performed to test the model agreement with the measurements.

The model was then used to represent the two selected climate scenarios, RCP-4.5 and RCP-8.5, at Mid-Future (year 2050) and Far-Future (year 2100) with and without MOSE closures

Water residence times (WRT) were computed following³⁷ Canu et al. (2012). To ensure the representativeness of the actual yearly conditions, and to reduce the effect of the tidal and meteorological conditions on the results, yearly mean WRT were computed by averaging over a set of 365 WRT fields, obtained by performing 365 simulations, each simulation starting in a different day and carried on for 30 days, a time interval long enough to ensure that the computational algorithm converge to stationary value for each of the lagoon area, and known to be longer than the present time WRT of any lagoon area. Monthly means WRT were computed also, for each of the 12 months.

Declarations

Acknowledgments:

This research activity was performed with the contribution of: Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia, provided through the concessionary of State

Consorzio Venezia Nuova and coordinated by CORILA (Venezia2021 project); the Italian National Biodiversity Future Center NFMF, project CN_00000033, the Danubius-RI research infrastructure ESFRI.

Data repository: DOI

Monthly averages fields of Temperature, Salinity water levels, WRT for the 4 simulations (4.5, 8.5 4.5_CLOSE 8.5_CLOSE) are shared in <https://doi.org/10.5281/zenodo.10276293>

Author Contribution

DMC and CS conceived the study, and defined the experimental design. CL, LA, GR and DMC produced the model set-up performed the simulations. All coauthors discussed the results. DMC and CS wrote the manuscript with contribution from all coauthors

Competing Interest

Authors declare no competing interest

References

1. Ammerman A. J.-McClenenn C. E., Saving Venice, Science, 289 2000
2. Loud Del Bello, Venice anti-flood gates could wreck lagoon ecosystem. Nature 564, 16 (2018)
3. Erik Stokstad, Venice's barrier against rising seas could jeopardize city's ecosystem Science 2021
4. Solidoro C., Bandelj V., Aubry Bernardi F., Camatti E., Ciavatta S., Cossarini G., Facca C., Franzoi P., Libralato S., Melaku Canu D., Pastres R., Pranovi F., Raicevich S., Socal G., Sfriso A., Sigovini M., Tagliapietra D., Torricelli P. 2010. Response of the Venice Lagoon Ecosystem to Natural and Anthropogenic Pressures over the last 50 years. In Coastal lagoons: critical habitats of environmental change. M. J. Kennish, H. W. Paerl Edit. pp. 483-512
5. Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Oceans and Coastal Ecosystems and Their Services. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550, doi:10.1017/9781009325844.005.
6. Giorgi F. 2006. Climate change hot-spots. Geophysical Research Letters, Vol. 33, L08707, doi:10.1029/2006GL025734.
7. Tuel A, Eltahir EAB (2020) Why is the Mediterranean a Climate Change Hotspot? Journal of Climate. 5829–5843. DOI: <https://doi.org/10.1175/JCLI-D-19-0910.1>
8. Cossarini G, Libralato S, Salon S, Gao X, Giorgi F, Solidoro C (2008) Downscaling experiment for the Venice lagoon. II. Effects of changes in precipitation on biogeochemical properties. Clim Res 38:45–

9. Lamon L., Rizzi J., Dubois C., Lazzari P., Ghenim L., Gana S., Somot S., Li L., Melaku Canu D., Solidoro C., Pinardi N., Marcomini A. 2013 An ensemble of models for identifying climate change scenarios in the Gulf of Gabes, Tunisia. 2013. *Regional Environmental Change* , 14 (SUPPL.1), pp. 31-40.
10. Kwiatkowski, L., Torres, O., Bopp, L., Aumont, O., Chamberlain, M., Christian, J. R., Dunne, J. P., Gehlen, M., Ilyina, T., John, J. G., Lenton, A., Li, H., Lovenduski, N. S., Orr, J. C., Palmieri, J., Santana-Falcón, Y., Schwinger, J., Séférian, R., Stock, C. A., Tagliabue, A., Takano, Y., Tjiputra, J., Toyama, K., Tsujino, H., Watanabe, M., Yamamoto, A., Yool, A., and Ziehn, T.: Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections, *Biogeosciences*, 17, 3439–3470, <https://doi.org/10.5194/bg-17-3439-2020>, 2020.
11. IPBES The regional assessment report on biodiversity and ecosystem services for Europe and central Asia. (2018)
12. Zunino S., Libralato S., Melaku Canu D. Solidoro C. 2021. Impact of Ocean Acidification on Ecosystem Functioning and Services in Habitat-Forming Species and Marine Ecosystems. *Ecosystems*.
13. Melaku Canu D., Ghermandi A., Nunes PaL.D., Lazzari P., Cossarini G., Solidoro C., 2015. Estimating the value of carbon sequestration ecosystem services in the Mediterranean sea: an ecological economics approach. *Global Environmental Change*. Volume 32, 1 May 2015, Pages 87-95
14. Gattuso, J.-P.J., Magnan, A., Bille, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., 2015. Contrasting futures for ocean and society from different anthropogenic CO₂emissions scenarios. *Science* 80. <https://doi.org/10.1126/science.aac4722>.
15. Zunino, S., Canu, D.M., Zupo, V., Solidoro, C. 2019. Direct and indirect impacts of marine acidification on the ecosystem services provided by coralligenous reefs and seagrass systems. *Global Ecology and Conservation*. Vol. 18 Article number: 00625.
16. Newton A., Brito Ana C., Icely John D, Derolez V., Clara I., Angus S., Schernewski G., Inacio M., Lillebø A.I., Sousa A.I., Bejaoui B., Solidoro C. Tosić M., Canedo-Arg M., Yamamuro M., Reizopoulou S., Tseng H.S, Melaku Canu D., Roselli L., Maanan M., Cristina S., A.C. Ruiz-Fernandez, Lima R., Kjerfve B., Rubio-Cisneros N., Perez-Ruzafa A., Marcos C., Pastres R., Pranovi F., Snoussi M., Turpie J., Tuchkovenko J., Dyack B., Brookes J., Povilanskas R., Khokhlov V. 2018. *Journal for Nature Conservation*. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. 44: 50,65. <https://doi.org/10.1016/j.jnc.2018.02.009>.
17. Umgiesser G. 2020. The impact of operating the mobile barriers in Venice (MOSE) under climate change. *Journal for Nature Conservation*. 54. 2020 125783.
18. Bandelj V, Solidoro C, Curiel D, Cossarini G, Melaku Canu D, et al. (2012) Fuzziness and Heterogeneity of Benthic Metacommunities in a Complex Transitional System. *PLoS ONE* 7(12): e52395. doi:10.1371/journal.pone.0052395

19. Guélorget, O., and J. P. Perthuisot. 1992. Paralic ecosystems. Biological organization and functioning. *Vie et milieu* 42:215-251.
20. Mc Lusky, D., and Elliot M. 2004. *The Estuarine Ecosystem. Ecology, threats and management.* Oxford University Press.
21. Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., Antonioli, F., Artale, V., Carminati, E., Ferrarin, C., Fofonova, V., Nicholls, R. J., Rubinetti, S., Rubino, A., Sannino, G., Spada, G., Thiéblemont, R., Tsimplis, M., Umgiesser, G., Vignudelli, S., Wöppelmann, G., and Zerbini, S.: Sea-level rise in Venice: historic and future trends (review article), *Nat. Hazards Earth Syst. Sci.*, 21, 2643–2678, <https://doi.org/10.5194/nhess-21-2643-2021>, 2021.
22. Salon S, Cossarini G, Libralato S, Gao X, Solidoro C, Giorgi F. (2008) Downscaling experiment for the Venice lagoon. I. Validation of the present-day precipitation climatology. *Clim Res* 38:31–41
23. Melaku Canu D, Solidoro C, Cossarini G, Giorgi F.. 2010 Effect of global change on bivalve rearing activity and the need for adaptive management. *Climate Research* 2010, Vol42:13-26. Melaku Canu, D., Solidoro, C., Umgiesser, G., 2003. Modelling the responses of the lagoon of Venice ecosystem to physical forcings variations *Ecological Modelling*, Volume 170, Issues 2–3, 15 pp. 265-289
24. Ferrarin, C., M. Bajo, D. Bellafore, A.Cucco, F. DePascalis, M. Ghezzi, and G. Umgiesser (2014), Toward homogenization of Mediterranean lagoons and their loss of hydrodiversity, *Geophys. Res. Lett.*, 41, 5935–5941, doi:10.1002/2014GL060843.
25. Umgiesser G., Melaku Canu D., Cucco A., Solidoro C. 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation *Journal of Marine Systems*, Volume 51, Issues 1-4, pp. 123-145
26. Melaku Canu, D., Umgiesser, G., Solidoro, C., 2001. Short term simulations under winter conditions in the lagoon of Venice: a contribution to the environmental impact assessment of a temporary closure of the inlets. *Ecological Modelling* 138 (1–3), 215–230.
27. Solidoro, C., Melaku Canu, D., Cucco, A., Umgiesser, G., 2004. A partition of the Venice Lagoon based on physical properties and analysis of general circulation. *Journal of Marine Systems*, Volume 51, Issues 1-4 pp. 147-160
28. Solidoro C, Cossarini G, Libralato S, Salon S (2010b) Remarks on the redefinition of system boundaries and model parameterization for downscaling experiments. *Prog Oceanogr* 84:134–137
29. Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., et al. (2016). A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* 141, 227–238. doi: 10.1016/j.pocean.2015.12.014
30. Bertolini, C., Pastres, R., 2021. Tolerance landscapes can be used to predict species-specific responses to climate change beyond the marine heatwave concept: using tolerance landscape models for an ecologically meaningful classification of extreme climate events. *Estuar. Coast Shelf Sci.* 252, 107284 <https://doi.org/10.1016/j.ecss.2021.107284>.
31. Bertolini C., D. Glaser, M. Canu, R. Pastres, Coupling habitat-specific temperature scenarios with tolerance landscape to predict the impacts of climate change on farmed bivalves, *Marine*

32. Furlan E, Torresan S, Critto A, Lovato T, Solidoro C, Lazzari P, Marcomini A. Cumulative Impact Index for the Adriatic Sea: Accounting for interactions among climate and anthropogenic pressures. *Sci Total Environ.* 2019 Jun 20;670:379-397. doi: 10.1016/j.scitotenv.2019.03.021. Epub 2019 Mar 3. PMID: 30904652.
33. Solidoro C.. 2021. Observing ocean state and marine life *Bull. Geophysics Oceanography* 62 (3), 79-85.
34. McKinley E., D. Burdon, R.J. Shellock, The evolution of ocean literacy: A new framework for the United Nations Ocean Decade and beyond, *Marine Pollution Bulletin*, Volume 186, 2023, 114467, ISSN 0025-326X, <https://doi.org/10.1016/j.marpolbul.2022.114467>.
35. Cucco, A., G. Umgiesser, C. Ferrarin, A. Perilli, D. M. Canu, and C. Solidoro (2009), Eulerian and lagrangian transport time scales of a tidal active coastal basin, *Ecol. Modell.*, 220, 913–922, doi:10.1016/j.ecolmodel.2009.01.008.
36. Monsen, N.E., Cloern, J.E., Lucas, L.V., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. *Limnol. Oceanogr.* 47 (5), 1545–1553.
37. Melaku Canu, D., C. Solidoro, G. Umgiesser, A. Cucco, and C. Ferrarin (2012), Assessing confinement in coastal lagoons, *Mar. Pollut. Bull.*, 64(11), 2391–2398, doi:10.1016/j.marpolbul.2012.08.007.
38. Umlauf L., Burchard H., Second-order turbulence closure models for geophysical boundary layers. A review of recent work, *Continental Shelf Research*, Volume 25, Issues 7–8, 2005, Pages 795-827, ISSN 0278-4343,
39. Smagorinsky J. 1993. Some historical remarks on the use of non-linear viscosities - 1.1 Introductory remarks. In B. Galperin and S. A. Orszag, editor, *Large Eddy Simulation of Complex Engineering and Geophysical Flows*, Proceedings of an International Workshop in Large Eddy Simulation, pages 1–32. Cambridge University Press, Cambridge, UK, 1993.
40. Madricardo, F., F. Foglini, A. Kruss, C. Ferrarin, N.M. Pizzeghello, C. Murri, M. Rossi, M. Bajo, D. Bellafore, E. Campiani, S. Fogarin, V. Grande, L. Janowski, E. Keppel, E. Leidi, G. Lorenzetti, F. Maicu, V. Maselli, A. Mercorella, G. Montereale Gavazzi, T. Minuzzo, C. Pellegrini, A. Petrizzo, M. Prampolini, A. Remia, F. Rizzetto, M. Rovere, A. Sarretta, M. Sigovini, L. Sinapi, G. Umgiesser, and F. Trincardi, 2017, High resolution multibeam and hydrodynamic datasets of tidal channels and inlets of the Venice Lagoon, *Sci. Data*, 4, 170121-, doi: 10.1038/sdata.2017.121.
41. Melaku Canu, D., Solidoro, C., Umgiesser, G., 2003. Modelling the responses of the lagoon of Venice ecosystem to physical forcings variations • *Ecological Modelling*, Volume 170, Issues 2–3, 15 pp. 265-289
42. Bucchignani, E., Montesarchio, M., Zollo, A. L., & Mercogliano, P. (2016). High-resolution climate simulations with COSMO-CLM over Italy: performance evaluation and climate projections for the 21st century. *International Journal of Climatology*, 36(2), 735-756.
43. Zollo, A. L., Rillo, V., Bucchignani, E., Montesarchio, M., & Mercogliano, P. (2016). Extreme temperature and precipitation events over Italy: assessment of high-resolution simulations with COSMO-CLM and

future scenarios. International Journal of Climatology, 36(2), 987-1004.

44. Lovato, T., Peano, D., Butenschön, M., Materia, S., Iovino, D., Scoccimarro, E., et al. (2022). CMIP6 simulations with the CMCC Earth System Model (CMCC-ESM2). Journal of Advances in Modeling Earth Systems, 14, e2021MS002814. <https://doi.org/10.1029/2021MS002814>
45. Reale M.; Cossarini G.; Lazzari P.; Lovato T.; Bolzon G.; Masina S.; Solidoro C.; Salon S. Acidification, deoxygenation, and nutrient and biomass declines in a warming Mediterranean Sea. Biogeosciences 1917 4035 4065 30, 3, 10.5194/bg-19-4035-2022
46. Solidoro C.; Cossarini G.; Lazzari P.; Galli G.; Bolzon G.; Somot S.; Salon S. Modeling Carbon Budgets and Acidification in the Mediterranean Sea Ecosystem Under Contemporary and Future Climate. Frontiers in Marine Science 8, 781522, 3 10.3389/fmars.2021.781522
47. Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A., and Yu, Y.: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B. (eds.)]. Cambridge University Press. In 970 Press. 2021

Figures

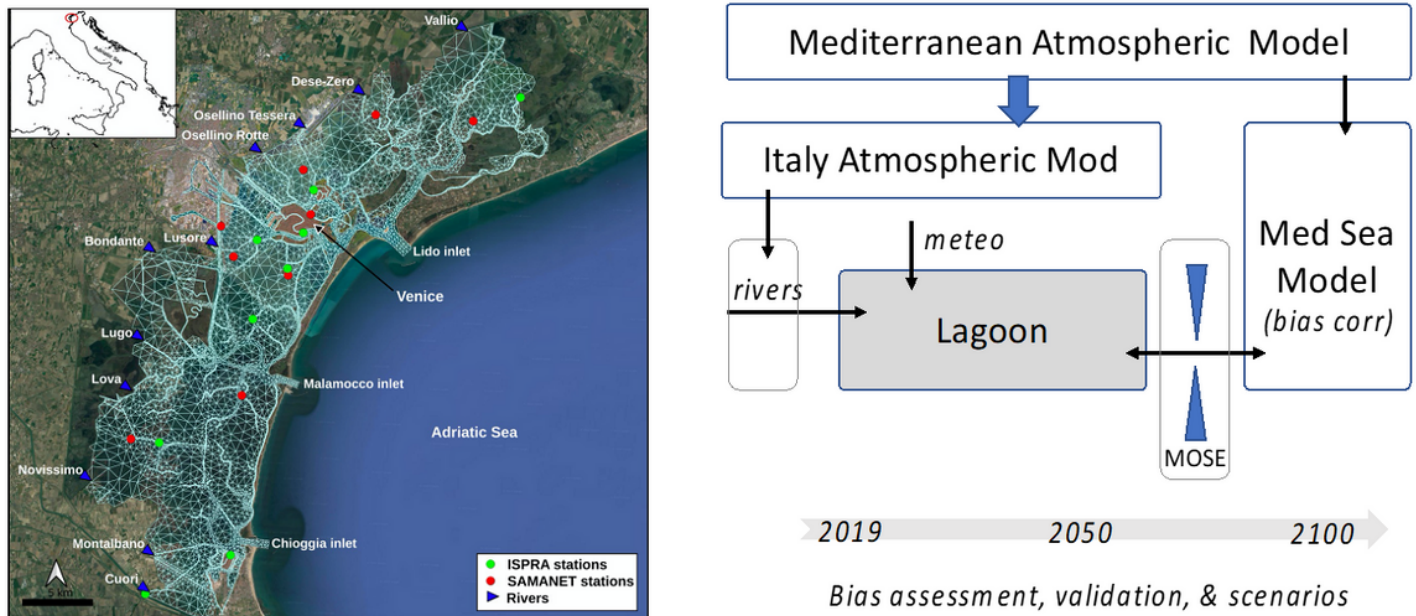


Figure 1

The computational grid of the Venice lagoon model (left) and the model system used for downscaling of the Future Climate Scenarios (right), including the MOSE closures.

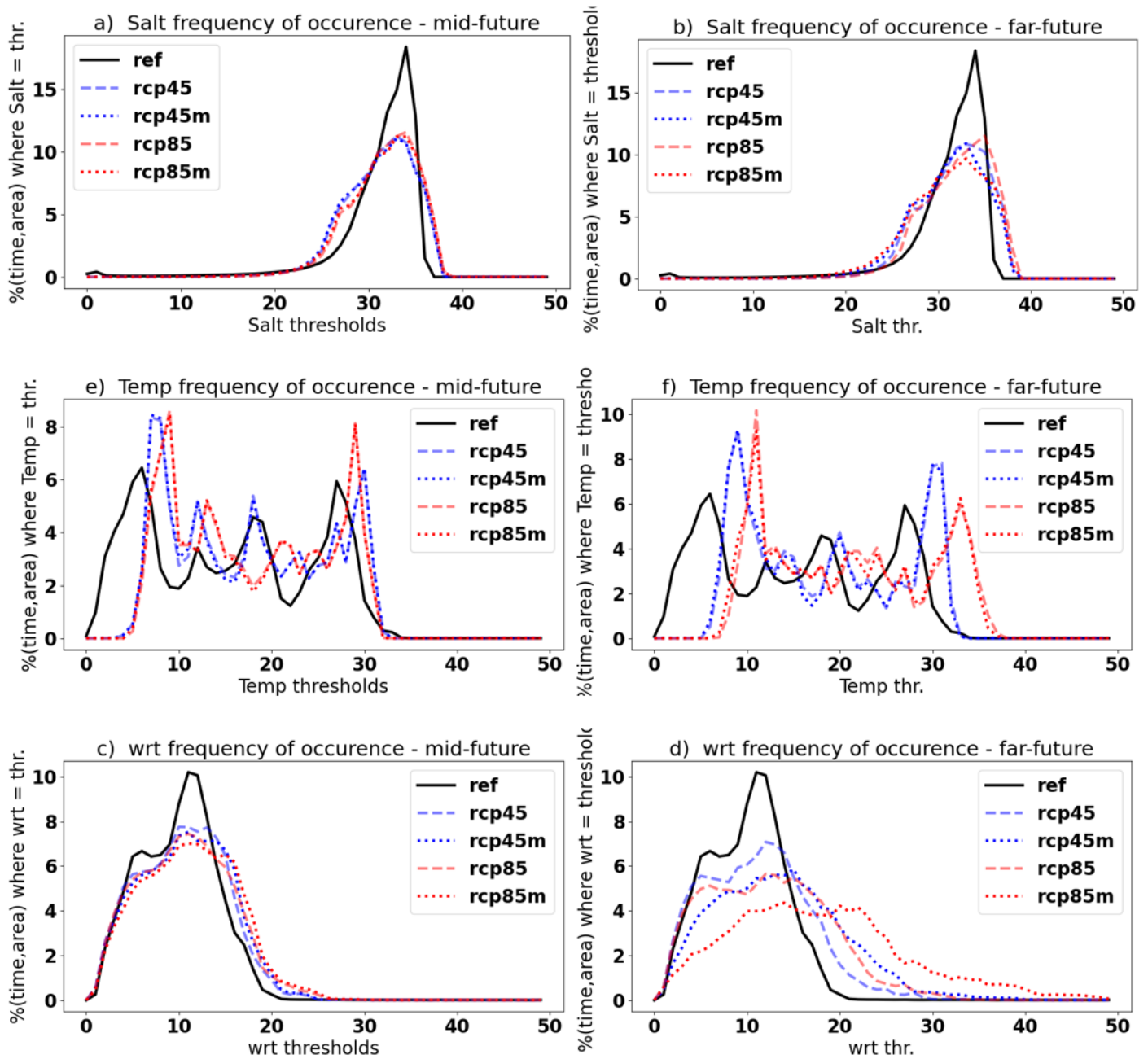


Figure 2

Comparison of frequency distributions of lagoon water variables salinity (top row), WRT (bottom row), and temperature (middle ear) for climate change (RCP-4.5 and RCP-8.5) and water regulation (without and with water regulation 'm') scenarios in the mid-future (left column) and far-future (right column).

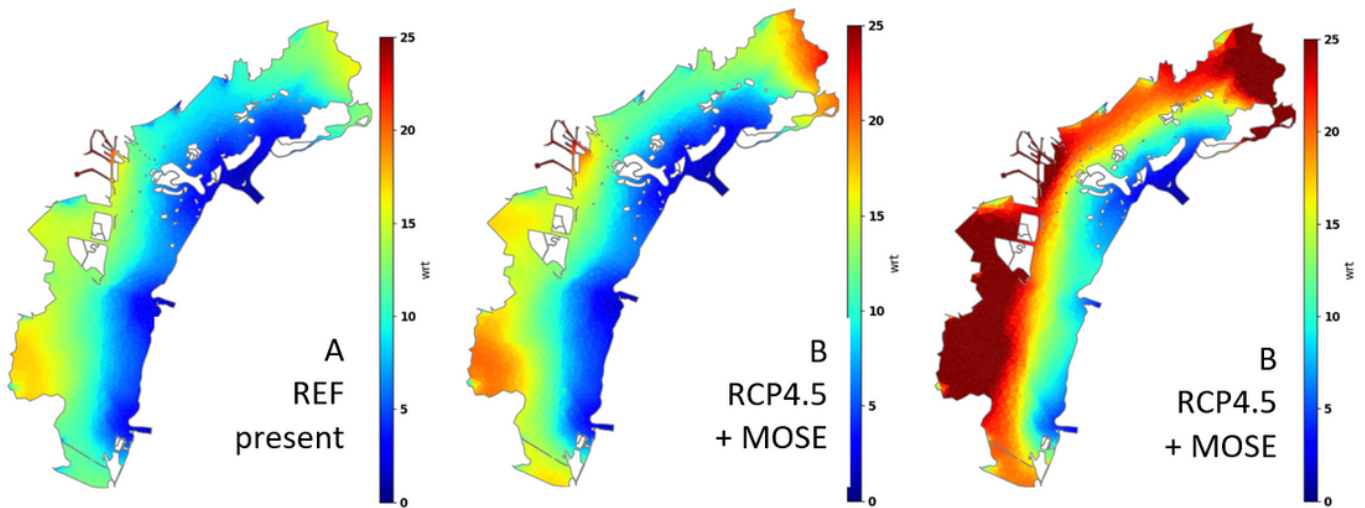


Figure 3

Average water residence time (WRT) calculated for present condition (A) and for the year 2100 for the RCP-4.5 (B), and RCP-8.5 (C), with MOSE closures associated to each scenario

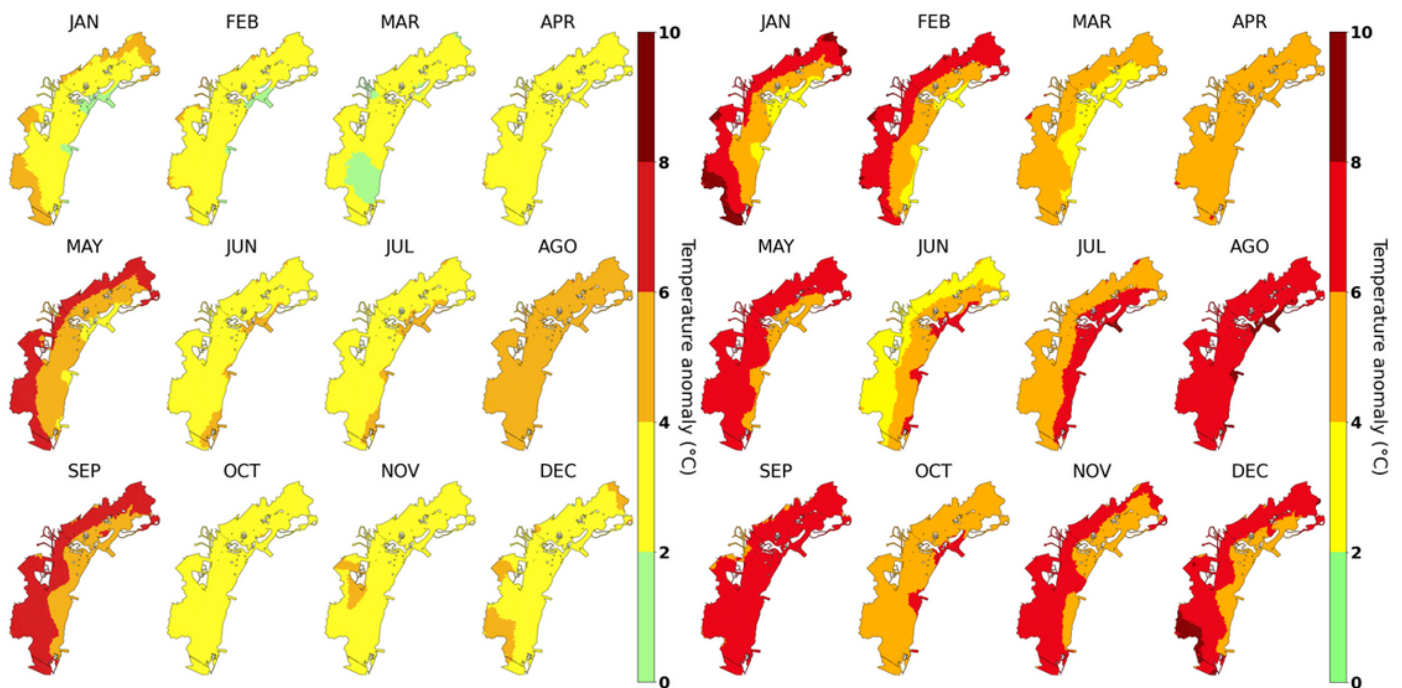


Figure 4

Lagoon monthly water temperature anomalies in respect to reference scenario under the far-future RCP-4.5 and RCP-8.5 climate scenarios.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SMVeniceMOSEClimatescenariosubm.docx](#)