Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate

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1. Technical references

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3. ABSTRACT

The Northern Adriatic region and the Orbetello lagoon, although limited in size with respect to the Mediterranean region, perfectly summarize the complexity often observed in the area. They are in fact characterized by complex land-distribution, by the presence of several important human and industrial settlements, high biodiversity and several hot-spots for fisheries, significant air-sea interaction and freshwater input from the inland. Due to the complexities of the areas under investigation, a proper assessment of the future evolution of the climate and marine ecosystems of the regions under different emission scenarios requires the adoption of modeling tools with a fine spatial resolution (both vertical and horizontal) that consider and solve the interaction among the different compartments of the climate system.

In this task, we introduce newly developed configurations of state-of-the-art climate and biogeochemical modeling tools able to simulate the dynamics of the atmosphere, rivers, ocean and marine ecosystems of the Northern Adriatic region and Orbetello lagoon.

The newly climate and biogeochemical projections dataset produced for the Northern Adriatic region shows a significant warming in the area of both inland and ocean compartments. Moreover, climate simulations project drier conditions over the region, lower river discharges as well as a dramatic increase in the intensity of the rainy events, in particular in the coastal areas between Veneto and Friuli Venezia Giulia. The remarkable warming of the region will also affect the marine ecosystem dynamics: the high-resolution projections of the Northern Adriatic biogeochemistry shows in the future a significant deoxygenation, acidification and decline in the phosphate content of the euphotic layer of the basin. On the other hand, an increase in the nitrate concentration has been observed in some areas of the basin like the Gulf of Trieste, probably related to the changes in local circulation.

For the Orbetello lagoon, the model shows interesting capabilities of describing, with high temporal and spatial resolution, the evolution of key parameters related to the lagoon's trophic state and it is proposed as a decision support tool for lagoon management under climate change conditions.

As already observed on the Mediterranean scale, climate change will dramatically affect the coastal areas and lagoons with significant effects on marine ecosystems and, possibly, on related ecosystem services.

4. List of Figures

5. High resolution modeling tools for coastal regions and open ocean areas

5.1 The Northern Adriatic region and the Orbetello lagoon (OGS, UNIFI)

5.1.1 Introduction

Coastal and open ocean areas of the Mediterranean Sea are experiencing significant changes such as warming, eutrophication, deoxygenation and acidification (MedECC, 2020; IPCC, 2022).

Although relatively small within the context of the Mediterranean, the Northern Adriatic region and the Orbetello Lagoon encompass the area's characteristic environmental complexity. Both systems feature intricate land–sea configurations, substantial urban and industrial development, high biodiversity and key fisheries hotspots, and are strongly shaped by pronounced air–sea interactions and freshwater inputs from inland. Moreover, the Northern Adriatic region is widely identified as a regional hot-spot for climate change in the Mediterranean area since climate projections have shown significant warming and increase in the intensity of the precipitation events over the region in the future (Lazoglou et al., 2024).

Due to the complexities of the areas under investigation, a proper assessment of the future evolution of the climate and marine ecosystems of the regions under different emission scenarios requires the adoption of modeling tools with a fine spatial resolution (both vertical and horizontal) that consider and solve the interaction among the different compartments of the climate system.

In this task, we introduce newly developed configurations of state-of-the-art climate and biogeochemical modeling tools able to simulate the dynamics of the atmosphere, rivers, ocean and marine ecosystems for the Northern Adriatic region and Orbetello lagoon. Moreover, we show some results of the analysis of the hindcasts and climate projections for the inland and ocean compartments that have been produced by using these modeling tools (see section 5.1.3).

5.1.2 The Northern Adriatic Sea and the Orbetello Lagoon

The Northern Adriatic region is a continental area formed by part of Northern East Italy and part of Croatia and Slovenia surrounding a relatively shallow basin, namely the Northern Adriatic Sea. The area is characterized by strong environmental gradients due to the complex orography surrounding the basin, the presence of strong air-sea interactions, and deep-water formation processes associated with Bora wind episodes in the Northern Adriatic Sea. Moreover, the presence of the Northern Adriatic Sea significantly affects the location and magnitude of several weather events (Miglietta and

Davolio, 2024). Both physical and biogeochemical dynamics of the coastal areas of the basin are strongly influenced by the presence of the Po river that is one of the major sources of freshwater and nutrients in the Mediterranean Sea. Moreover, the basin is characterized by the presence of coastal lagoons, such as the Venice Lagoon and the Marano-Grado Lagoon, which offer nursery and refuge area for several marine organisms and seabirds, thus supporting lively ecosystems. In the framework of the Return project the Northern Adriatic has been identified as Proof-of-Concept by Spoke 8 WP2 (Figure 1, red box in the left panel).

The Orbetello Lagoon (Figure 1, right panel) consists of two partially connected coastal brackish basins, known as the Ponente Basin (to the northwest) and the Levante Basin (to the southeast), with a total surface area of approximately 27 km². The lagoon is heavily exploited for the extensive farming of euryhaline species, which constitutes the area's most important economic resource (Lenzi, 1992, Cocchi et al, 2005; Lenzi et al., 2003). Three artificial inlets, each about 2 km long, connect the lagoon to the sea: Nassa and Fibbia inlets in the Ponente Basin and Ansedonia inlet in the Levante Basin (Figure 1, right panel). These inlets have a limited cross-sectional area relative to the total volume of the lagoon (15-25 m in width and 1.3-1.8 m in depth), and are partially obstructed by grates, gates, and fish traps that fully occupy some of their cross sections, used for fishing activities. As a result, water exchange with the sea is limited and strongly influenced by wind direction and water level variations due to large-scale atmospheric phenomena. To enhance water renewal, two pumping stations are typically activated during spring and summer to increase seawater inflow from the Nassa and Fibbia inlets (in the Ponente Basin), leaving the Ansedonia inlet in the Levante Basin as the only outflow point (Zannella et al., 2025).

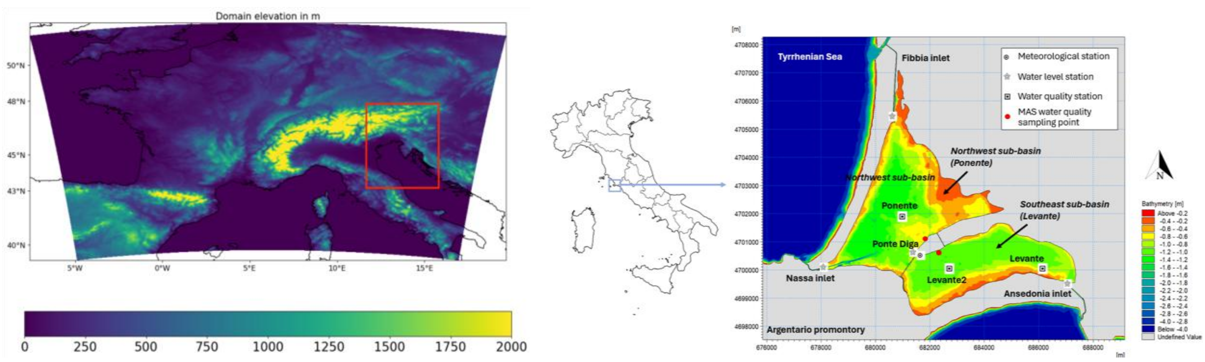


Figure 1- The Northern Adriatic region (red box, left panel) and the Orbetello lagoon (panel on the right), with topography and bathymetry (in m), location and naming conventions for measuring stations.

5.1.3 Modelling approaches

In this task we developed a series of high-resolution configurations for several climate and biogeochemical modeling tools that have been then used to produce hindcasts and climate projections datasets for the Northern Adriatic region and the Orbetello lagoon. For both areas, these configurations come from the synergistic efforts within the Return project among participants of the spoke VS4 and between spoke VS4 and DS8, in collaboration with the PNRR project TeRABIT and the computational resources of the ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing – Spoke 4 Earth and Climate.

In particular here we considered for the Northern Adriatic region:

- the Regional Climate Model RegCM v5 (hereafter $RegCM5_{std}$, Giorgi et al., 2023) with a horizontal resolution of 3 km and 41 vertical levels (convection permitting). Furthermore, the model adopts CLMU as an urban climate model. The model has been employed to produce convection permitting hindcast for the period 1987-2020 by using ERA5 as initial and boundary conditions and climate projections for three 10-years windows (under emission scenarios SSP3-7.0) corresponding timely to three different levels of Global warming (GLW), namely 1.5°C (2005-2014, present climate), 3°C (2053-2062) and 4°C (2072-2081). For the latter initial and boundary conditions derive from a previous downscaling at 12 km of the CMIP6 model EC-EARTH3-Veg (Doescher et al., 2022; also produced by $RegCM5_{std}$).
- the Cetemps Hydrological Model CHyM (hereafter $CHyM_{std}$, Coppola et al., 2007) with a horizontal resolution of approximately 1 km. The model has been employed to produce high-resolution hindcasts and climate projections for the same GLWs windows considered before by using as input the total runoff from $RegCM5_{std}$.
- The ocean-biogeochemical model $MITgcm_{STD}$-BFM (Cossarini et al., 2017; Marshall et al., 1997 a,b; Vichi et al., 2023) with a horizontal resolution of approximately 700 m and 27 vertical levels. The model has been employed to simulate the dynamics of the basin in two 10-years windows (1995-2005 and 2041-2050) under RCP8.5 emission scenario. The $MITgcm_{STD}$-BFM is forced offline by precomputing fields derived from a previous downscaling of the CMIP5 HadGEM2-ES model (Jones et al., 2011) made by using RegCM v4.7 in convection permitting configuration (Pichelli et al., 2021). Initial and Boundary conditions for the ocean physics and biogeochemistry have been derived from Reale et al., (2022).

- the Regional Earth System Model RegCM-ES (Reale et al., 2020) that uses RegCM5 (Giorgi et al., 2023) with a horizontal resolution of 3 km and 41 vertical levels (convection permitting), CHyM (Coppola et al., 2007) with a horizontal resolution of approximately 1 km and MITgcm (Marshall et al., 1997a,b) with a horizontal resolution of approximately 700 m and 59 vertical levels. The modeling tool has been used to produce an hindcast for the period 1987-2003 by using as initial and boundary conditions ERA5 for the atmosphere and Copernicus Marine Service Physical Reanalysis for the ocean compartment.

For the Orbetello lagoon, models from the MIKE suite developed by the Danish Hydraulic Institute (DHI) were used (Li et al, 2024). The model solves the fully nonlinear depth-averaged shallow-water equations and includes simulations of the operation of the pumping systems installed at each inlet and heat exchange processes between the lagoon and the atmosphere. It employs an unstructured grid composed of triangular and quadrangular elements with sizes ranging from 2 m to 250 m, to accurately discretize the lagoon inlets while keeping computational time to acceptable values. Regarding the ecological component, the model uses twenty-five state variables to describe the nutrient cycle, the growth and decay of phytoplankton, zooplankton, and detritus, rooted vegetation, and macroalgae, as well as the nitrogen and phosphorus cycles in sediments, all through mass balance equations. The model also simulates dissolved oxygen (DO) dynamics. As boundary conditions the model uses the hourly value of solar radiation, wind from meteorological station, hourly water levels, temperature, and salinity data extracted from the Mediterranean Sea Physics Analysis and Forecast database of Copernicus Monitoring Environment Marine Service (CMEMS) (Clementi et al., 2021). The marine-coastal waters (MAR) database (with sampling points MAR-SS, MAR-AL, MAR-AS) of the Environmental Information System of the Tuscany Region (SIRA-ARPAT, n.d.) was the main source of data for providing initial and boundary conditions to the ecological model (for phytoplankton, chlorophyll-a, inorganic nitrogen, inorganic phosphorus, DO).

5.1.4 Results

The advantages of using a high-resolution modeling tool for the Northern Adriatic region is clearly shown in Figure 2. The figure shows the simulated 2 temperature and wind field at 10 m in two rather (from a meteorological point of view) extreme situations: the cold wave of February 2012 (left panel) and the heatwave of August 2003 (right panel). The high resolution of the modeling tool allows for example to detect the stripes over the marine waters associated with the Bora wind flowing over the Northern Adriatic Sea or the anomalous 2m temperatures in the Po Valley associated with the heatwave.

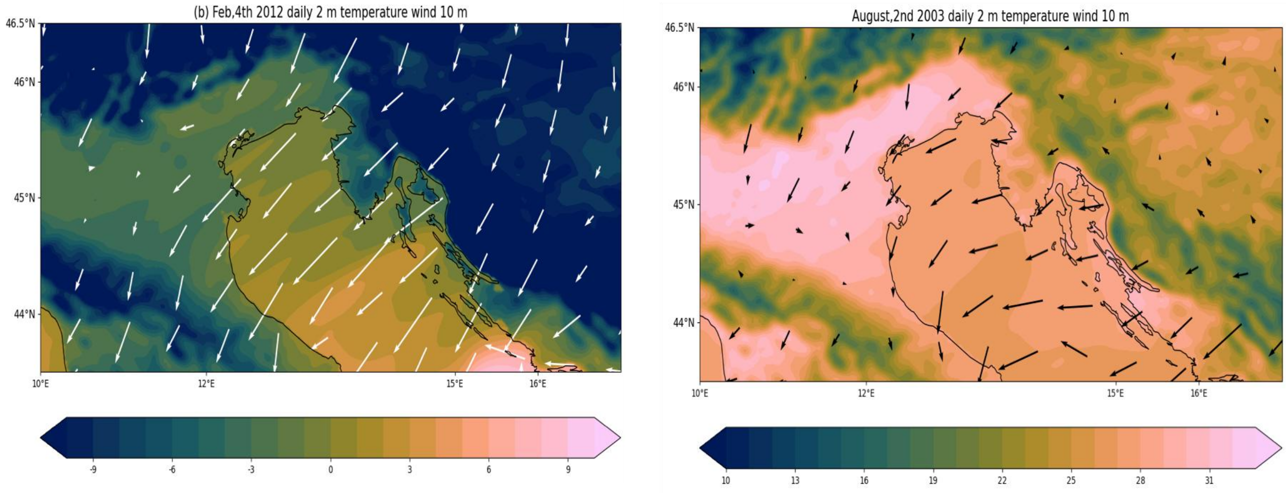


Figure 2- Simulated by RegCM5$_{STD}$ 2 m Temperature (in °C) and 10 m wind fields (in m/s) on February, 4th 2012 (left panel) and August, 2nd 2003 (right panel). Initial and boundary conditions come from ERA5.

On the other hand, Figure 3 shows the simulated 2 m in the present climate (GLW1.5, left panel) during the summer season and the projected changes in the GLW3 (central panel) and GLW4 (right panel) under emission scenario SSP3-7.0. In the present climate RegCM5$_{std}$ captures well the spatial pattern of the temperature in the region with the clear signature of the presence of the mountains: colder/warmer over the mountains/in the Po Valley. As expected, with the increase of the GLW values the simulations show a dramatic warming of the area. In particular, the Po valley will be experiencing an increase of the temperature of about 4-5 °C with a peak in the areas between Italy and Slovenia and in the coastal areas of Croatia.

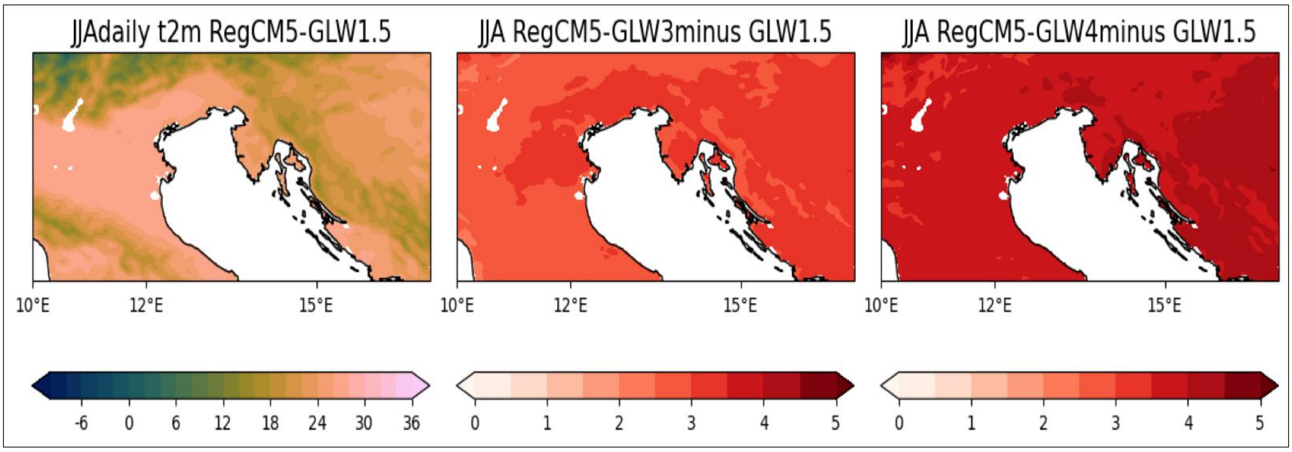
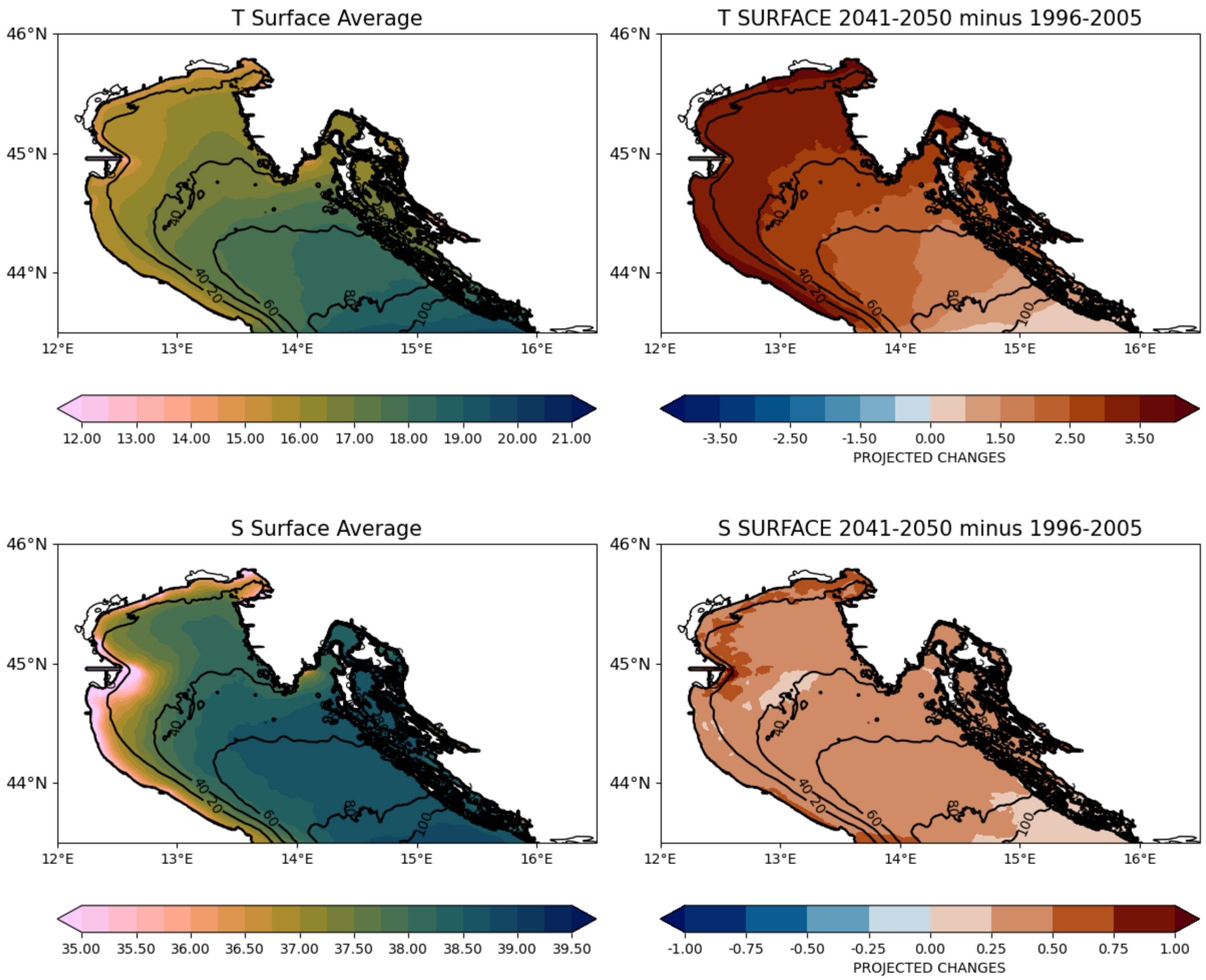
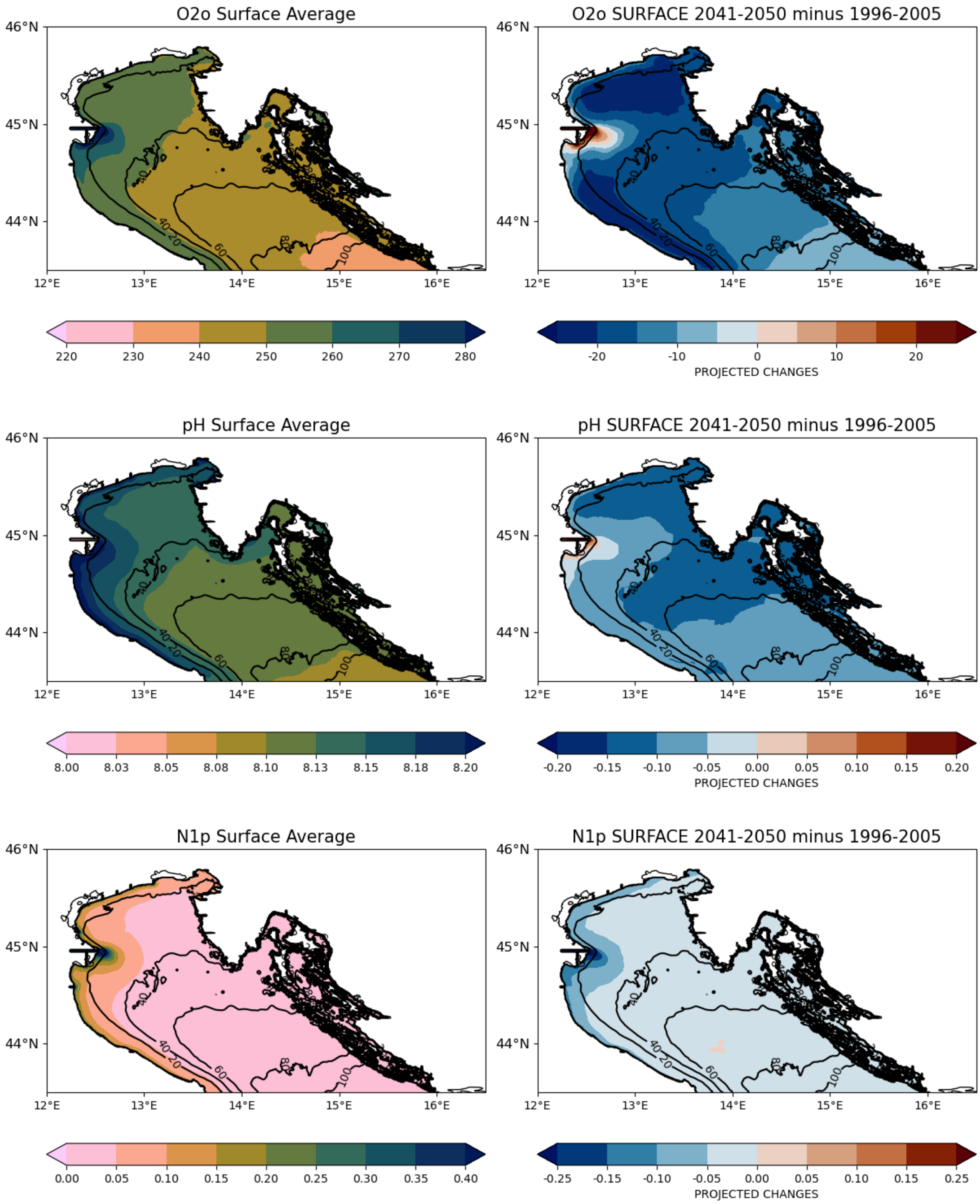


Figure 3- Simulated by RegCM5$_{STD}$ 2 m Temperature (in °C) in summer under GLW1.5 (left panel) and projected changes under GLW3 (central panel) and GLW4 (right panel) under emission scenario SSP3-7.0. Initial and boundary conditions come from EC-EARTH3-Veg.

The warming of the area will not only affect the land compartment of the region but also the ocean domain and the marine ecosystems. Figure 4 shows the simulated by MITgcm$_{STD}$-BFM sea surface temperature, salinity, DO, pH, phosphate and nitrate in the present (left column) and the projected changes in the period 2041-2050 under emission scenario RCP8.5 (right panel). First, the high resolution of the ocean model captures the spatial gradient in all the variables between coastal and open ocean areas driven by the bathymetry (black lines) and the presence of the rivers, in particular the Po. Then the projections show a more dramatic change in both physics and biogeochemistry of the coastal areas with respect to the open ocean areas: in particular although the entire basin will be affected by a significant warming, salinification, deoxygenation, acidification and decline in phosphate availability these changes will be stronger in the coastal areas. It is interesting to note that the concentration of nitrate will increase in the Northern Eastern part of the basin, likely driven by changes in the ocean circulation of the area.




O2o Surface Average
O2o SURFACE 2041-2050 minus 1996-2005
pH Surface Average
pH SURFACE 2041-2050 minus 1996-2005
N1p Surface Average
N1p SURFACE 2041-2050 minus 1996-2005
46°N
45°N
44°N
12°E
13°E
14°E
15°E
16°E
20
40
60
80
100
220 230 240 250 260 270 280
-20 -10 0 10 20
8.00 8.03 8.05 8.08 8.10 8.13 8.15 8.18 8.20
-0.20 -0.15 -0.10 -0.05 0.00 0.05 0.10 0.15 0.20
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
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PROJECTED CHANGES

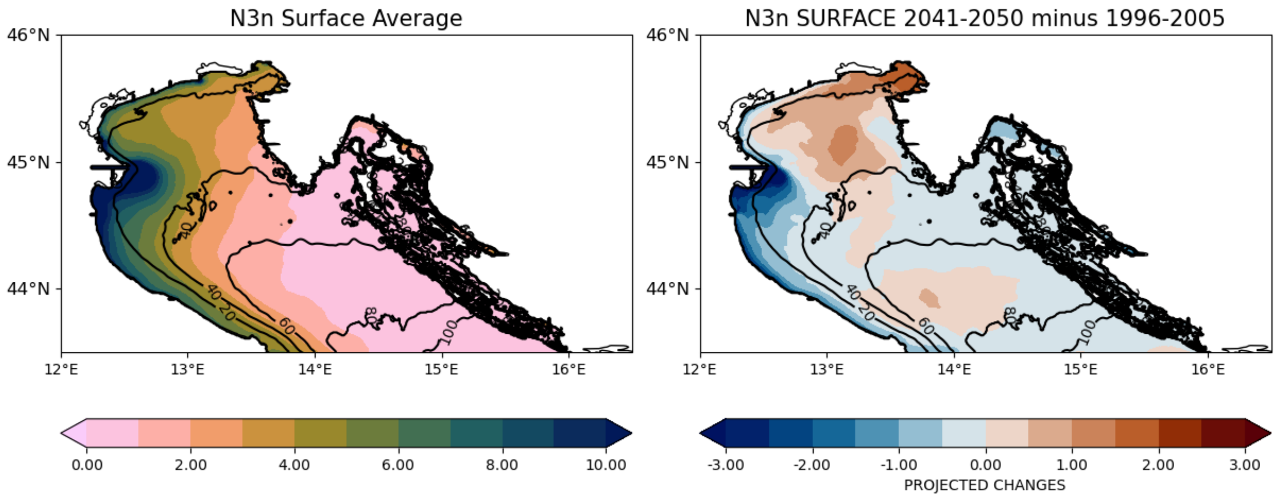

Figure 4- Simulated by MITgcm$_{STD}$ -BFM Sea Surface Temperature (in ºC), Salinity, Dissolved oxygen (DO, in mmol/m^3), pH, phosphate (N1p, in mmol/m^3) and nitrate (N3n, in mmol/m^3) in the period 1996-2005 (left panel) and projected changes in the period 2041-2050 (right panel) under emission scenario RCP8.5. Atmospheric initial and boundary conditions come from HadGEM2-ES.

Figure 5 shows the simulated daily precipitation in the present climate (GLW1.5, left panel/first row) during the autumn season (the wettest season over the area) and the projected changes in the GLW3 (central panel) and GLW4 (right panel) under emission scenario SSP3-7.0. The second row shows the projected changes for the r10mm. The latter measures the number of days when the daily precipitation is greater than 10 mm and is used as an index to measure changes in extreme precipitation events. In the present climate RegCM5$_{std}$ captures well the spatial pattern of the precipitation with higher values over the mountains and drier conditions in the Po Valley. With the increase of the GLW values the simulations show drier conditions for the region over both mountains and planes. On the other hand, something different happens for the extreme precipitation events: some areas (for example Veneto and Friuli Venezia Giulia) will experience an increase in the frequency of these extremes. This means that the coastal region of the Northern Adriatic will experience drier conditions but more concentrated intense precipitation events.

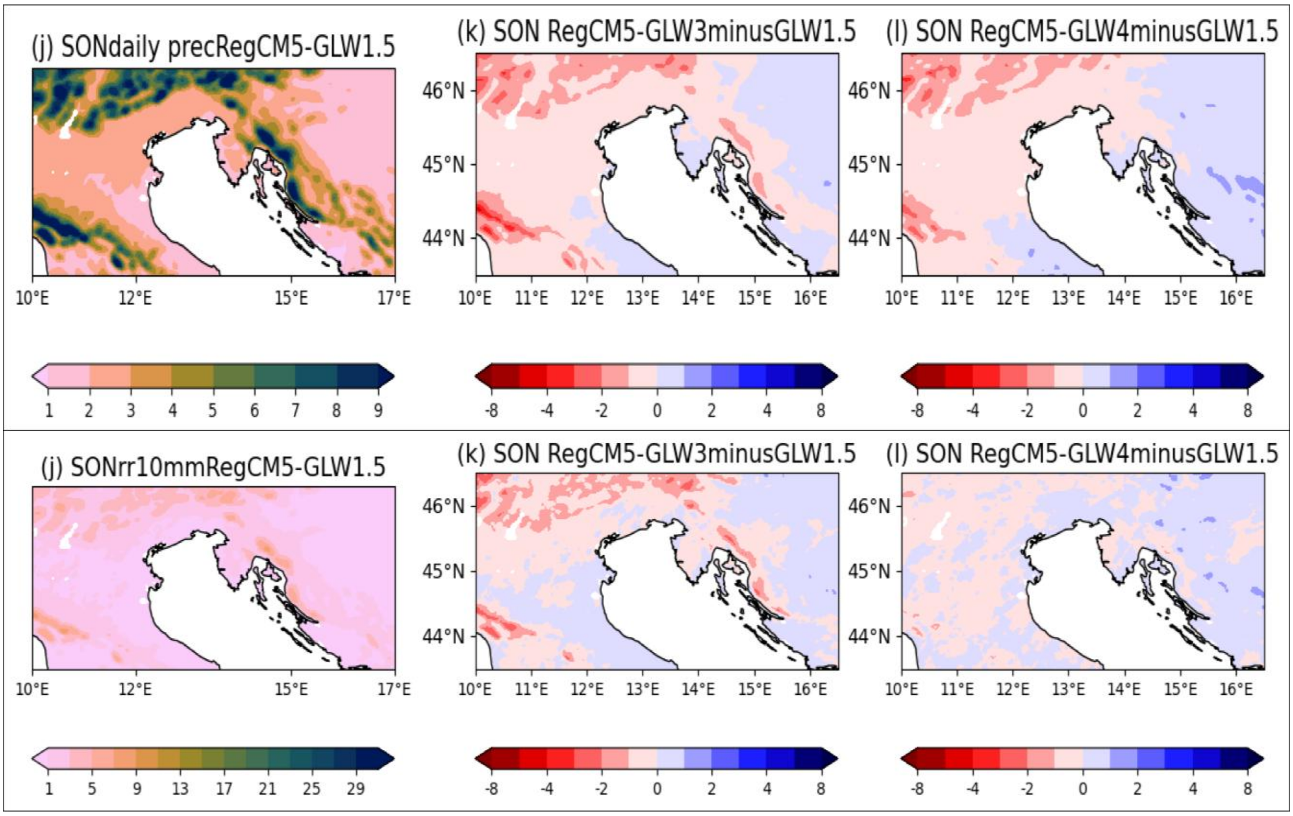

Figure 5- First row: Simulated by RegCM5$_{STD}$ daily precipitation (in mm) under GLW1.5 (left panel) and projected changes under GLW3 (central panel) and GLW4 (right panel) under emission scenario SSP3-7.0. Second row: as the first row but for r10mm (in number of days). Initial and boundary conditions come from EC-EARTH3-Veg.

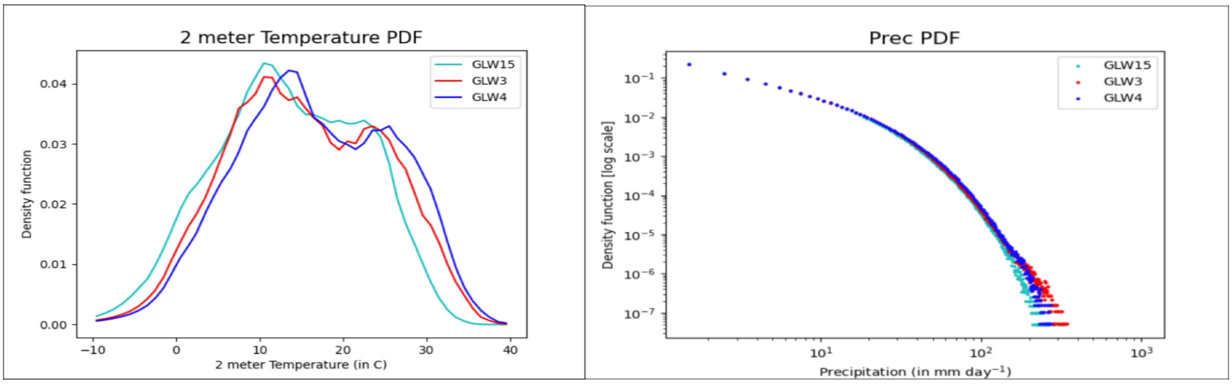

Figure 6- Relative frequency of daily values of 2 m temperature (in ºC, left panel) and precipitation (right panel, in log scale mm) simulated by RegCM5$_{STD}$ under GLW1.5 (cyan), GLW3 (red) and GLW4 (blue) under emission scenario SSP3-7.0. Initial and boundary conditions come from EC-EARTH3-Veg.

The changes in the temperature and precipitation regime under increasing GLWs are shown in Figure 6. The left panel shows a clear shift of the relative frequency of daily temperature towards hotter temperatures in function of the GLW considered. The right shows the same but for the daily precipitation. In particular for the daily precipitation the pdf (in log scale) shows the extreme precipitation will be “more” extreme in the GLW3 than in GLW4. This behaviour could be explained by the fact that the intensity of precipitation events is not a function of the thermodynamics of the event but also the circulation: thus, GLW4 will be likely associated with changes in the circulation of moisture that will further dampen the intensification of rainy events.

Figure 7 shows the r20mm according to the EURO4M dataset (Isotta et al., 2014, first panel on the left), the minimum biases between the simulated r20mm by $RegCM5_{STD}$ and RegCM-ES (central panel) and the added value (AV, panel on the right) defined as:

$$100*abs(BIAS_{STD})-abs(BIAS_{CPL})/abs(BIAS_{STD}) \quad (1)$$

where STD and CPL are respectively $RegCM5_{STD}$ and RegCM-ES. Where AV is greater than 0, the coupled model improves the simulation of r20mm. This index, similarly to r10mm, measures the number of days when the daily precipitation is greater than 20 mm and is used as an index to measure changes in extreme precipitation events. It is clear that the models overestimate (underestimate) the r20mm over the Alps (Po Valley). On the other hand, the AV is positive along the coastal areas of the Northern Adriatic Sea, that are the areas under the direct influence of the coupling between atmosphere and ocean, showing that coupling improves the simulation of the precipitation in the coastal areas of the Northern Adriatic.

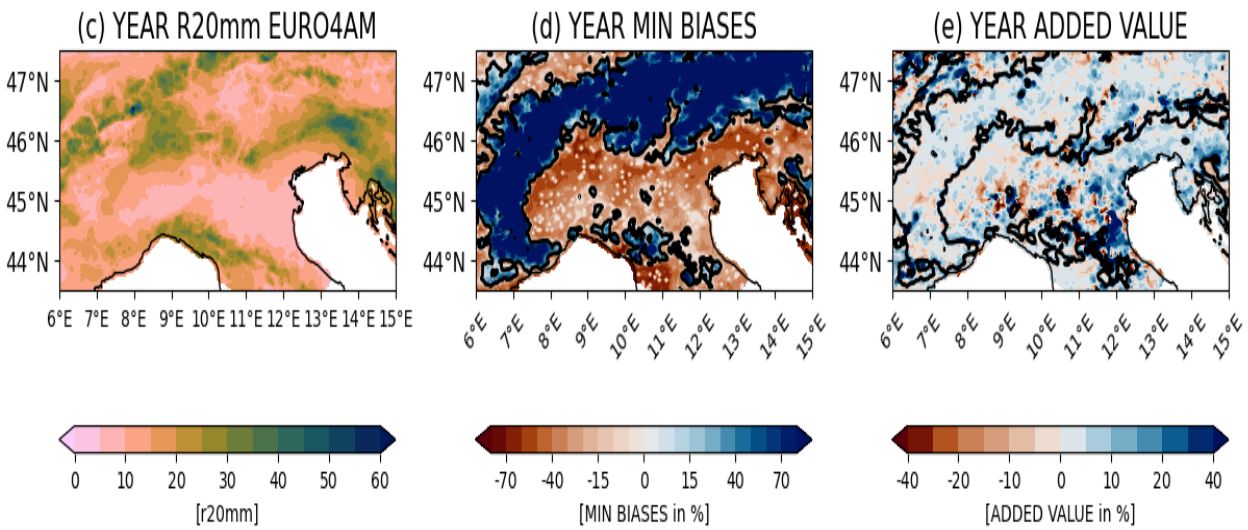

Figure 7- Yearly r20mm according to EURO4M dataset (left panel, in number of days), minimum biases between simulated r20mm and the observations (central panel) and the added value (in %, see the text for the definition) in the period 1989-2003. The contour line represents the minimum bias equal to zero.

Figure 8 shows the analysis for the simulated river discharge by $CHyM_{STD}$ (left panel) and $CHyM_{CPL}$ (right panel). Each dot represents the location of a station measuring the discharge of a river. Each station is compared with the simulated river discharge by the model and colors represent the bias (in %) between model and observations. Once again comparing $CHyM_{STD}$ (left panel) and $CHyM_{CPL}$

(right panel) it is clear that, in particular, around the Adriatic area the coupling also improves the simulation of river discharges.

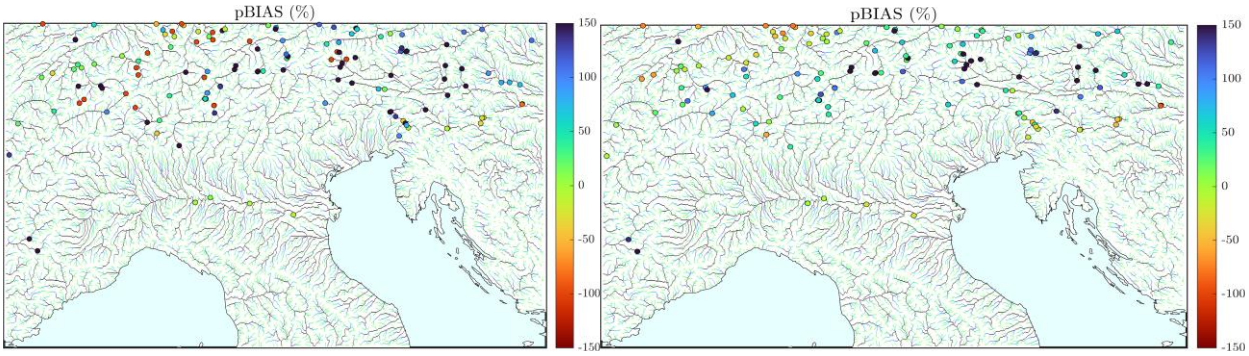

Figure 8- River discharges biases (in %) between station-based observations (dots) and $CHyM_{STD}$ (left) and $CHyM_{CPL}$ (right panel) in the period 1989-2003

Figure 9 shows the hourly values of simulated DO, IN (total nitrogen) and IP (total phosphorus) in the Orbetello lagoon during the year 2021. The comparison with measurements collected at the Levante2 water quality monitoring station (Fig.1, right panel) and ARPAT at the MAS sampling points demonstrates a significant agreement between the simulated data and the measured values. For example, for DO an RMSE of 1.12 mg/l and a determination R^2 of 0.76 has been found. Moreover, the model captures well the seasonality of the oxygen in the lagoon. For example, the minimum in DO during the warm season is mainly determined by two factors: the catabolic activity of macroalgae (cellular respiration) and bacterial oxidation of organic matter in the sediment (the major component). Other contributions to consumption, such as from phytoplankton, zooplankton, and detritus, are quantitatively smaller. In the cold season, the lower temperatures inhibit both algal growth (production) and bacterial activity (consumption), leaving reaeration as the main factor for minimal oxygen consumption.

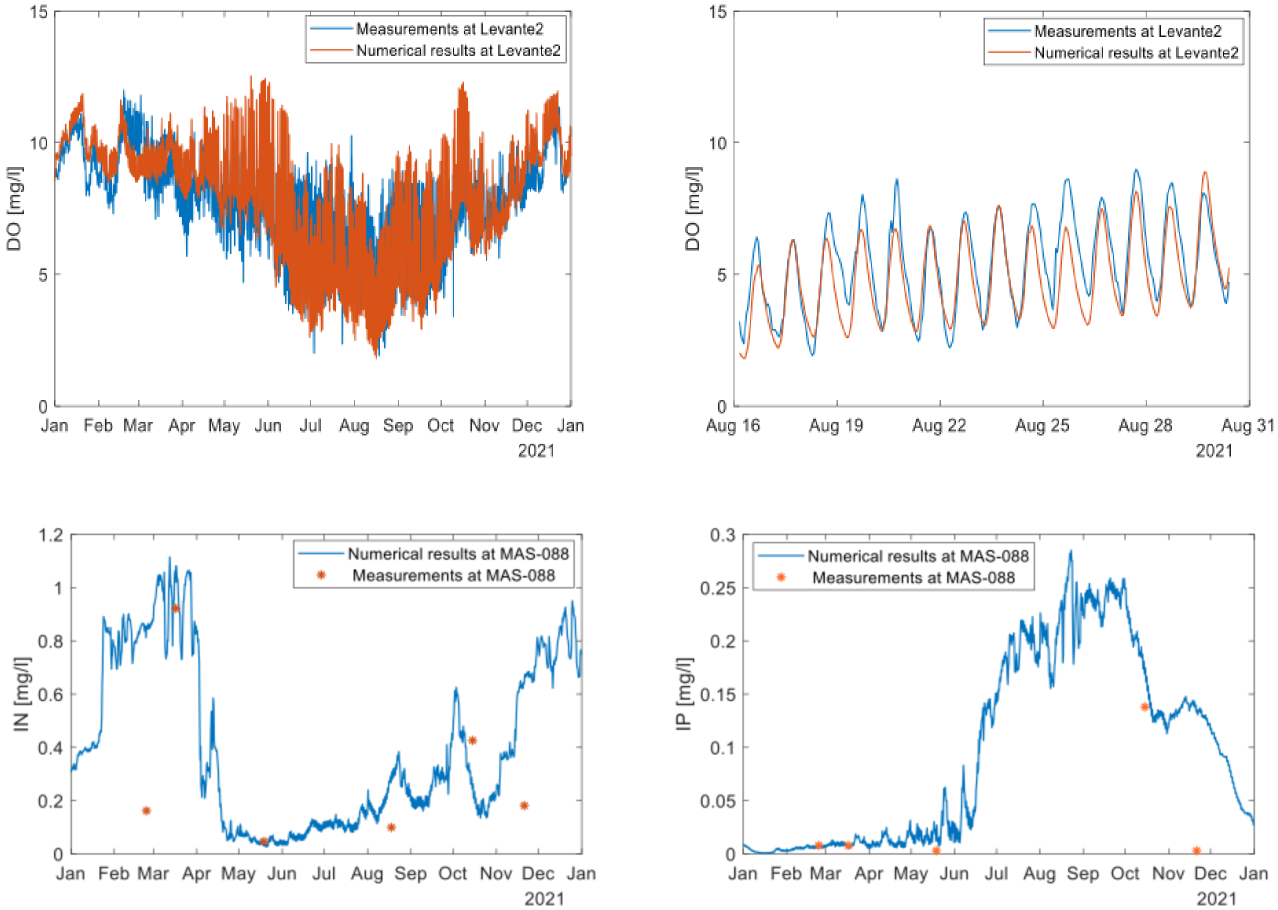

Figure 9 First row: DO concentrations (in mg/l) simulated with the numerical model and measured in the lagoon at Levante2 station for the year 2021 (left) and zoom on the period 16-31/08/2021- Second Row: – IN (left) and IP (right) concentrations (in mg/l) simulated with the numerical model and measured in the lagoon at the location of MAS-088 sampling point for the year 2021.

The model can provide the parameters of interest for each point in the lagoon. Figure 10 illustrates, for July 12th, the spatial and temporal variations of DO across the entire lagoon at two moments of the day (6:00 AM and 6:00 PM), confirming, in presence of high temperatures, the significant daily fluctuations of DO typical of eutrophic lagoons. The utility of this model is clear in terms of supporting the management of the lagoon. As an example of the possible application of the model toward this aim, we discuss the impact of various intervention scenarios on DO levels in the lagoon. As aforementioned, in each of the inlets connecting the lagoon to the sea, there are structures designed to capture fish during their migration towards the sea, consisting of concrete basins, metal grids and gates. These obstructions reduce water flow in and out of the lagoon, significantly increasing the hydraulic water residence time (WRT). With reference to the environmental conditions of 2021, the natural circulation with partially obstructed inlets would result in a reduction in minimum DO levels during the summer compared to the current management scenario. On the other hand, the removal of obstructions in the inlets, still under natural circulation conditions (pumps off), would result in a general improvement in minimum DO levels during the summer due to increased water circulation and greater exchange between the sea and the lagoon (Fig. 10 a-c).

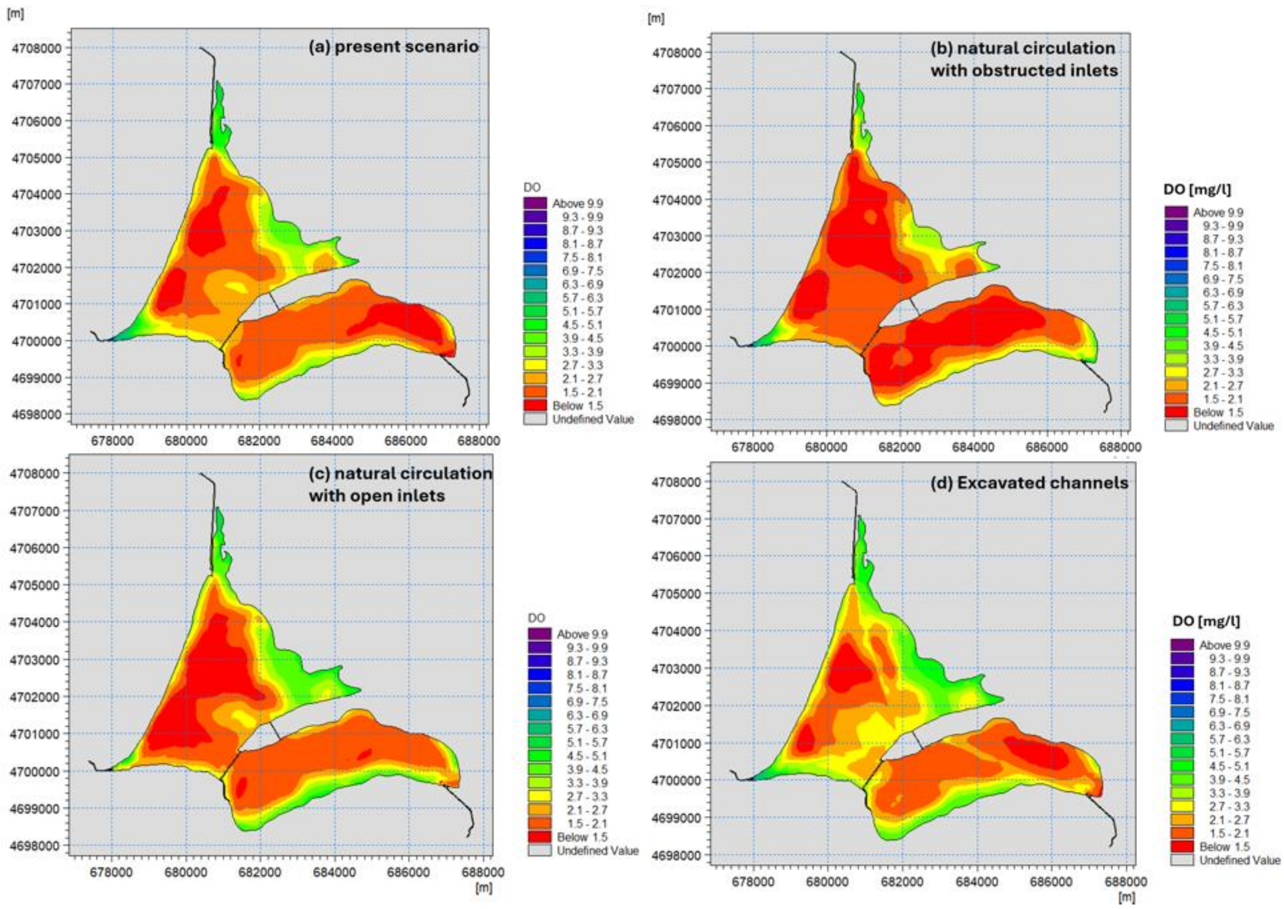

Figure 10 – Maps of minimum DO concentration (in mg/l) simulated with the ecological model for the month of August 2021, in the present scenario (a), for the natural circulation (no pumps at the inlet) with the obstruction of grids and gates for fishing activities (b), for the natural circulation without obstructions in the inlets (c) and for the scenario with channels excavated in the bottom (d).

5.1.5 Scientific products and dissemination

Reale et al.,2025 High-resolution km-scale modeling of the Northern Adriatic region. Return conference, Trieste (Italy), 4-6 March 2025.

Reale et al.,2025 High-resolution hindcasts and climate projections over the Northern Adriatic region (proof of concept of Return DS8) by using modeling tool of increasing complexity. Return conference, Milano (Italy), 5-6 June 2025.

Reale et al., 2025 Strumenti modellistici per la valutazione dei cambiamenti climatici nella regione Nord Adriatica Convegno Return Cambiamenti climatici e rischi costieri – Un approccio multi-rischio in ambiente urbano, 20 Ottobre 2025

5.2 Conclusions

A series of high-resolution configurations of state-of-the-art climate and biogeochemical models have been built and then used to produce hindcasts and climate projection for the Northern Adriatic region (Proof-of-Concept WP2 Spoke 8) and the Orbetello lagoon. All these new datasets are characterized by a relatively high temporal and spatial resolution and thus they are suitable to provide a robust representation of tendencies and variability of the physical and biogeochemical processes in coastal and open ocean areas.

The climate projections' datasets estimate a significant warming of the Northern Adriatic region and of the coastal areas of the Adriatic Sea with respect to the open ocean areas under different emission scenarios. Moreover, climate simulations project drier conditions over the region as well as a dramatic increase in the intensity of the rainy events with respect to the present, in particular in the coastal areas between Veneto and Friuli Venezia Giulia. The considerable warming of the region will also affect the marine ecosystem dynamics of the area: the high-resolution projections of the Northern Adriatic biogeochemistry shows a significant deoxygenation, acidification and decline in the phosphate content of the euphotic layer of the basin.

Regarding the Orbetello lagoon, the calibrated model shows interesting capabilities of describing the evolution of key parameters related to the lagoon's trophic state, thanks to its temporal and spatial high resolution. Therefore, it can be a powerful decision support tool for lagoon management, addressing the need for modelling tools capable of simulating the overall ecological response of the system in the medium to long term and providing qualitative insights into the impact of various stress factors and intervention actions (Simonetti et al., 2024).

The analysis of climate simulations has shown that climate change will play a crucial role, strongly affecting the shallow coastal areas of the Mediterranean Sea where local factors will likely amplify the effects of global warming. Adverse impacts of climate change on shallow water ecosystems of the Mediterranean Sea have already been reported (e.g., Bertolini et al., 2021), and are expected to exacerbate under likely scenarios of climate change evolution threatening sea life, particularly organisms with reduced motility that are unable to move toward more suitable habitats (Galli et al., 2017). The degradation of marine ecosystems and biodiversity loss will in turn likely hamper the capability to provide essential ecosystem services.

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