SPECIAL PROJECT PROGRESS REPORT

Reporting year	2022
Project Title:	Numerical modelling of the Adriatic-Ionian decadal and inter-annual oscillations: from realistic simulations to process-oriented experiments
Computer Project Account:	SPCRDENA
Principal Investigator(s):	Cléa Lumina Denamiel
Affiliation:	Institut Ruđer Bošković (IRB)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Ivica Vilibić (IRB); Manuel Bensi and Vedrana Kovačević (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS); Albin Ullmann (University of Bourgogne, France); Ivan Güttler (Meteorological and Hydrological Service – DHMZ)
Start date of the project:	01/01/2021
Expected end date:	01/01/2024

Computer resources allocated/used for the current year and the previous one
(if applicable)

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	20,000,000	12,000,000	10,000,000	211,176
Data storage capacity	(Gbytes)	25,000	13,000	50,000	25,000

Summary of project objectives (10 lines max)

The physical explanation of the thermohaline oscillations of the Adriatic-Ionian System (BiOS) is still under debate as they are thought to be generated by either pressure and wind-driven patterns or dense water formation travelling from the Northern Adriatic. The aim of the special project is to numerically investigate and quantify the processes driving the inter-annual to decadal thermohaline variations in the Adriatic-Ionian basin with both (1) a realistic high resolution Adriatic-Ionian coupled atmosphere-ocean model based on the use and development of the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modelling System (COAWST; Warner et al., 2010) and (2) a simplified kilometre-scale Ionian-Mediterranean ocean model also based on COAWST to conduct process-oriented numerical experiments.

Summary of problems encountered (10 lines max)

Two major problems (unrelated to the usage of ECMWF supercomputing facilities) were encountered during the past year. First, my previous employer – the Institute of Oceanography and Fisheries, Split, Croatia (IOR) – suddenly removed, without any warning nor concertation, my full access to the server (hosted at IOR) where the AdriSC climate simulation data are stored. An ex-colleague (Dr. Hrvoje Mihanović) – with the approval of current IOR director (Dr. Živana Nincević) – also attributed to himself administrative rights on my personal files on the server without my consent nor my permission. This on-going issue is dealt with by my new employer (IRB) legal services. Second, the old MEDSEA product originally used to force the process-oriented numerical experiments did not properly reproduce the northern boundary dynamics of the Ionian-Mediterranean model. Consequently, all previously performed simulations during the past year have to be redone with updated forcing.

Summary of plans for the continuation of the project (10 lines max)

The present project is the continuation of the previous three years of the SPCRDENA special project which now provides realistic simulations in evaluation mode (1987-2017) and for RCP 8.5 climate projections (2070-2100) during extreme events and as 31-year long continuous runs. The first objective of the project is fulfilled and the 31-year long RCP 8.5 continuous run is now finished. The second objective of the project is to keep analysing the results of the evaluation run and start processing the results of the RCP 8.5 run. The last objective of the project is to implement the simplified Ionian-Mediterranean model and start running and analysing basic experiments.

List of publications/reports from the project with complete references

- Denamiel, C., Tojčić, I., Tojčić, I., Pranić, P. and Vilibić, I.: Modes of the BiOS-driven Adriatic Sea thermohaline variability. Clim. Dyn. (2022). https://doi.org/10.1007/s00382-022-06178-4
- Denamiel, C. and Vilibić, I.: Next-generation (sub-)kilometre-scale climate modelling for extreme storm-surge hazard projections. [Preprint], Research Square (2022). https://doi.org/10.21203/rs.3.rs-1532623/v1
- Tojčić, I., Denamiel, C. and Vilibić, I.: Kilometer-scale trends and variability of the Adriatic present climate (1987-2017). [Under review], Clim. Dyn. (2022).
- Denamiel, C., Tojčić, I. and Vilibić, I.: Meteotsunamis in orography-free, flat bathymetry and warming climate conditions. JGR: Oceans, 127, e2021JC017386 (2022). https://doi.org/10.1029/2021JC017386

Summary of results

1. Analysis of the AdriSC 31-year long simulations (evaluation & RCP 8.5 scenario)

The 31-year long realistic simulations in evaluation mode (1987-2017) has already been used to thoroughly assess the skills of the AdriSC climate model (Denamiel et al., 2019, 2021; Pranić et al., 2021; see details in previous reports). It was previously demonstrated (i.e., first year report) that AdriSC reproduces the regional and coastal circulation in the Adriatic region in the atmosphere with the Weather Research and Forecasting (WRF v3.9.1.1) model (Skamarock et al., 2005) and in the ocean with the Regional Ocean Modeling System (ROMS svn 885) (Shchepetkin & McWilliams, 2009). This second year report mostly focus on the first in depth analyses performed with the AdriSC climate results (i.e., evaluation and RCP 8.5 simulations).

1.1 Modes of the BiOS-driven Adriatic Sea thermohaline variability

One of the main objective of running the AdriSC climate model was to be able to quantify the impact of the BiOS over the entire Adriatic Sea for the very first time. Here, the newly evaluated 31-year long ocean historical results (Pranić et al. 2021) of the kilometer-scale AdriSC model – which has demonstrated a decent level of skills in reproducing the Adriatic overall thermohaline properties and dynamics, including generation of dense waters – are thus used to connect the BiOS phases to the long-term variability of the Adriatic Sea. First, along the Northern Adriatic and Palagruža Sill long-term monitoring transects (Figure 1), the modelled BiOS-driven phases are compared with those already derived in Mihanović et al. (2015). Then, the temporal and spatial patterns of the AdriSC model results are connected to the BiOS regimes.

Hereafter, the temporal variability of the BiOS signal is defined as the second normalized spatial EOF component and associated time series of amplitude derived from the MEDSEA SSH fields in the Ionian Sea during the 1987-2017 period (left top panel, Figure 2). The spatial extent as well as the interannual to decadal variabilities of the obtained signal are in good agreement with indices calculated from altimetry data (Gačić et al. 2010, 2014), cruise observations (Civitarese et al. 2010), and model results (Liu et al. 2021). More precisely, the anticyclonic phases (positive sign of the EOF amplitude) are clearly seen for the 1987-1997 and 2006-2009 periods, while the cyclonic phases (negative sign of the EOF amplitude) are present for the 1998-2005 and 2010-2017 periods.

First, the EOF analysis is performed along the two long-term monitoring Adriatic transects in order to find potential long-term variabilities. The five main EOF components (representing the highest percentages of the signal) of salinity monthly detrended anomalies are extracted and presented along both transects in Figure 1 (bottom panels) for the first component (hereafter referred as EOF 1). Along the northern Adriatic transect, none of the EOF components captures interannual to decadal variabilities. By contrast, the Palagruža Sill transect located in the middle of the Adriatic Sea in deeper waters less influenced by river discharges, tides and atmospheric conditions, is more likely to capture long-term variabilities. For the AdriSC ROMS 1-km salinity results, the time series of amplitude associated with the EOF 1 (representing 78.5% of the signal) clearly shows some well-defined interannual to decadal oscillations. More importantly, the oscillations obtained with the AdriSC ROMS 1-km salinity results are in good agreement with the BiOS driven phases defined by Mihanović et al. (2015) with a Self-Organizing Maps (SOM) method applied to temperature, salinity and dissolved oxygen observations along the Palagruža Sill transect during the 1952-2010 period. Indeed, the mostly negative amplitudes are obtained for the 1987-1990, 1999-2006 and 2012-2017 periods instead of the 1987-1990 and 1999-2005 periods found in Mihanović et al. (2015). And, the mostly positive amplitudes are occurring for the 1991-1998 and 2007-2011 periods instead of 1991-1996 and 2009-2010 periods described in Mihanović et al. (2015). The fact that certain phases are shifted by a year or two compared to Mihanović et al. (2015) can be largely attributed to their definition of intermittent phases for the 1997-1998 and 2006-2008 periods. This definition is directly linked to their interpretation of the results derived with the SOM method and does not apply to the

EOF method nor, more generally, to the BiOS indices (Gačić et al. 2010, 2014; Civitarese et al. 2010; Liu et al. 2021).

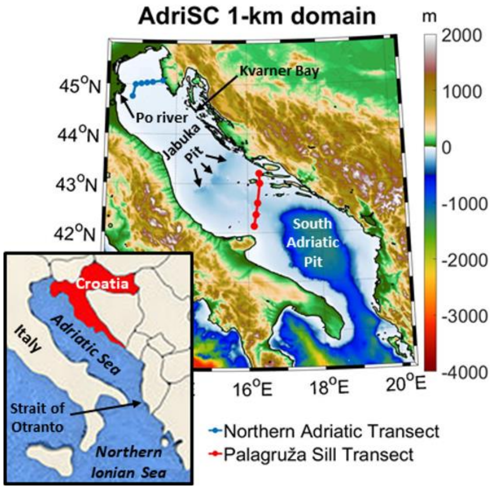
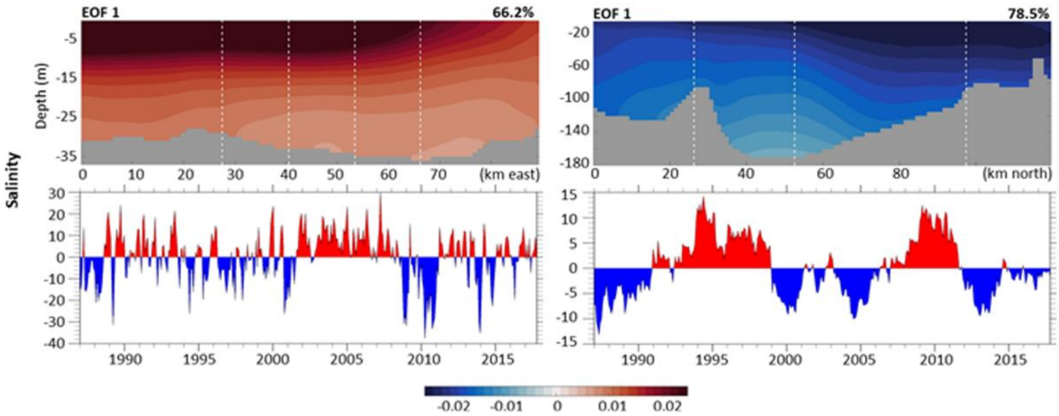


Figure 1. Top panels: **Orography and bathymetry of the AdriSC 1-km domain with the path of the two long-term monitoring Adriatic transects (northern Adriatic transect in blue and Palagruža Sill transect in red) and the location of the CTD observations marked as dots.** Bottom panels: **First normalized spatial EOF components and associated time series of amplitude derived along the northern Adriatic (left panels) and the Palagruža Sill (right panels) transects during the 1987-2017 period from the AdriSC ROMS 1-km salinity monthly anomalies. The dotted white lines represent the locations of the sampling stations along the long-term monitoring transects.**



Further, correlation analyses are performed between the time series of temperature and salinity EOF amplitudes extracted along the long-term monitoring northern Adriatic and Palagruža Sill transects and the BiOS signal with 0-year and 2-year lags. The only meaningful correlation is found between the BiOS signal with a 2-year lag and the salinity EOF 1 amplitude time series along the Palagruža Sill transect (i.e. correlation coefficient of 0.62). The fact that the Adriatic Sea haline response is delayed by approximately two years compared to the BiOS reversals sheds some light on the previously presented results. For example, the salinity EOF 1 amplitude sudden and short reversal from negative to positive seen in 2014-2015 along the Palagruža Sill (bottom right panel, Figure 1) can be associated to the observed premature inversion of the BiOS signal in late 2012 caused by substantial generation of dense waters (Gačić et al. 2014). Other sudden and short reversals from negative to positive or variability of the salinity EOF 1 amplitude along the Palagruža Sill transect could also be the 2-year delayed response to BiOS signal variability driven by extreme bora events.

Second, the five main EOF components (representing the highest percentages of the signal) derived from the AdriSC results are analyzed by correlating the Ionian BiOS signal (hereafter simply referred as BiOS signal; left top panel Figure 2) with the time series of EOF amplitude (left 3 bottom panels Figure 2). The correlation coefficients obtained between the BiOS signal and the time series of temperature, salinity and current speed EOF amplitudes at the surface, 100 m depth, and the bottom of the Adriatic Sea are calculated for the BiOS signal with 0-year and 2-year lags. The re-scaled time series of the BiOS signal on top of the re-scaled EOF amplitudes with the highest correlation coefficients and representing the highest percentages of the signal are also plotted in Figure 2 (left 3 bottom panels). For the salinity, the highest correlations are obtained between the BiOS signal with 2-year lag and EOF 3 amplitude at the sea-surface (0.55) as well as EOF 1 amplitudes at 100 m depth (0.66) and the sea-bottom (0.53). For the current speed, the highest correlations are also obtained between the BiOS signal with 2-year lag and EOF 2 amplitude at 100 m depth (0.44) as well as EOF

1 amplitude at the sea-bottom (0.51). As expected, surface current speeds that are mainly driven by the atmospheric processes only present anti-correlations with the BiOS signal and EOF 4 that has the strongest anti-correlation with the BiOS signal is used hereafter. Further, except for the sea-surface, the temperature EOF amplitudes are well-correlated with the BiOS signal, including 2-year lag with 0.55 for EOF 2 at 100 m depth and 0.50 for EOF 3 at the sea-bottom.

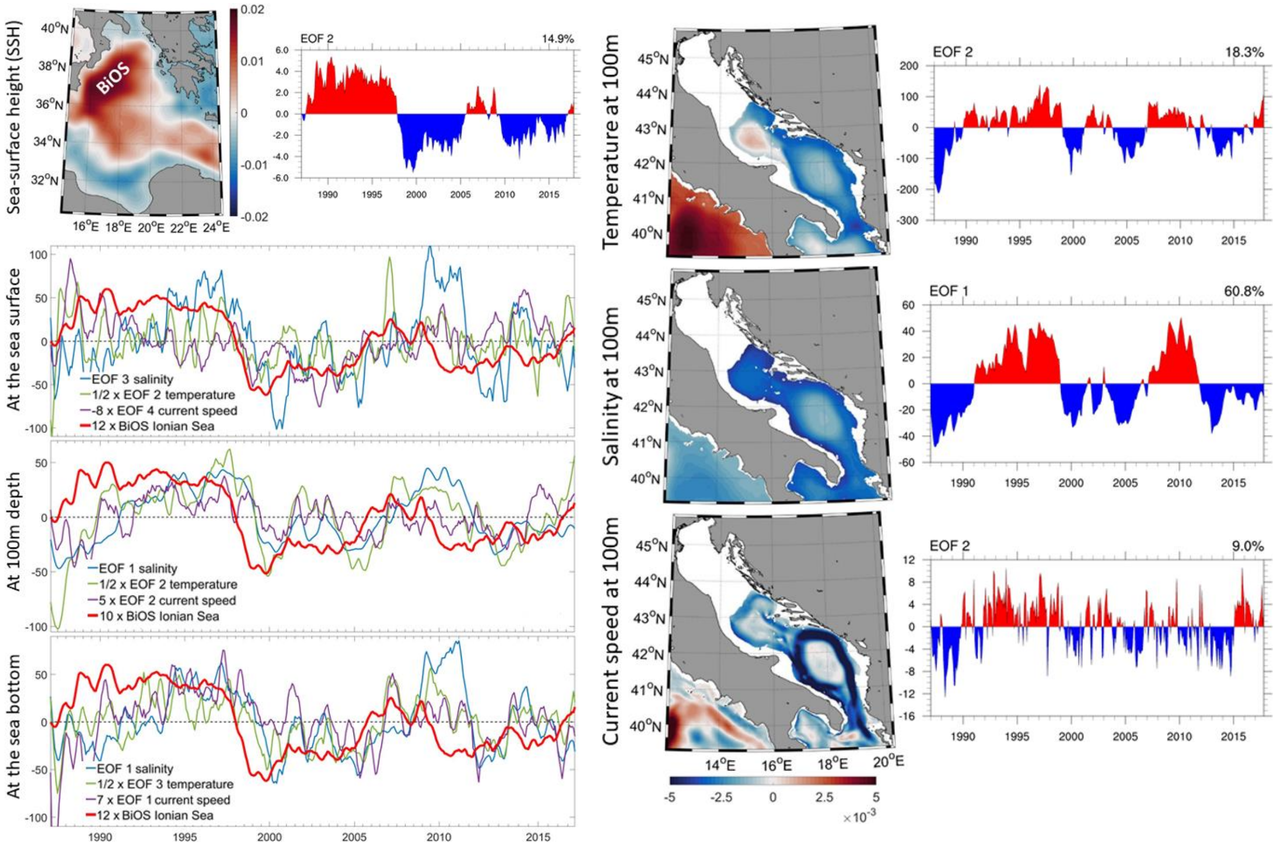


Figure 2. Left panels: Second normalized spatial EOF component and associated time series of amplitude – characteristic of the BiOS signal – derived in the Ionian Sea during the 1987-2017 period from the MEDSEA reanalysis sea-surface height results. Comparison of the re-scaled BiOS signal with the time series of re-scaled normalized EOF amplitudes – with the highest correlations to the BiOS signal including a 2-year lag – derived during the 1987-2017 period from the AdriSC ROMS 1-km temperature, salinity and current speed monthly anomalies at the surface, the bottom and 100 m of depth. Right panels: AdriSC ROMS 1-km 100 m-depth temperature, salinity and current speed normalized spatial EOF components and associated time series of amplitude with the highest (anti) correlation to the BiOS signal (including a 2-year lag) during the 1987-2017 period.

Finally, spatially at 100 m depth where correlations are high (right panels Figure 2), the thermohaline circulation is dominant: (1) the obtained EOFs all represent a large or major part of the signal (18.3% for the temperature, 60.8% for the salinity and 9.0% for the current speed), (2) the associated time series all display the 2 year delayed response in reaching maximum correlations to the BiOS signal and (3) the spatial patterns with a mostly negative signal are all nearly homogeneous over the entire Adriatic Sea, in particular for the salinity. Additionally, for all the variables, the weakest signal is found in the middle of the South Adriatic Pit which seems less influenced by the BiOS signal than the rest of the domain. Indeed, the center of the South Adriatic Pit is the center of the cyclonic gyre, where upwelling and deep convection take place (i.e. vertical processes are bringing more water masses from the deep and surface Adriatic than at the perimeter of the gyre) while being somehow separated from the advected waters. In contrast, the perimeter of the South Adriatic Pit is characterized by a persistent and strong current, bringing waters from the Ionian Sea and keeping about 90% of them in the loop (Gačić et al. 2014). This can be seen in the spatial patterns of the current speed EOF 2 where the South Adriatic Gyre is highly sensitive to the BiOS signal despite the associated time series of amplitudes displaying a BiOS related signal strongly embedded in the interannual variabilities. Further, the spatial EOF of the temperature at 100 m clearly shows a distinct area with positive signal in the western part of the Jabuka Pit and southern Palagruža Sill which are known collectors of the dense waters formed during extreme bora events. It should also be noted that the brief inversions of the BiOS signal, already mentioned for the salinity EOF analysis along the Palagruža Sill transect, can clearly be seen in the time series of both temperature and salinity EOF amplitudes.

In brief, the main findings of the presented analysis are twofold. On the one hand, the AdriSC ROMS 1-km model is proven to be, to this date, the only numerical model capable to reproduce the BiOS-driven phases observed along the Palagruža Sill long-term monitoring transect at a climate scale. On the other hand, over the entire Adriatic basin, the BiOS signal is demonstrated to be only weakly correlated to the sea-surface circulation and the two main temperature EOF time series, but better correlated with a 2-year lag to the salinity and current speed two main EOF time series at 100 m depth and the sea-bottom.

1.2 Trends and variability of the Adriatic present climate

In this analysis the kilometer-scale coupled atmosphere-ocean AdriSC climate model is used to analyze, for the very first time, the ocean trends and variability of the Adriatic present climate during the 1987-2017 period which remained, till this day, partially unknown. Hereafter we only present the results in surface.

Decadal trends and variability in the ocean are analyzed horizontally at the surface in Figure 3. Sea surface temperature trends vary between 0.4 ºC and 0.6 ºC per decade, with lowest trends over the deepest Southern Adriatic Pit, where quasi-permanent cyclonic gyre is generating an upwelling (Gačić et al., 2002), and northernmost areas of the Adriatic Sea strongly affected by freshwater load (Franco and Michelato, 1992). Further, the temperature total variance (Fig. 3; middle panels) is the highest (over 35 $^{o}C^{2}$) along the Po River plume but generally low over the entire Adriatic Sea (below 15 ºC2) and the temperature percentage anomalies mirror the patterns of the total variance. The variability is, as expected, mostly seasonally driven at depths above the seasonal thermocline, with non-seasonal values up to 10 % and particularly low in the shallow northern Adriatic and Po River plume. This implies that the Po River plume is keeping the heat near the surface due to a strong haline-driven stratification and therefore exhibiting much stronger seasonal variability in temperature than the rest of the Adriatic. Salinity trends and variability are however quite different. Salinity percentage anomalies are the lowest along the shore, below 65 %, while increasing to 90 % and above when moving away from the shore and going above the deeper sea areas. Indeed, low seasonal surface salinity variability is resembling stable structures, not affected by seasonality in coastal dynamics, like the inflow of surface waters from the Ionian Sea and their recirculation within the cyclonic gyre in the Southern Adriatic Pit. Further, surface salinity trends are positive, with the lowest values, down to 0.03 per decade, in the deep Adriatic area, and the highest values up to 0.2 per decade, along the Po River plume. This is in agreement with Vilibić et al. (2013), who found positive trends along the whole Palagruža Sill transect in the middle Adriatic Sea, but much higher in the coastal regions occupied by freshened waters. Further, positive trends in salinity are resembling reduced inflow by rivers, also in nutrients as the northern Adriatic is resembling much lower productivity in the last 10 years (Djakovac et al., 2012; Totti et al., 2019). Total variance is, as expected, the highest along the Po River plume and in areas with freshwater flowing into the sea, like the Albanian and eastern middle Adriatic rivers, with values up to 40. Current speed trends and variabilities contrast with the temperature and salinity results. First, it should be noted that areas with insignificant trends exist and are marked by light-gray color on the plots. Second, for the middle and northern Adriatic, surface current speed is increasing with decadal trend values mostly around 0.05 m s^{-1} and up to 0.1 m s^{-1} per decade. In the southern Adriatic and Otranto Strait, there are pronounced patchy patterns in trends all over the water column, indicating that the major dynamic features there – the southern Adriatic cyclonic gyre and the water mass exchanges through the Otranto Strait – are exhibiting spatial changes in time. For example, the negative current speed trend near the eastern coast of the southern Adriatic conjoined with positive trends off the coast are indicating shrinking of the gyre and offshore displacements of the Eastern Adriatic Coastal Current in the 2000s and 2010s.

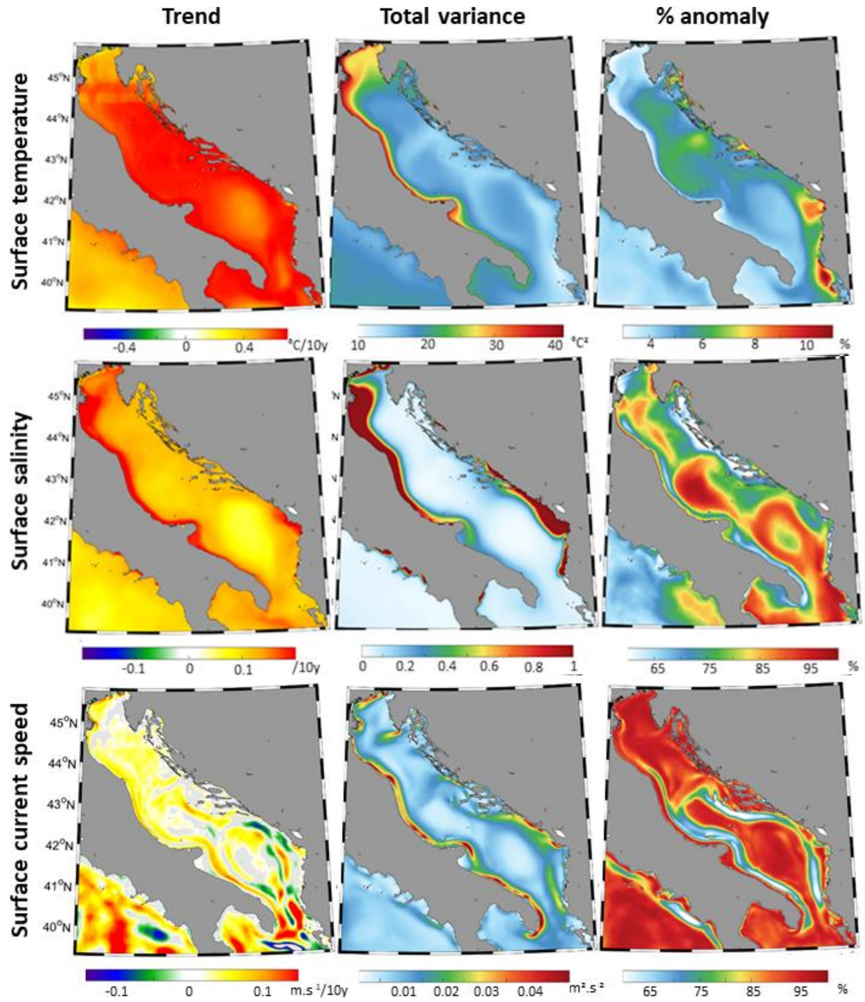


Figure 3. Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for temperature, salinity and currents at the surface. Insignificant trends (significance <0.95) are shown in light grey in the left panels.

The ongoing climate change, well-documented in many studies including the presented work, has increased the scientific and policy maker's interest in climate modelling. This study explicitly shows how kilometer-scale coupled atmosphere-ocean modelling is crucial for comprehensive climate studies at the regional to local scales, as it captures some local characteristics that have not been properly reproduced by climate models up till now. For example, this includes (1) the variations in the bora wind intensities strongly affecting the transportation, energetics, etc., in coastal regions but also driving the formation of the densest waters in the Mediterranean Sea and thus bringing oxygen to the deep ocean layers, or (2) the shrinking and weakening of the Southern Adriatic Gyre which is impacting the whole Adriatic Sea by transporting water masses of different temperature, salinity and oxygen concentration than the surrounding waters. Further, with the recent completion of the AdriSC future climate run (RCP 8.5, 2070-2100), the impact of extreme climate warming at the kilometer-scale can now be quantified, for the very first time, for all these processes in the Adriatic basin.

1.3 Sub-kilometre-scale climate modelling for extreme storm-surge hazard projections

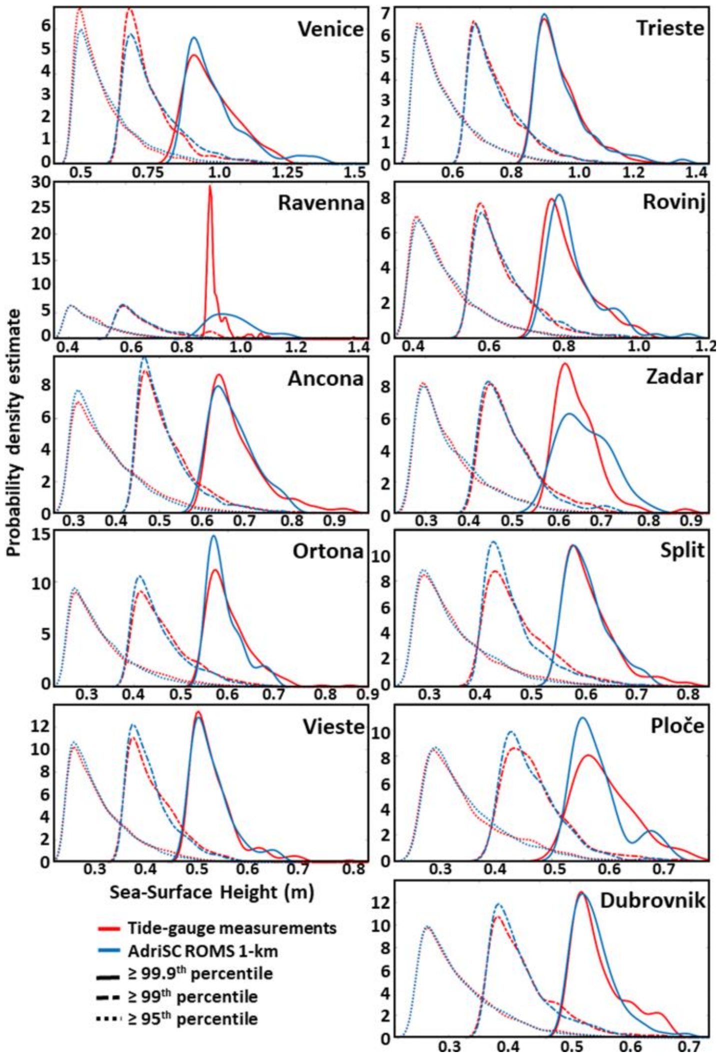
Extreme sea-level hazard assessments are highly influenced by local processes shaped by both mesoscale atmospheric processes (e.g., occurrences, durations and intensities of the storms) and local geomorphology of the coastal areas (e.g., coastal and harbour resonances, topographic shoaling), while global and regional climate models are often too coarse to properly represent both extreme storms and endangered coastlines. The AdriSC extreme event module is used to further downscales the climate results to 1.5 km in the atmosphere and to an unstructured mesh at up to 10 m resolution along the coasts with a coupled ocean-wave barotropic model. The extreme event module is only run for 1.5-day long simulations for an ensemble of moderate to extreme sea-level events extracted from both the evaluation and climate projection runs of the general circulation module.

In order to perform the evaluation of the AdriSC 1-km detrended sea-level results during the 1987–2017 period, we used 11 long-term hourly sea-level measurements. We perform the evaluation of the AdriSC 1-km detrended hourly sea-levels in two different steps. First, some statistics such as Root Mean Square Error (RMSE), correlation, and differences between 95th, 99th, 99.9th percentiles, maximum values and ranges are presented in Table 3 to assess the AdriSC model basic skills. Second, and most importantly for this study, the comparison between observations and AdriSC model results is done for the distributions of the sea-levels above the 95th, 99th, 99.9th percentiles (Fig. 4). The basic statistical analysis shows that correlation between observations and model are equal or above 0.80 for all the stations (except 0.798 at Ploče) and RMSE is below 15 cm (except 15.5 cm at Venice). Further differences between the percentiles derived from observations and model are always below 10 cm and are on average around 5 cm. However, differences in maximum value can reach up to 26 cm in Venice. The comparisons of the distributions of extreme detrended hourly sea-levels above the 95th, 99th and 99.9th percentiles, show that: (1) for most stations the AdriSC ROMS 1-km model is capable to reproduce the most extreme atmospherically-driven sea-level events, (2) some outlier values were not removed from the measurements at Ravenna station which resulted in an unrealistic distribution of the sea-levels above the 99.9th percentile, (3) the strongest difference in distributions occur at the Zadar and Ploče stations with the lowest hourly coverages (25% and 13% respectively; Table 3) for the sea-levels above the 99.9th percentile and (4) for the Trieste station with 100% of hourly coverage, the model distributions nearly perfectly fit the observational ones. In brief, following this evaluation against 11 tide-gauge observations for the 1987-2017 period, we demonstrate that the AdriSC model is suitable to study storm-surges in the Adriatic Sea.

Here, as sea-level rise (SLR) is not included in the long-term simulations carried out with the AdriSC general circulation module, we estimate it by interpolating/extrapolating in space and time the IPCC-AR5 2015 RCP 8.5 results – at 1° resolution obtained from an ensemble of 12 global models – to the AdriSC ROMS 1-km grid. As can be seen with the sea-level trends presented in Figure 4 (top right panels), the global models of the IPCC-AR5 ensemble are able to capture some spatial variations within the Adriatic Sea. First, for both 1987-2017 (baseline) and 2070-2100 (RCP 8.5) periods, the southern Adriatic sea-levels are rising about 1.3 time faster than in the northern Adriatic. Second, the accelerated SLR in the far future is smoothed compared to the baseline conditions. It is just regularly decreasing from the southern (0.04 m and 0.09 m per decade for the baseline and RCP 8.5 conditions respectively) to the northern part (0.034 m and 0.08 m per decade for the baseline and RCP 8.5 conditions respectively) of the Adriatic Sea while in the baseline conditions more variations are captured in the northern Adriatic in particular SLR reaches up to 0.038 m per decade in the middle northern shelf. Further, we consider 3 categories of extreme storm-surges: (1) moderate for sea-levels between the 10-year and 30-year return periods, (2) severe for sea-levels between the 30-year and 50-year return periods and (3) extreme for sea-levels above the 50-year return period. The spatial variations of these return periods are presented in Figure 4 (bottom right panels) for 2 different areas of the Adriatic Sea. It can be seen that the differences between the 10-year and 50-year return periods are only of the order of 10 cm in the Venice Lagoon and the Rijeka Bay. This means that, given all the cumulated uncertainties of climate modelling, it is better to consider all moderate, severe and extreme events while assessing the coastal hazards in the Adriatic Sea.

We use classical engineering methods to project the impact of climate change on the duration and frequency of moderate, severe and extreme events (Fig. 5, left panels). The storm-surge hazards are derived from both the AdriSC 1-km detrended hourly sea-levels only (top panels) and with sea-level rise (SLR) added (bottom panels). The analysis is presented for 6 sub-domains – the Venice and Marano lagoons, Gulf of Trieste, Rijeka, Split and Mali Ston bays – where the impact of climate change was found to be the strongest. For the storm-surge only, the analysis of the unique occurrences of moderate to extreme events, highlights the large spatial variability of the climate change impact under RCP 8.5 scenario (Fig. 5, top left panel). For example, the occurrences of moderate to extreme conditions are expected to decrease by 2 hours in the Venice Lagoon but to be multiplied by more than 2.5 in the Marano Lagoon located less than 90 km further in the northern Adriatic. Also, the severe and extreme conditions are expected to increase by approximately 1.5 times in the Venice

Lagoon, 7 times in the Marano Lagoon, 2.5 times in the Split Bay and 3 times in the Mali Ston Bay but to decrease by 3 times in the Rijeka Bay. When SLR is added, the number of unique days with moderate to extreme events, including all sub-domain points, is multiplied by nearly 2 and more than 150 for the baseline and RCP 8.5 conditions, respectively. Due to this dramatic change in mean sea-level (i.e., up to 0.5 m SLR under RCP 8.5 scenario), the occurrences of the moderate events are expected to increase by 1 to 3 orders of magnitude for all the sub-domains (Fig. 5, bottom left panel). Further, severe and extreme storm-surge conditions are expected to occur in average: (1) more than 2500 hours, instead of 2-5 hours under the baseline conditions, in Split and Mali Ston bays, (2) 150 hours instead of 1.5 hours in the Rijeka Bay, and (3) between 20 and 40 hours, instead of less than 10 hours, in the Venice and Marano lagoons and in the Gulf of Trieste. Consequently, independently of the intensification of the atmospherically driven storm-surges, the Rijeka, Split and Mali Ston bays are found to be the locations the most endangered by SLR in the Adriatic Sea.



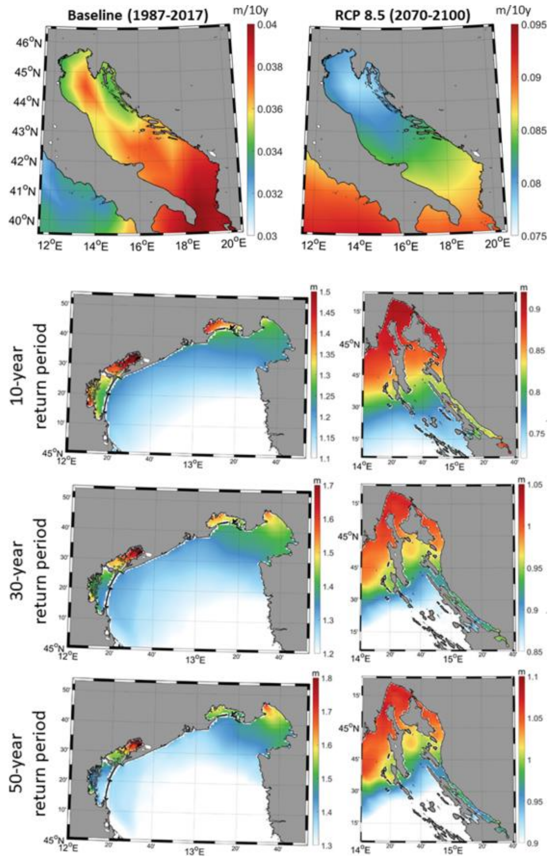


Figure 4. Left panels: Comparison of the tide-gauge observation and the AdriSC ROMS 1-km model distributions of extreme detrended hourly sea-levels above the 95th, 99th and 99.9th percentiles at 11 stations along the Adriatic Sea for the 1987-2017 period. Right top panels: Spatial distribution of the Sea-Level Rise (SLR) trends over the entire Adriatic Sea derived from the 1° resolution IPCC-AR5 2015 data for the Historical 1987-2017 and RCP 8.5 2070-2100 periods. Right bottom panels: Spatial distributions of the 10-, 30- and 50- year return periods in the different Adriatic sub-domains derived from the detrended SSH baseline conditions for the 1987-2017 period.

In order to quantify the storm-surge hazards, we run the AdriSC extreme module for the ensemble of unique days extracted from the storm-surge only analysis (Fig. 5, right panels). However, we also add SLR to the AdriSC 1-km detrended sea-levels forcing the unstructured ocean mesh for these events. Here, we present the distributions of maximum sea-levels, significant wave height, peak period, wind speed and associated direction as well as minimum pressure for all the 6 sub-domain points, under both baseline and RCP 8.5 conditions for the selected moderate to extreme daily events (Fig. 5). To conclude, despite many well-funded public and private projects studying climate change in the Venice Lagoon, the preliminary results presented in this study reveal that, in the Adriatic Sea, other locations less studied by lack of funding, interest, expertise, etc., may be more endangered by the direct impact of climate warming. These areas are the Marano Lagoon where the largest marina of Italy is located, the Split Bay, the second most populated area of Croatia which heavily relies on tourism and cruises, and the Mali Ston Bay internationally known for the quality of its oysters. Scientists, engineers and local decision makers should thus shift their attention to these locations in order, for example, to better understand the impact of (1) the wave height increase on the Marano mooring complex, (2) SLR, likely to flood historical towns in the Split area and (3) the storm-surge intensification on the production of oysters in the Mali Ston Bay.

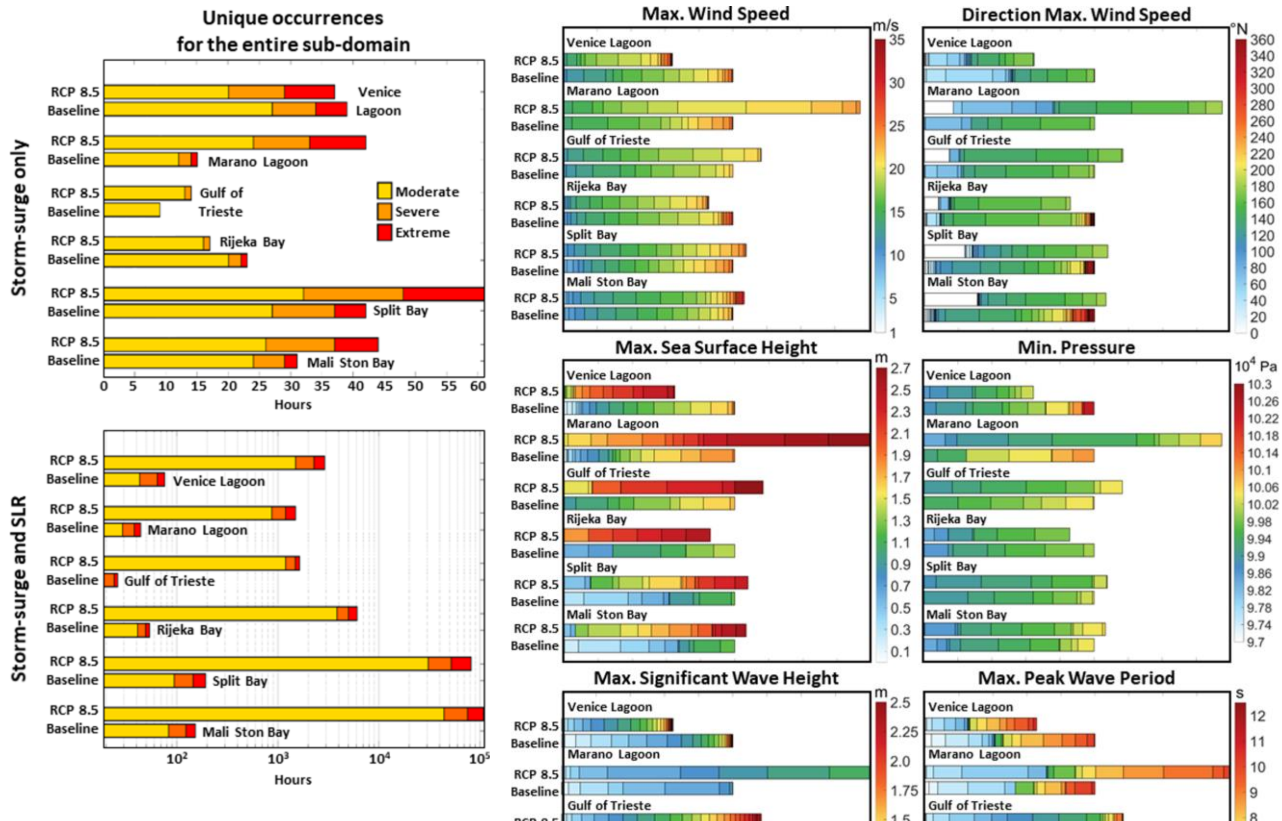


Figure 5. __Left panels__: **Storm-surge hazard assessments in 6 Adriatic Sea sub-domains (i.e., Venice Lagoon, Marano Lagoon, Gulf of Trieste, Rijeka Bay, Split Bay and Mali Ston Bay) for three categories: moderate, severe and extreme conditions.** __Right panels__: **Distributions of the (sub-)kilometre-scale maximum (max.) wind speed and associated direction at 10 m, minimum (min.) mean sea-level atmospheric pressure, maximum sea surface height, maximum significant wave height and peak period for the baseline and RCP 8.5 moderate, severe and extreme unique daily events.**

2. Process-oriented simulations

No new material is presented in this report due to the previously mentioned problems encountered with the old MEDSEA forcing.

3. Conclusions

Despite the extreme slowness and numerical cost of the realistic AdriSC climate simulations (evaluation and RCP 8.5 scenario), the generous amount of SBUs allocated to this and the previous projects has allowed to demonstrate the interest of kilometre-scale coupled atmosphere-ocean climate modelling in the Adriatic region.

References

Civitarese G, Gačvić M, Lipizer M, Borzelli G (2010) On the impact of the Bimodal Oscillating System (BiOS) on the biogeochemistry and biology of the Adriatic and Ionian Seas (Eastern Mediterranean). Biogeosci Discussions 7(5)

Denamiel, C., Šepić, J., Ivanković, D., and Vilibić, I.: The Adriatic Sea and Coast modelling suite: Evaluation of the meteotsunami forecast component, Ocean Model., 135, 71–93, doi:10.1016/j.ocemod.2019.02.003, 2019.

Denamiel, C., Pranić, P., Ivanković, D., Tojčić, I. and Vilibić, I.: Performance of the Adriatic Sea and Coast (AdriSC) climate component – a COAWST V3.3-based coupled atmosphere-ocean modelling suite: atmospheric part, Geosci. Model Dev., accepted, doi:10.5194/gmd-2021-3, 2021b.

Djakovac T, Degobbis D, Supić N, Precali R (2012) Marked reduction of eutrophication pressure in the northeastern Adriatic in the period 2000-2009. Estuar Coast Shelf Sci 115:25-32. https://doi.org/10.1016/j.ecss.2012.03.029.

Franco P, Michelato A. (1992). Northern Adriatic Sea: Oceanography of the basin proper and of the western coastal zone. In A. Vollenweider, R. Marchetti, & R. Viviani (Eds.), Marine and Coastal Eutrophication (pp. 35–62). Amsterdam: Elsevier.

Gačić M, Civitarese G, Miserocchi S, Cardin V, Crise A, Mauri E (2002) The open-ocean convection in the Southern Adriatic: A controlling mechanism of the spring phytoplankton bloom. Cont Shelf Res 22:1897– 1908. doi:10.1016/S0278-4343(02)00050-X

Gačić M., Borzelli GLE, Civitarese G, Cardin V, Yari S (2010) Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example. Geophys Res Lett 37:L09608. doi:10.1029/2010GL043216

Gačić M, Civitarese G, Kovačević V, Ursella L, Bensi M, Menna M, Cardin V, Poulain PM, Cosoli S, Notarstefano G, Pizzi C (2014) Extreme winter 2012 in the Adriatic: an example of climatic effect on the BiOS rhythm. Ocean Sci 10(3):513–522

Liu F, Mikolajewicz U, Six KD (2021) Drivers of the decadal variability of the North Ionian Gyre upper layer circulation during 1910–2010: a regional modelling study. Clim Dyn. https://doi.org/10.1007/s00382-021-05714-y

Mihanović H, Vilibić I, Dunić N, Šepić J (2015) Mapping of decadal middle Adriatic oceanographic variability and its relation to the BiOS regime. J Geophys Res 120(8):5615–5630

Pranić, P., Denamiel, C., and Vilibić, I.: Performance of the Adriatic Sea and Coast (AdriSC) climate component – a COAWST V3.3-based coupled atmosphere-ocean modelling suite: ocean part, Geosci. Model Dev. Discuss., [preprint], https://doi.org/10.5194/gmd-2021-155, in review, 2021.

Shchepetkin, A. F., and McWilliams, J. C.: Correction and commentary for "Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the regional ocean modeling system" by Haidvogel et al., J. Comput. Phys., 227, pp. 3595–3624, J. Comput. Phys., 228, 8985–9000, doi:10.1016/j.jcp.2009.09.002, 2009.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W., Powers, J. G.: A description of the Advanced Research WRF Version 2. NCAR Technical Note NCAR/TN-468+STR, doi:10.5065/D6DZ069T, 2005.

Totti C, Romagnoli T, Accoroni S, Coluccelli A, Pellegrini M, Campanelli A, Grilli F, Marini M (2019) Phytoplankton communities in the northwestern Adriatic Sea: Interdecadal variability over a 30-years period (1988–2016) and relationships with meteoclimatic drivers. J Mar Syst 193:137-153. https://doi.org/10.1016/j.jmarsys.2019.01.007

Vilibić I, Šepić J, Proust N (2013) Observational evidence of a weakening of thermohaline circulation in the Adriatic Sea. Clim Res 55:217–225. https://doi.org/10.3354/cr01128