SPECIAL PROJECT FINAL REPORT

Project Title:	The Adriatic decadal and inter-annual oscillations: modelling component
Computer Project Account:	SPCRDENA
Start Year - End Year :	2018 - 2020
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Summary of project objectives

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 a 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). The Adriatic-Ionian model consists in two nested atmospheric grids of 15-km and 3-km and two nested ocean grids of 3-km and 1-km and run for a 31-year re-analysis period (1987-2017) as well as a 31-year RCP 8.5 scenario (2070-2100) via a Pseudo-Global Warming (PGW) method.

Summary of problems encountered

No major problem was encountered in terms of usage of the supercomputing facilities. However, as discussed in previous reports, due to the general slowness and numerical cost of the modelling suite, a new strategy (PGW method) was implemented in order to be able to generate high resolution evaluation and RCP 8.5 projection climate runs within the three years of this special project. Further, as the originally requested resources (SBUs) were not enough to cover for our needs, additional resources were generously attributed to us every year – up to 10,000,000 SBUs in 2020. At the end, as pointed out by one of the previous year reviewer, this project will cost double the SBUs originally planned/requested but we truly believe that its final outcomes will also be more valuable for the climate community than those originally forecasted.

Experience with the Special Project framework

Overall, I had an excellent experience with the special project framework. The ECMWF supporting staff has been extremely helpful, prompt to reply to any request, knowledgeable and has provided several technical suggestions that greatly help the success of the project. Concerning the administrative part of the project, I am satisfied with the set-up of both the application and progress report procedures (i.e. format, frequency, review process, etc.). My only mildly negative criticism concerns the reviewing process which, from my user point of view, has been extremely inconsistent – i.e. ranging from a review writing that the project was dealing with Arctic modelling (1st year) to an excellent review pointing both real strengths and weaknesses of the project (2nd year) to no review at all (3rd year).

Summary of results

In this ECMWF special project, our efforts were mostly concentrated in setting up the high resolution coupled climate model (AdriSC: Adriatic Sea and Coast) and running both a 31-year evaluation period run (1987-2017) and a 31-year RCP 8.5 scenario run (2070-2100). Given the relative slowness and the numerical cost of the AdriSC modelling suite, this final report reflects a major change of strategy (implemented and tested during the 2019-2020 period) compare to the original proposal. This new strategy is based on the use of the Pseudo-Global Warming (PGW) method which was extended, for the very first time, to coupled atmosphere-ocean models and was tested for an ensemble of short-term simulations during extreme events in the Adriatic region.

1) AdriSC modelling suite set-up

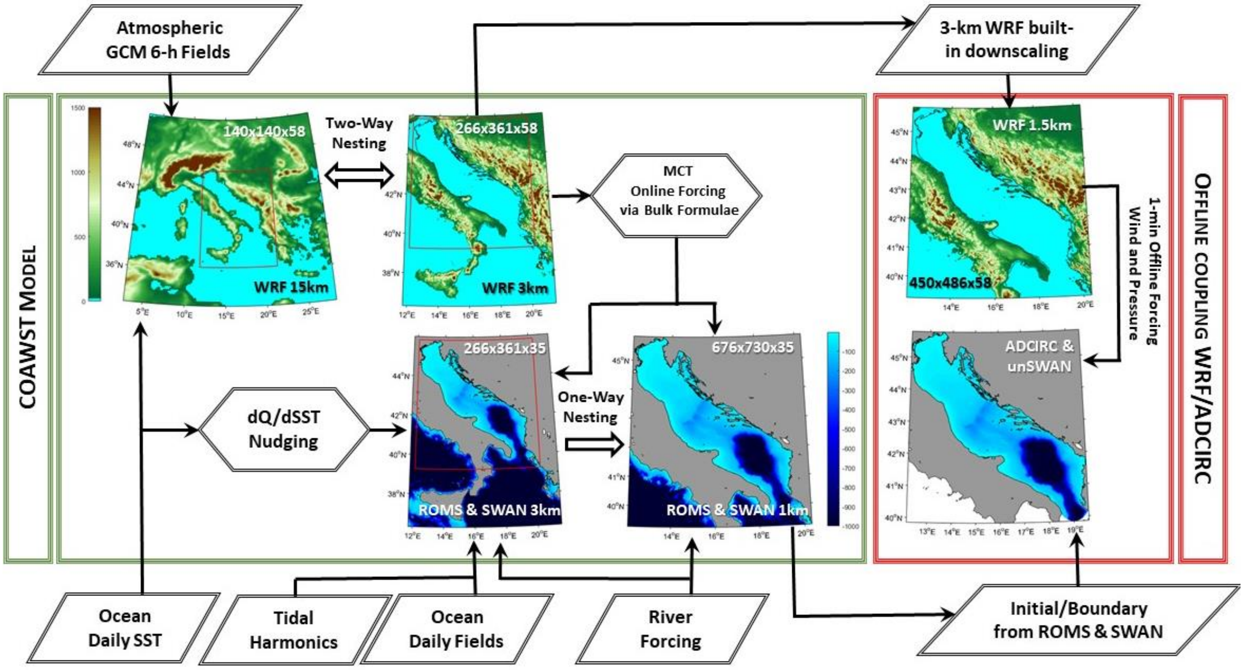


Figure 1. Schematic representation of the AdriSC modelling suite structure (Basic module in green and Nearshore module in red)

The Adriatic Sea and Coast (AdriSC) modelling suite (Denamiel et al., 2019a) has been developed with the aim to accurately represent the processes driving the atmospheric and oceanic Adriatic circulation, in particular during extreme weather conditions. In this spirit, two different modules of the AdriSC modelling suite have been developed conjointly (Fig. 1 & Table 1): (1) a basic module providing atmospheric and oceanic Adriatic baroclinic circulation at the deep sea and coastal scales, and (2) a dedicated nearshore module used to better reproduce atmospherically driven extreme sea level events.

Table 1. AdriSC modelling suite main features

	Basic module				Nearshore module	
	Atmosphere		Ocean		Atmosphere	Ocean
Models	WRF		ROMS-SWAN		WRF	ADCIRC-SWAN
Domains	2		2		1	1
Horizontal res.	15 km	3 km	3 km	1 km	1.5 km	5 km to 10 m
Vertical res.	58 levels		35 levels		58 levels	/
Init. & bound. Cond.	ERA-Interim		MEDSEA		WRF 3-km	ROMS/SWAN 1-km
Climate run duration	Evaluation: 1987-2017 w/o SWAN RCP 8.5 scenario: 2070-2100 w/o SWAN				/	/
PGW test duration (d0: event day at 0 h)	72 h from d0 – 48 h to d0 + 24 h with SWAN				36 h from d0 - 12 h to d0 + 24 h with SWAN	
Frequency of outputs	Hourly				1-min	

In the basic module, for the atmosphere, a 15-km grid (horizontal size: 140 x 140) approximately covering the central Mediterranean basin and a nested 3-km grid (266 x 361) encompassing the entire Adriatic and Ionian Seas allow for the proper modelling of the Adriatic atmospheric circulation, depending on both local orography and Mediterranean regional forcing. While for the ocean, a 3-km grid identical to the atmospheric grid and a nested additional 1-km grid (676 x 730) provide a good representation of both the exchanges with the Ionian Sea and the complex geomorphology of the Adriatic Sea and, most particularly, of the Croatian coastline.

In the nearshore module, both atmospheric and oceanic domains cover the entire Adriatic Sea with resolutions of 1.5-km for the atmosphere (450x486) and ranging from 5-km in the deepest part of the domain to 10 m at the coast for the mesh used for the ocean.

The vertical discretization of the grids (except for the barotropic ocean model of the nearshore module) is achieved via terrain following coordinates: 58 levels refined in the surface layer for the atmosphere (Laprise, 1992) and 35 levels refined near both the sea surface and bottom floor for the ocean (Shchepetkin, 2009).

The basic module of the AdriSC modelling suite – which produces hourly atmospheric and oceanic results, is based on a modified version of the Coupled Ocean-Atmosphere-Wave-Sediment-Transport (COAWST V3.3) modelling system developed by Warner et al. (2010). The state-of-the-art COAWST model couples (online) the Regional Ocean Modeling System (ROMS svn 885) (Shchepetkin & McWilliams, 2009), the Simulating WAves Nearshore (SWAN) model and the Weather Research and Forecasting (WRF v3.9.1.1) model (Skamarock et al., 2005) via the Model Coupling Toolkit (MCT v2.6.0) (Larson et al., 2005) and the remapping weights computed – between the 15-km, 3-km and 1-km atmospheric and ocean grids, with the Spherical Coordinate Remapping and Interpolation Package (SCRIP).

In this nearshore module, the ADvanced CIRCulation unstructured model fully coupled with an unstructured version of SWAN (ADCIRC-SWAN v52.30; Dietrich et al. 2012) is forced every minute with the off-line atmospheric results of a dedicated high-resolution WRF 1.5-km grid. In more details, the hourly results from the WRF 3-km grid obtained with the basic module are first downscaled to a WRF 1.5-km grid covering the Adriatic Sea and the hourly sea surface elevation from the ROMS 1-km grid, the 10-min spectral wave results from the SWAN 1-km grid and finally the 1-min results from the WRF 1.5-km grid are then used to force the unstructured mesh of the ADCIRC-SWAN model.

The AdriSC modelling suite was compiled with the Intel 17.0.3.053 compiler, the PNetCDF 1.8.0 library and the MPI library (mpich 7.5.3) on the ECMWF's High Performance Computing Facility (HPCF). In addition, ecFlow 4.9.0 – the work flow package used by all ECMWF operational suites, was set-up to automatically and efficiently run all the modules of the AdriSC modelling suite in a controlled environment. In terms of workload, no hyper threading is used. The COASWT model optimally runs on 260 CPUs with both the WRF and ROMS grids decomposed in 10 x 13 tiles while the WRF 1.5-km model runs on 210 CPUs with its grid decomposed in 14 x 15 tiles and the ADCIRC-SWAN model runs with 200 CPUs.

In terms of the efficiency, for long-term simulations only using the Basic module of the AdriSC modelling suite, the optimal configuration presented above produces a month of model results per day while for short-term simulations using both modules of the AdriSC modelling suite, around 22 hours are needed to produce 3 days of results with the Basic module and 1.5 day of results with the Nearshore module (see Table 1).

More on the AdriSC modelling suite can be found in Denamiel et al. (2019a).

Since the beginning of the special project, the AdriSC modelling suite has been used in many different applications: operational forecast (Denamiel et al., 2019a; Tojčić et al., 2021), surrogate/stochastic modelling (Denamiel et al., 2018, 2019b, 2020a), impact of climate change on extreme events (Denamiel et al., 2020b, 2020c, 2021a) and long-term climate simulations (Denamiel et al., 2021b; Pranić et al., 2021). However, in this report, only the last two kinds of applications will be presented as they were used to respectively test the PGW methodology and fulfill the main objective of the special project.

2) Implementation and test of the PGW methodology

2.1) Implementation of the methodology

In this project, the climate scenarios (RCP 4.5 and 8.5) were originally thought to be forced with coupled RCM results from the MED-CORDEX experiments. Unfortunately, after discussion with different institutes producing the results, we realized that the fields were not saved at high enough frequency (and with high enough vertical distribution) to be used as boundary conditions. Given this fact and the slowness of the AdriSC modelling suite (1 month of simulation per day), it was judged impossible to follow the classical climate downscaling approach as presented in MED-CORDEX: one 50-year historical run and at least two 100-year scenario runs.

It was thus decided to use the PGW approach (Schär et al., 1996). Concerning the implementation of the PGW simulations, the choice of the forcing was limited to the LMDZ4-NEMOMED8 results which, due to a reported issue with the CNRM-CM5 CMIP5 forcing for the historical run (that removes reliability of this product), were at the time, the only high resolution coupled model results from the Med-CORDEX experiment available for the historical period (1950-2005) and the two climate scenarios rcp 4.5 and rcp 8.5 (2006-2100). The principle of the PGW methodology – as defined by Schär et al. (1996), is to impose an additional climatological change (e.g. a temperature change ΔT representative of the increase in temperature between past and future climate; see Figures 2 and 3) to the forcing used to produce a control run. As in this study the control run (1987- 2017) extends beyond the historical run period (1950-2005), two continuous LMDZ4-NEMOMED8 runs (1950-2100) – referred as scen 4.5 and scen 8.5, are defined by extending the historical run with respectively the rcp 4.5 and rcp 8.5 runs (2006-2100). The climatological changes are then derived from scen 4.5 and scen 8.5 between the 1987-2017 and the 2070-2100 31-year periods.

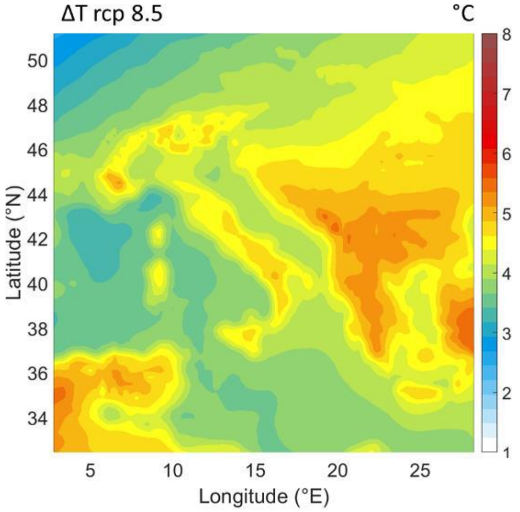
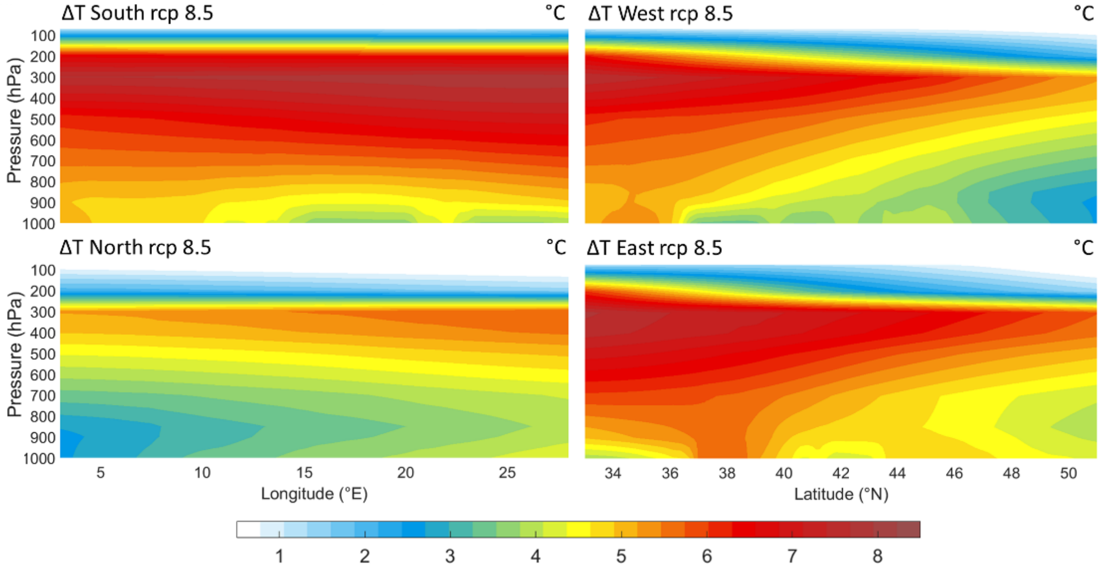


Figure 2. Surface (top panel) and vertical (bottom panels) distributions of the mean temperature (ΔT) applied to the boundaries of the 15-km atmosphere domain for the rcp 8.5 scenario. For the atmosphere, the WRF model is forced with ERA-Interim (ECMWF) global reanalysis defined on 37 atmospheric pressure levels. The ERA-I air temperature is modified between 1000hPa and 70hPa as well as in surface with ΔT derived from scen 8.5. The boundary and initial temperature conditions of the AdriSC scenario run are thus given by:

$$T^{SCEN}(x,y,p) = T^{ERAI}(x,y,p) + \Delta T(x,y,p)$$



The new strategy for climate projection (the PGW method), replacing the original downscaling one, has been implemented in order to produce the necessary climate projection runs. To our knowledge, the AdriSC climate model is the first climate coupled model running at such high resolution (coastal scale) and the implementation of the PGW method for coupled atmosphere-ocean models was first achieved within this special project (Denamiel et al., 2020a). The PGW method was used to overcome the following challenges: (1) the forcing of the climate simulations, (2) the slowness of the model, (3) the computational resources needed to run such a model, etc. However, it was also untested method for coupled atmosphere-ocean models and thus one of the objective of the project became to prove that the PGW method could be used within the AdriSC modelling suite.

2.2) Test of the methodology

To test the PGW methodology, the strongest historical storms driven by either bora or sirocco winds in the Adriatic Sea during the 1979-2019 period were reproduced and their behavior under climate change projections (RCP 4.5 and RCP 8.5 scenarios) was assessed. The choice of the studied extreme events was mostly driven by the available information and measurements recorded during the 1979-2019 period. For the sirocco events, the 14 selected storms were extracted from the long-term record of the Venice extreme flooding (https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali). For the bora events, only 22 of the most recent extreme storms were selected as more measurements became available in the Adriatic Sea at the end of the 20th century. The majority of the selected bora events peaked in the northern Adriatic, where bora wind is the strongest (Grisogono and Belušić 2009).

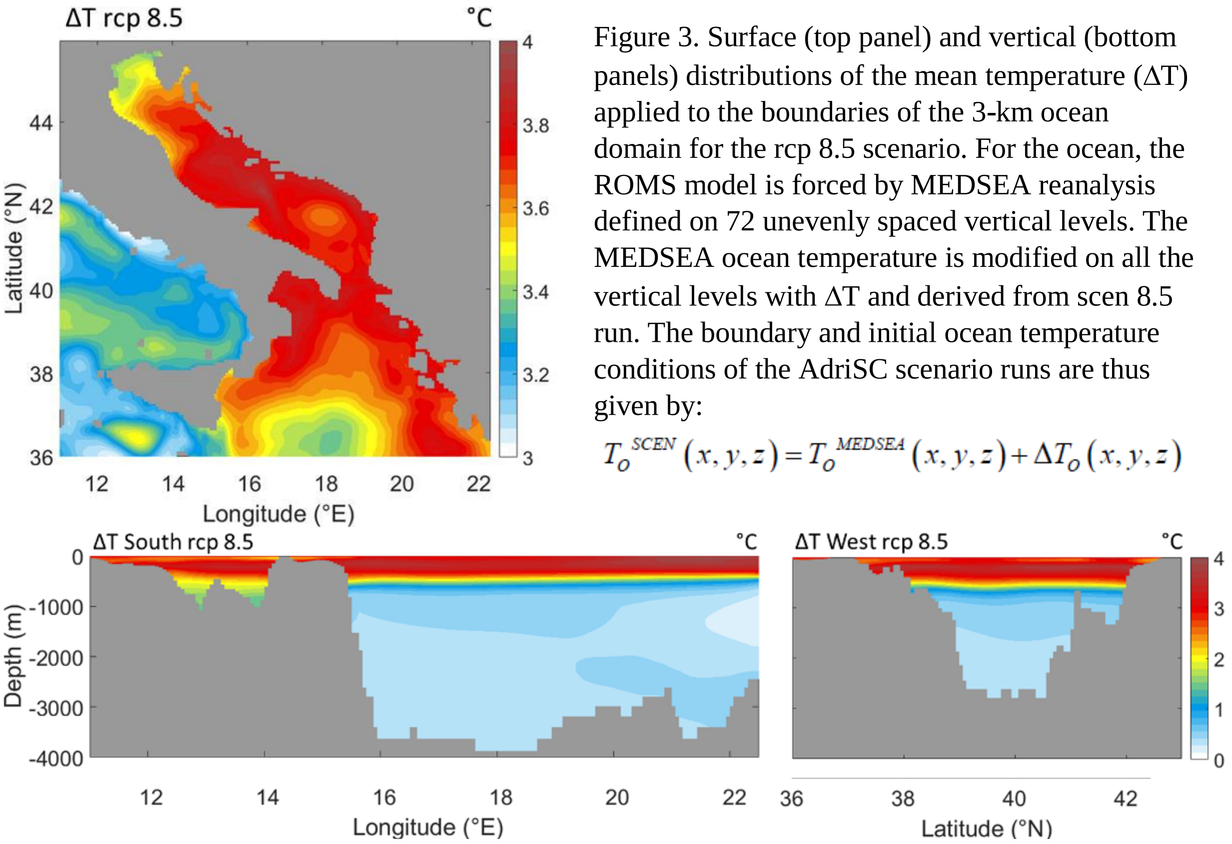


Figure 3. Surface (top panel) and vertical (bottom panels) distributions of the mean temperature (ΔT) applied to the boundaries of the 3-km ocean domain for the rcp 8.5 scenario. For the ocean, the ROMS model is forced by MEDSEA reanalysis defined on 72 unevenly spaced vertical levels. The MEDSEA ocean temperature is modified on all the vertical levels with ΔT and derived from scen 8.5 run. The boundary and initial ocean temperature conditions of the AdriSC scenario runs are thus given by:

$$T_O^{SCEN}(x,y,z) = T_O^{MEDSEA}(x,y,z) + \Delta T_O(x,y,z)$$

The test of the PGW method consisting in running ensembles of short simulations for extreme events, led to the statistical approach presented in Figures 4 and 5. Concerning the extreme bora events, this approach provided some new insights in terms of the future of the bora dynamics and sea surface cooling for the 2060-2100 period under both RCP 4.5 and RCP 8.5 scenarios (main results presented in Figure 5):

- the sharp decrease in intensity of the bora horizontal wind speeds between the surface and 2 km of height – also seen, to some extent, by the EURO-CORDEX ensemble (Belušić Vozila et al., 2019), is mostly due to the strong decrease in intensity of the wave breaking along the lee of the Velebit mountain range which is generally not well captured by regional climate models (Josipović et al., 2018; Denamiel et al., 2020b);
- due to the decrease in relative humidity, the intensity of the negative latent heat fluxes, driving the sea surface cooling in the northern Adriatic Sea, is expected to increase under global warming despite the decrease of the bora wind speeds;
- the extreme sea surface cooling (below -1 °C) is expected, on the one hand, to require more intense latent heat fluxes (due to the presence of warmer waters) and, on the other hand, to remain identical or even to slightly increase in the future, even though not necessarily at the same locations than in evaluation mode.

Following these results presented for a future warmer climate, due to an increase in latent heat losses driven mostly by a decrease in relative humidity, the rates of dense water formation might remain untouched which might have important consequences concerning the thermohaline circulation in the Adriatic-Ionian region. In particular, it may influence the future of the decadal oscillations of the Adriatic thermohaline and biogeochemical properties driven by the Adriatic-Ionian Bimodal Oscillating System (BiOS, Gačić et al., 2010; Civitarese et al., 2010; Vilibić et al., 2012; Batistić et al., 2014).

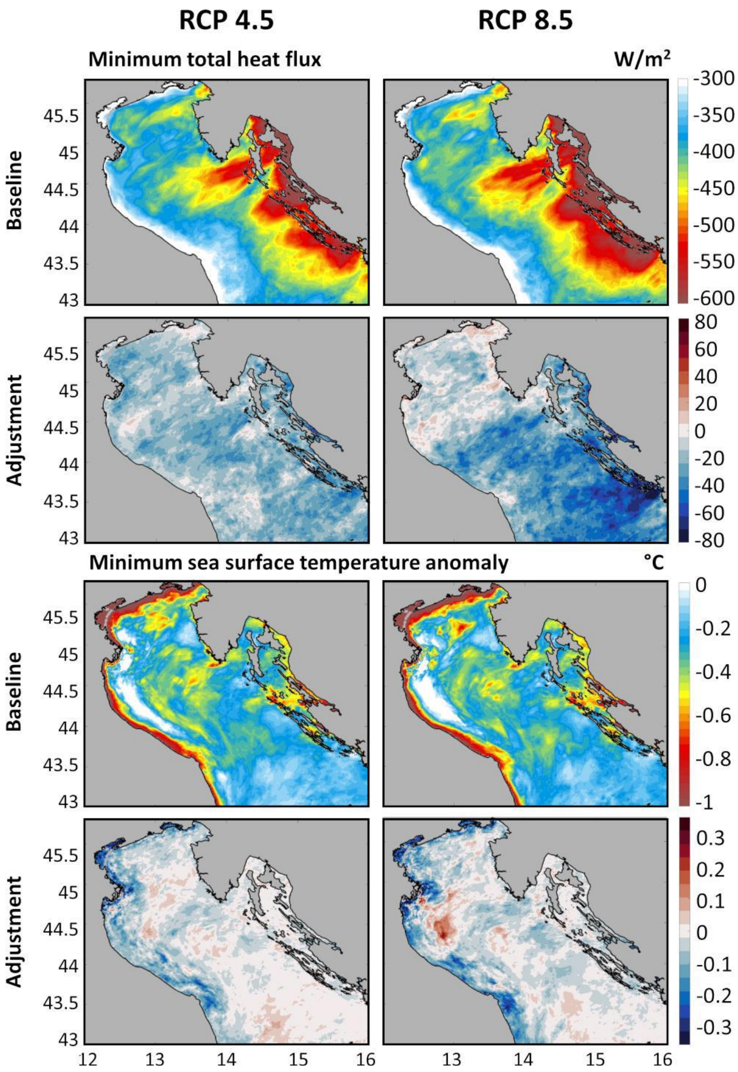


Figure 4. Baseline RCP 4.5 and RCP 8.5 conditions (median of the scenario results) and climate adjustment (median of difference between scenario and evaluation results) for the minimum of both the total heat flux and the sea surface temperature anomaly during each of the 22 selected events.

The other important component of this approach was to provide a thorough evaluation of the AdriSC modelling suite skill to reproduce historical extreme events and to provide meaningful climate projections via the PGW method. The evaluation of the distributions of both the wave parameters (significant height, peak period and mean direction) against 11 stations located along the Adriatic coast and the storm surges against the Venice and Trieste tide gauges (Figure 5), revealed that overall the AdriSC model is capable of reproducing the selected 36 historical extreme events.

Concerning the climate simulations with the PGW method, the wave and storm surge distributions – showing a general decrease of the extreme bora and sirocco intensity for both RCP 4.5 and RCP 8.5 scenarios, follow the previous studies published in the Adriatic Sea (Benetazzo et al. 2012; Lionello et al. 2012; Androulidakis et al. 2015; Bonaldo et al. 2017; Pomaro et al. 2017; Belušić Vozila et al. 2019) and thus the statistical approach consisting in running ensembles of short simulations for extreme events seems to provide robust results.

To conclude, despite the known numerical cost and slowness of the AdriSC climate model (Denamiel et al., 2019, 2020a), the conjoint use of an ensemble approach and the pseudo-global warning (PGW) methodology for short-term simulations (i.e. 3 days) allowed to both accurately represent historical bora storms (Denamiel et al., 2020b) and better understand the impact of global warming on extreme bora dynamics and sea surface cooling in the northern Adriatic region (under both RCP 4.5 and RCP 8.5 scenarios). This has been achieved using far less computational resources than a traditional regional climate model running 31 years in evaluation mode, 50 years in historical mode and 100 years in scenario mode.

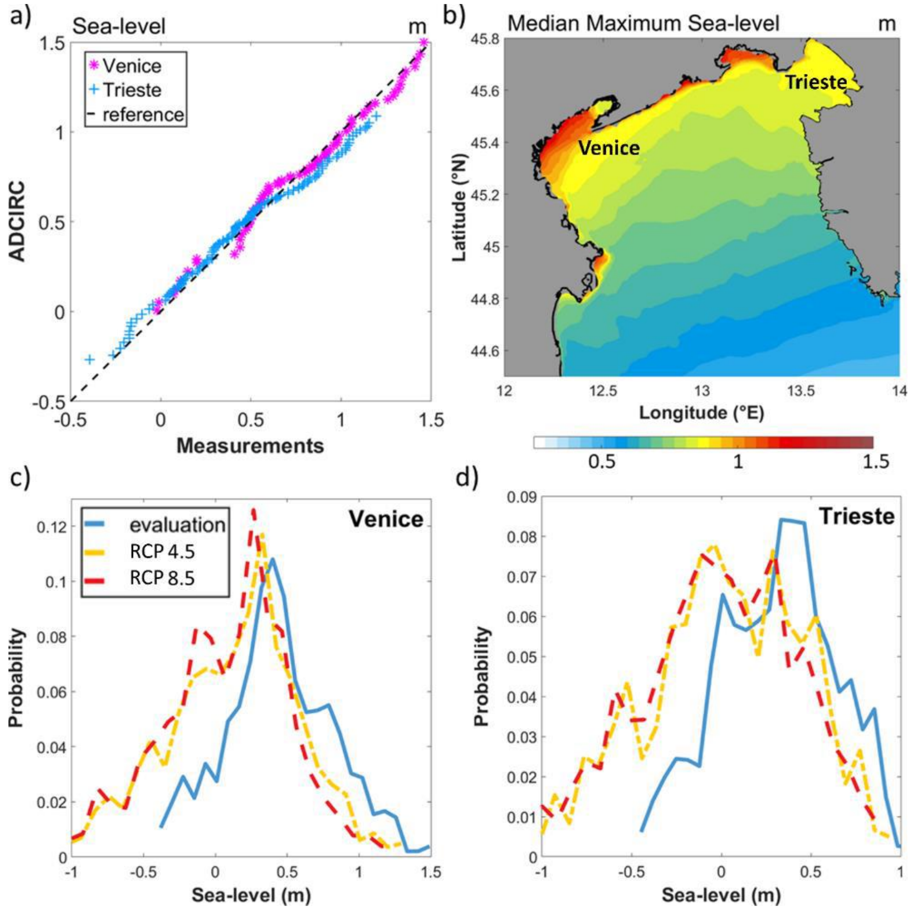


Figure 5. Analysis of the northern Adriatic storm surge distributions during the 14 sirocco events: a) quantile-quantile analysis of the AdriSC ADCIRC results and the measurements at Venice and Trieste tide-gauge stations, b) baseline sea-level plot defined as the median of the maximum sea-levels generated by each storm, c) and d) sea-level distributions derived from the 1-min AdriSC ADCIRC evaluation and climate projection (RCP 4.5 and RCP 8.5) results and extracted at Venice and Trieste tide gauge stations.

3) Evaluation of the 31-year long AdriSC climate simulation for the 1987-2017 period

At the end of the special project, only the 31-year long simulation in evaluation mode (1987-2017) was completed while the RCP 8.5 scenario run was still running and will be completed this year within the framework of another special project in continuation of this one. However, the evaluation has been used to thoroughly assess the skills of the AdriSC climate model to reproduce the regional and coastal circulation in the Adriatic region in the atmosphere and in the ocean.

3.1) Atmosphere

For the atmosphere, the AdriSC WRF 3-km model performance was assessed for 6 different variables (i.e. temperature, dew point, rain, pressure and wind speed and direction) by comparison to a comprehensive collection of freely available observational data retrieved for the 1987-2017 period from in situ measurements, gridded datasets and remote-sensing products (Figure 6): (1) the E-OBS (v21.0e) ensemble dataset (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php), (2) the Cross-Calibrated Multi-Platform or CCMP V2 (Atlas et al., 2011; Mears et al., 2019), (3) the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis TMPA (3B42), (4) ground-based stations (hereafter NOAA stations) accessible from the Integrated Surface Database (ISD) hosted by the National Oceanographic and Atmospheric Agency (NOAA) and (5) soundings from the database of the University of Wyoming (UWYO; http://weather.uwyo.edu/upperair/sounding.html).

However, the evaluation of kilometer-scale coupled atmosphere-ocean models – which requires high quality observations with dense spatial coverage and hourly records – is not yet state-of-the-art in the climate community. Consequently, the quality of the comprehensive dataset of open source remote sensing and in situ observations was also discussed at length based on the assumption that the quality of the observational datasets can also be assessed with climate models following Massonnet et al. (2016).

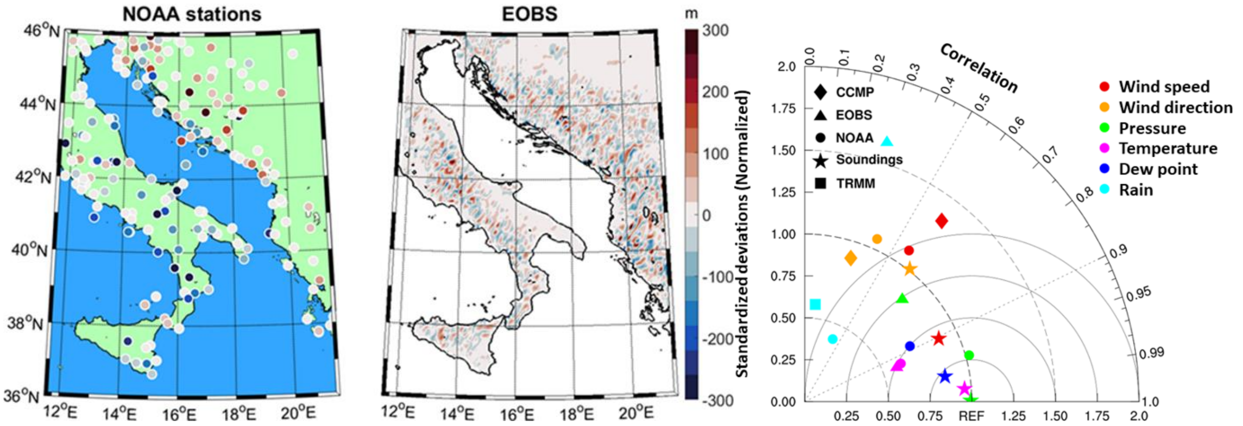


Figure 6. Biases between the AdriSC WRF 3-km orography and both the NOAA stations and the E-OBS dataset elevations (left and middle panels). Taylor diagram (right panel) summarizing the skills of the AdriSC WRF 3-km model to reproduce wind speed and direction, sea-level pressure, temperature, dew point and rain compared to freely available observations (i.e. E-OBS gridded dataset, CCMP and TRMM remote-sensing gridded products, NOAA ground-based stations and UWYO soundings in situ measurements).

The atmospheric evaluation (Denamiel et al., 2021b) thus aimed at answering the following questions: What are the strengths and shortcomings of the AdriSC atmospheric model depending on the evaluated essential climate variables and how are they related to the physical set-up of the model? Are the skills of the newly developed climate model similar at the daily and hourly time-scales? How the performance of the kilometer-scale atmospheric model compare to the RCMs set-up within the CORDEX community? What is the quality and the reliability of the freely available observations in the Adriatic region?

Overall, the evaluation of the AdriSC WRF-3km model highlighted three important points. First, the AdriSC WRF 3-km model demonstrates some skill to represent the climate variables and particularly the climatology of the precipitations and the dew point temperatures (Figures 6 and 7), with the exception of the summer temperatures systematically underestimated by up to 5 °C over the entire domain (left panels, Figure 7). Second, some of the quantified biases are directly linked to the physics set-up of the AdriSC WRF 3-km model. For example, as the AdriSC WRF 3-km model resolves some of the small-scale convective clouds, boundary effects can be seen in the spatial rain biases linked to the Kain-Fritch cumulus parametrization used in the mother grid (i.e. the AdriSC WRF 15-km model). More importantly, the summer temperature biases found over the entire 3-km Adriatic-Ionian 1domain can definitely be linked to the choice of the MYJ and Eta numerical schemes (Janjić, 1994) used for the planetary boundary and surface layers, respectively. Indeed, Varga and Breuer (2020) have recently demonstrated that replacing the MYJ scheme with the University of Washington (UW; Bretherton and Park, 2009) parameterization could improve the representation of the temperature over their domain partially covering the Adriatic region. And third, several problems exist over the Adriatic region concerning the open source observations collected for the evaluation. For example, the E-OBS dataset presents spurious results of mean sea-level pressure along the eastern Adriatic coast and the quality of the ground-based station records provided by the NOAA seems to have been degraded due to successive unit conversions and rounding errors leading to non-continuous distributions (i.e. probability density functions with a hedgehog shape, bottom panels, Figure 7).

Despite these limitations, the added value of the AdriSC WRF 3-km over the Adriatic region has clearly been demonstrated. The use of the AdriSC WRF 3-km model indeed leads to a better representation of the temperatures (except in summer), the atmospheric pressure and above all the precipitations compared to the results of the WRF models from the EURO-CORDEX RCM ensemble (e.g. Kotlarski et al., 2014; Varga and Breuer, 2020).

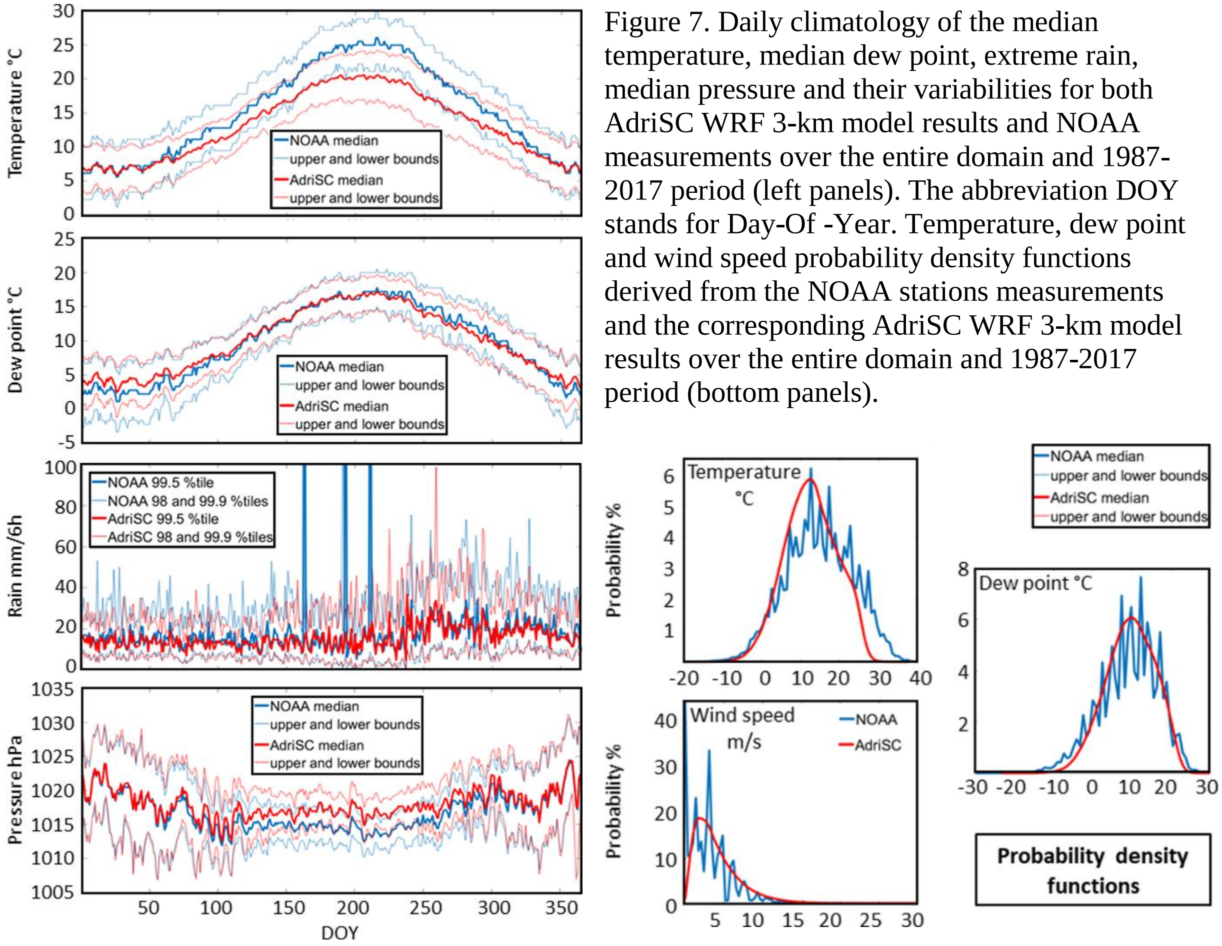


Figure 7. Daily climatology of the median temperature, median dew point, extreme rain, median pressure and their variabilities for both AdriSC WRF 3-km model results and NOAA measurements over the entire domain and 1987-2017 period (left panels). The abbreviation DOY stands for Day-Of -Year. Temperature, dew point and wind speed probability density functions derived from the NOAA stations measurements and the corresponding AdriSC WRF 3-km model results over the entire domain and 1987-2017 period (bottom panels).

3.2) Ocean

For the ocean, the AdriSC ocean model (ROMS 3-km and ROMS 1-km) performances are assessed for 5 different variables (sea-surface height, temperature, salinity, ocean current speed and direction) by comparison to a comprehensive collection of observational data retrieved for the 1987-2017 period from in situ measurements and remote-sensing gridded products: (1) the Sea Surface Height Anomalies (SSHA) gap-free remote sensing (L4) product, SEA_SURFACE_HEIGHT_ALT_GRIDS_L4_2SATS_5DAY_6THDEG_V_JPL1812 (Zlotnicki et al., 2019), (2) two different sea-surface temperature (SST) gap-free remote sensing (L4) products: AVHRR_OI-NCEI-L4-GLOB-v2.0 (National Centers for Environmental Information, 2016) and MUR-JPL-L4-GLOB-v4.1 (JPL MUR MEaSUREs Project, 2015), (3) a comprehensive collection of temperature and salinity in situ Conductivity Temperature Depth (CTD) observations with diverse temporal and spatial coverages (left top panel, Figure 4) and (4) a collection of ocean currents speed and direction combining Acoustic Doppler Current Profiler (ADCP) and Rotor Current Meter (RCM) in situ observations with diverse temporal coverage (right top panel, Figure 4).

The findings of the ocean evaluation are fourfold. First (not presented here), the AdriSC ROMS 3-km model has been found to show some skill in reproducing (1) the observed decadal signal of sea-surface height anomaly interpreted as the BiOS cycles – despite presenting a weaker intensity compared to the seasonal and interannual variabilities, and (2) the observed SST – despite presenting a persistent negative bias within the Adriatic Sea probably linked with the summer cold bias found in the AdriSC WRF 3-km model (Denamiel et al., 2021b).

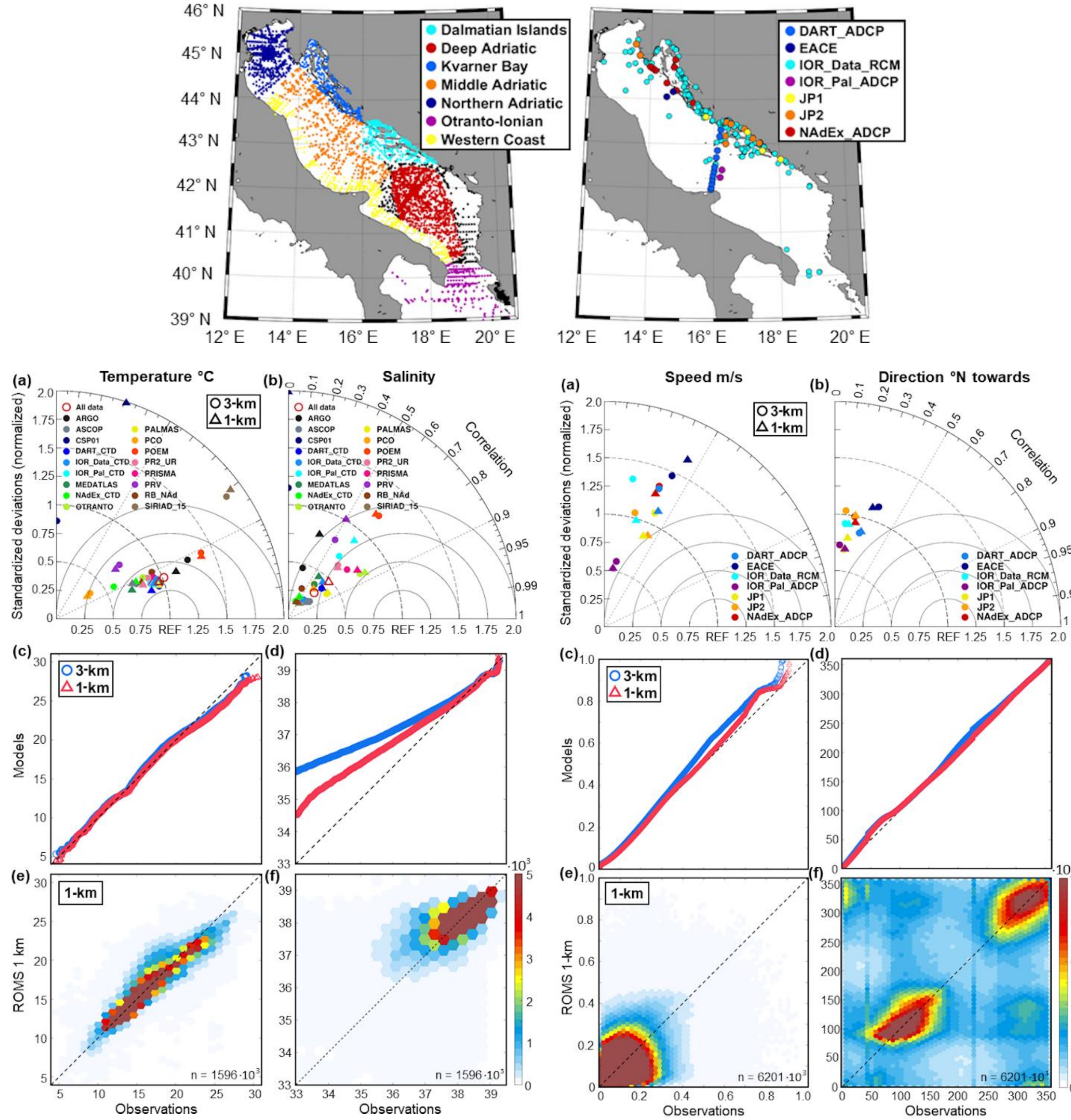


Figure 8. Conductivity Temperature Depth (CTD) observations separated in 7 sub-domains and Acoustic Doppler Current Profiler (ADCP) or Rotor Current Meter (RCM) measurements from 7 different sources (top panels). Evaluation of the AdriSC ROMS 3-km and 1-km thermohaline properties (left bottom panels) with temperature and salinity results against observations from 17 different datasets with Taylor diagrams and quantile–quantile plots as well as, only for the 1-km model, scatter plots showing the density (number of occurrences) with hexagonal bins and total number of points n. Evaluation of the AdriSC ROMS 3-km and 1-km dynamical properties (right bottom panels) with current speeds and directions against observations from 7 different datasets with Taylor diagrams and quantile–quantile plots as well as, only for the 1-km model, scatter plots showing the density (number of occurrences) with hexagonal bins and total number of points n.

Second, the AdriSC ROMS 1-km model has been found to be more suitable to reproduce the observed daily temperatures and salinities as well as hourly ocean currents than the AdriSC ROMS 3-km model (bottom panels, Figure 8), thus highlighting the necessity for higher resolution ocean climate simulations in the Adriatic Sea.

Then, the detailed analysis of the AdriSC ROMS 1-km simulation revealed that (1) for the daily temperature and salinity, better results are found in the deepest parts than in the shallow shelf and coastal parts, particularly for the surface layer of the Adriatic Sea, while, (2) for the hourly ocean currents, better results are found for the RCMs and ADCPs located along the eastern coast and the north- eastern shelf than for the ADCPs located in the middle-eastern coastal area and the deepest part of the Adriatic Sea. Finally, the AdriSC ROMS 1-km model was found (1) to perform well in reproducing the seasonal thermohaline properties of the water masses over the entire Adriatic Sea, despite a common overestimation of PDAs lower than 26 kg m-3, and (2) consequently, to be a suitable modelling framework for studying the long-term thermohaline circulation triggered by the dense waters forming in the northern Adriatic Sea, cascading along the Italian coast and reaching the northern Ionian Sea where they potentially influence the BiOS regimes.

An important issue raised by this ocean evaluation is that a proper comparison of the ocean climate model skills in the Mediterranean is particularly difficult to achieve due to the absence of standardized ocean observational datasets (similar to the E-OBS products in the atmosphere). Instead, ocean models are evaluated at different spatial and temporal ranges based on the observational datasets available to given researchers of given countries, which makes a fair comparison between models almost impossible. Therefore, inter-comparing ocean climate models in the Mediterranean could only be achieved through the creation of such standardized datasets and, consequently, a change of the ocean data sharing policies, at least at the European level.

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 project has allowed to demonstrate the interest of kilometer-scale coupled atmosphere-ocean climate modelling in the Adriatic region. In particular, studies done during the project, have demonstrated the need for kilometer-scale atmospheric forcing (Denamiel et al., 2021a) as well as the feasibility of using the Pseudo-Global Warming (PWG) methodology to project the impact of climate change for coupled atmosphere-ocean modelling systems (Denamiel et al., 2020a, 2020b). The thorough evaluation presented in this report shows the higher performance of the AdriSC climate model compared to the Regional Climate Models (RCMs) of the EURO- and MED- CORDEX projects (Denamiel et al., 2021b; Pranić et al., 2021). The RCP 8.5 realistic simulation actually running on the continuation of this project is forecasted to finish in fall 2021. By then, it is also expected that more analyses of the evaluation run will be performed.

List of publications/reports from the project with complete references

- Denamiel, C., Šepić, J., Vilibić, I.: Impact of geomorphological changes to harbor resonance during meteotsunamis: The Vela Luka Bay test case. Pure and Applied Geophysics, 175, 3839-3859, 2018.
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Future plans

We have been granted another special project in continuation to this one with the title “Numerical modelling of the Adriatic-Ionian decadal and inter-annual oscillations: from realistic simulations to process-oriented experiments”. This project will allow us (1) to finalize the RCP 8.5 run and then (2) to get new insights concerning the processes involved in the BiOS reversal dynamics with fast process-oriented 100-year long Ionian-Mediterranean simulations run for different forcing conditions.

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