SPECIAL PROJECT PROGRESS REPORT

Reporting year	2021
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
Data storage capacity	(Gbytes)			25,000	13,000

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)

No major problem was encountered in terms of usage of the supercomputing facilities.

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 already provided realistic simulations in evaluation mode (1987-2017) and for RCP 8.5 climate projections (2070-2100) during extreme events and partially as 31-year long continuous runs. The first objective of the project is to finish the 31-year long RCP 8.5 continuous run (currently only 23 years of simulation were carried out). 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 as soon as it is finished. 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. and Vilibić, I.: Balancing accuracy and efficiency of atmospheric models in the northern Adriatic during severe bora events, J. Geophys. Res. Atmos., 126, e2020JD033516, doi:10.1029/2020JD033516, 2021a.
- 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.
- 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.
- Tojčić, I., Denamiel, C., and Vilibić, I.: Performance of the Adriatic early warning system during the multi-meteotsunami event of 11–19 May 2020: an assessment using energy banners, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2020-409, in review, 2021.

Summary of results

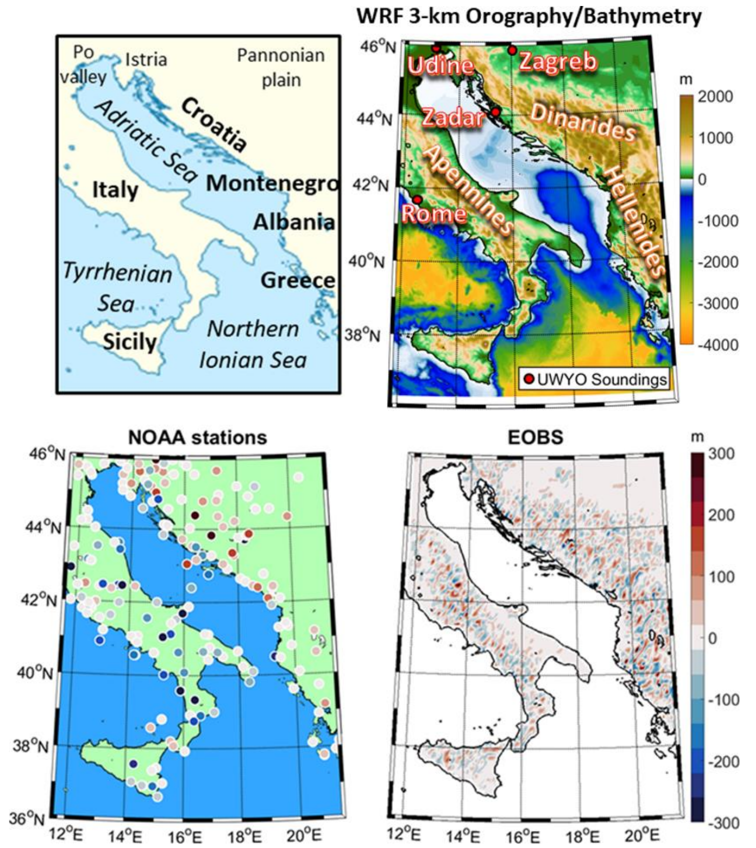
1. Evaluation of the realistic 31-year long simulation

As the continuation of the previous 3 years of the special project, the 31-year long realistic simulations in evaluation mode (1987-2017) was already available at the start of 2021 and has been used to thoroughly assess the skills of the AdriSC climate model (Denamiel et al., 2019; see details in previous reports and Table 1) to reproduce the regional and coastal circulation in the Adriatic region (top left panels, Figure 1) 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).

Table 1. Summary of the AdriSC climate component main features for the evaluation run.

	Atmosphere		Ocean	
Models	WRF		ROMS	
Number of domains	2		2	
Horizontal resolution	15 km	3 km	3 km	1 km
Vertical resolution	58 levels		35 levels	
Time step	60 s	12 s	150 s	50 s
Initial and boundary Conditions	ERA-Interim		MEDSEA	
31-year period	1987-2017			
Frequency of outputs	Hourly			

1.1 Atmospheric model



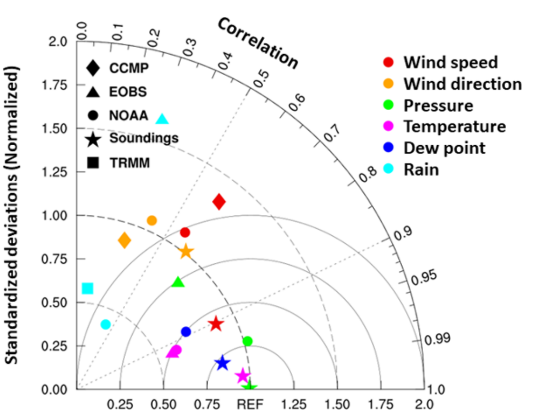


Figure 1. Name of the geographical and orographic/bathymetric features of the AdriSC WRF 3-km model domain, location of the UWYO soundings and biases between the AdriSC WRF 3-km orography and both the NOAA stations and the E-OBS dataset elevations (left panels). Taylor diagram (bottom panel) summarizing 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).

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 1, left panels): (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).

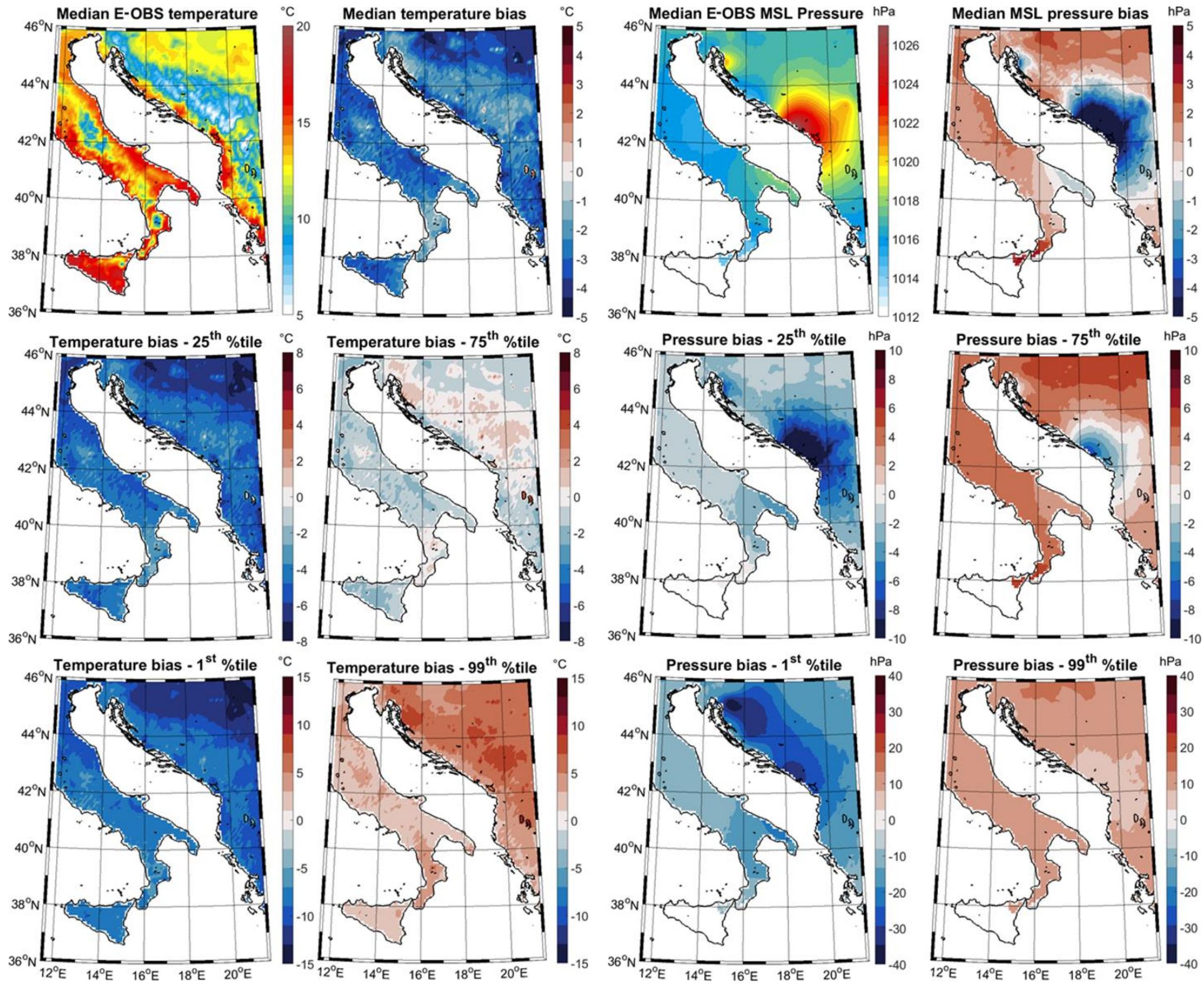


Figure 2. Median of the E-OBS daily mean temperature dataset over the land as well as median and 25th, 75th, 1st percentile, 99th percentiles of the daily temperature biases between AdriSC WRF 3-km model results and E-OBS dataset over the land during the 1987-2017 period (left panels). As for left panels but for the atmospheric pressure (right panels).

However, the evaluation of kilometre-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 be assessed with climate models, Massonnet et al. (2016) highlighted the need to provide guidance for a more objective selection of the observations used in evaluation studies.

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 kilometre-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?

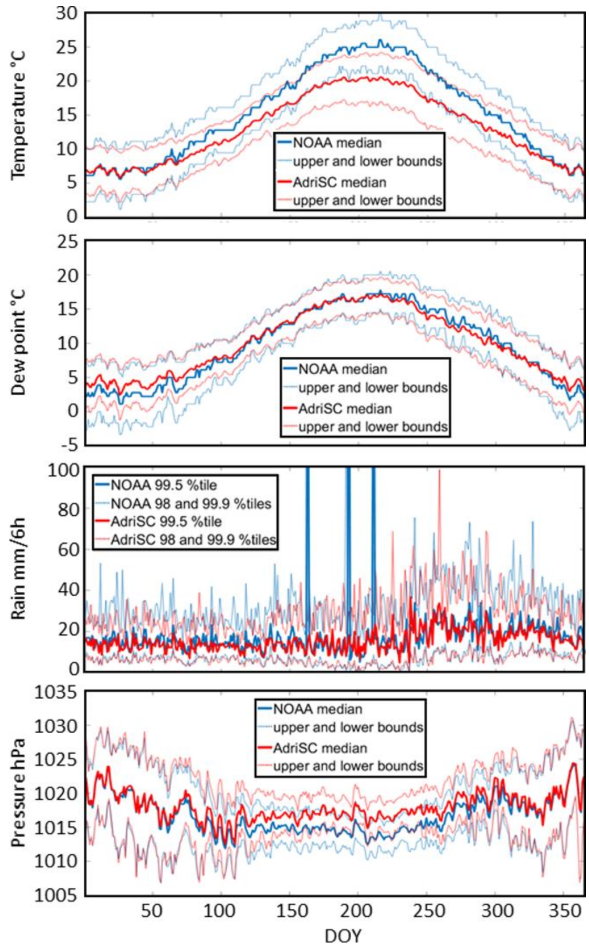
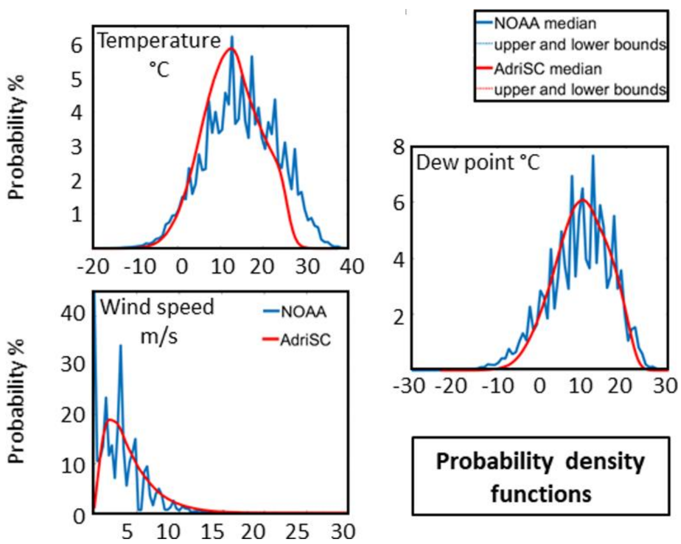


Figure 3. Daily climatology of the median temperature, median dew point, extreme rain, median pressure and their variabilities for both AdriSC WRF 3-km model results and NOAA measurements over the entire domain and 1987-2017 period (left panels). The abbreviation DOY stands for Day-Of -Year. Temperature, 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). It is important to notice that the probability density functions are obtained via a kernel smoothing method, which presents the advantage of generating continuous distributions but may overestimate the tails of these distributions.



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 1 to 3), with the exception of the summer temperatures systematically underestimated by up to 5 °C over the entire domain (left panels, Figures 2 and 3). 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 (right panels, Figure 2) 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 3).

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).

1.2 Ocean models

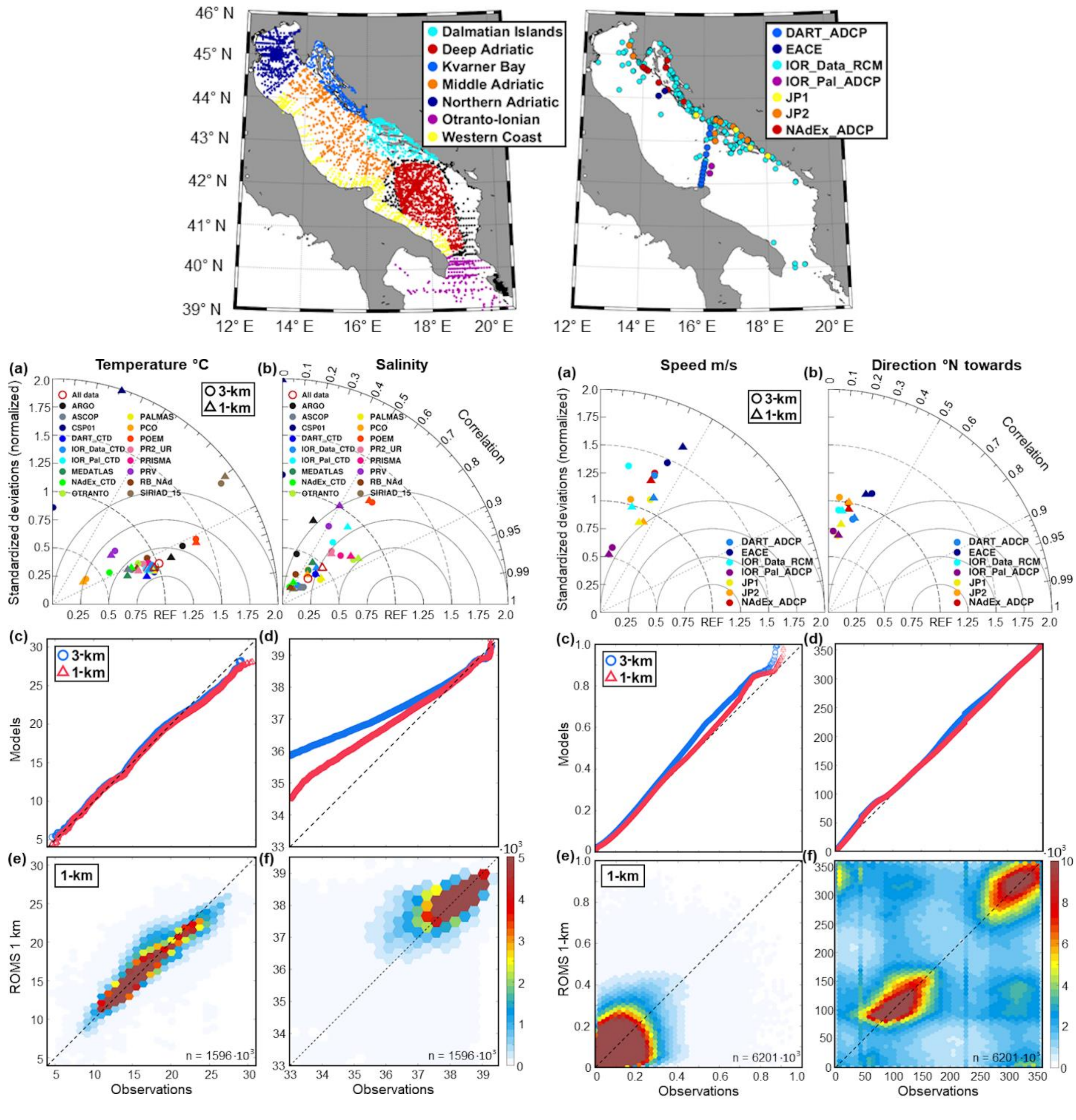


Figure 4. Conductivity Temperature Depth (CTD) observations separated in 7 sub-domains and Acoustic Doppler Current Profiler (ADCP) or Rotor Current Meter (RCM) measurements from 7 different sources (top panels). Evaluation of the AdriSC ROMS 3-km and 1-km thermohaline properties (left bottom panels) 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.

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).

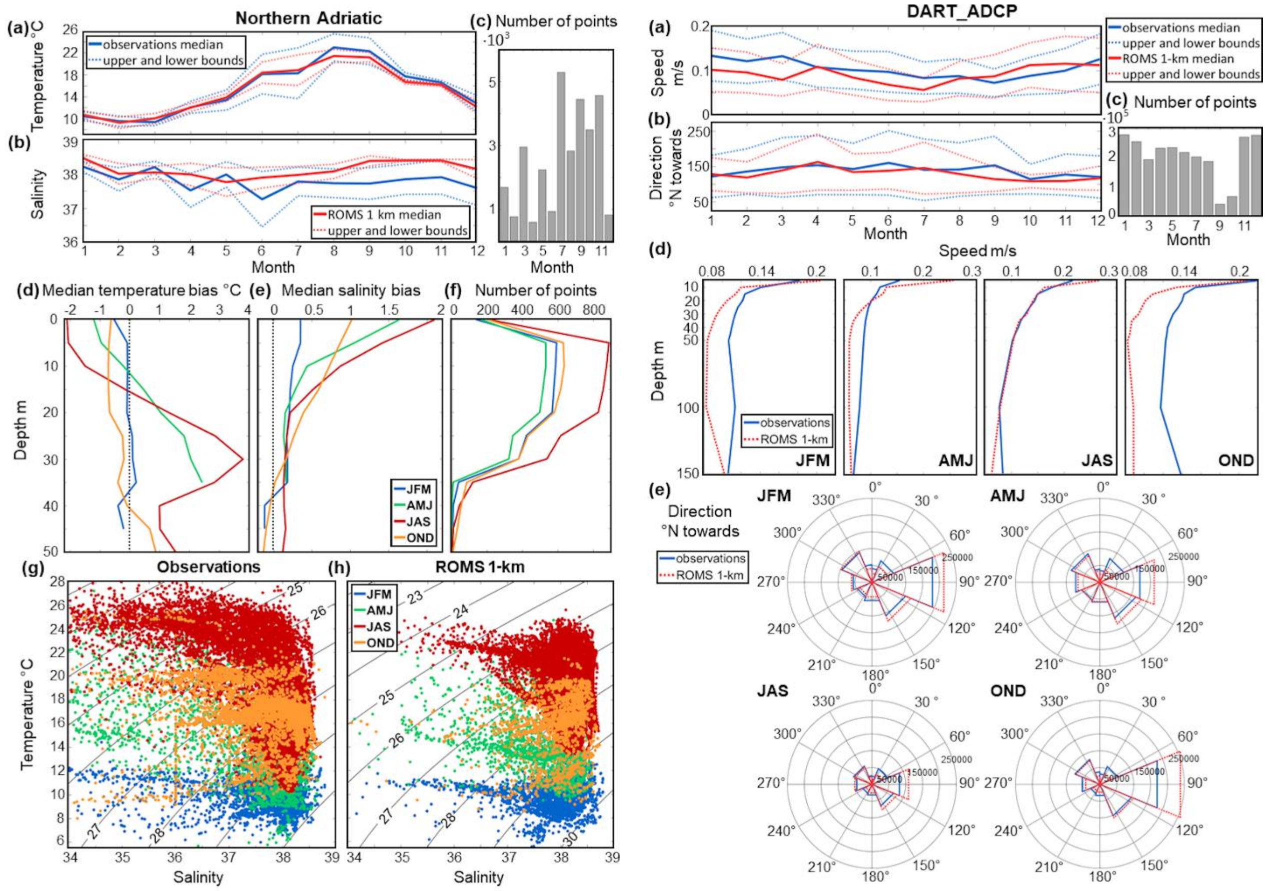


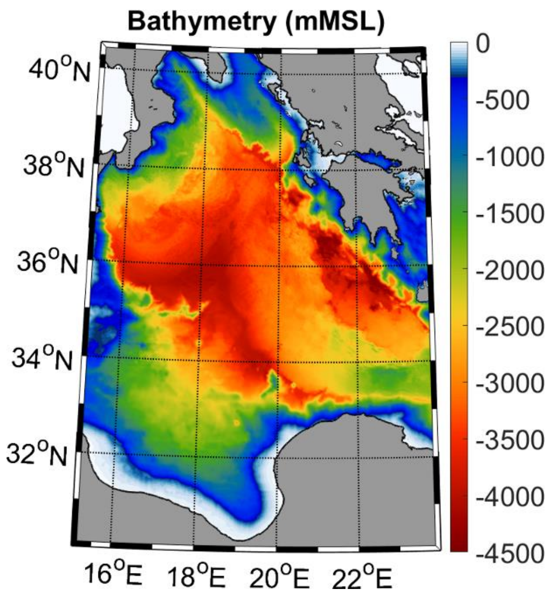
Figure 5. Northern Adriatic subdomain (left panels) with monthly climatology of AdriSC 1-km and in situ (a) median temperature, (b) median salinity and their variabilities (i.e. upper and lower bounds defined as ±MAD) as well as (c) number of observations per month. Seasonal variations of the (d) temperature and (e) salinity biases between the AdriSC ROMS 1-km model and observations depending on the depth as well as (f) number of observations per depth. Seasonal T-S diagrams for (g) the CTD observations and (h) the AdriSC ROMS 1-km model with Potential Density Anomaly (PDA) isolines. DART_ADCP dataset (right panels) with monthly climatology of AdriSC 1-km and in situ (a) median speed, (b) median direction and their variabilities (i.e. upper and lower bounds defined as ±MAD) as well as (c) number of observations per month. Seasonal variations of the (d) speed of AdriSC ROMS 1-km model and observations depending on the depth. Seasonal rose plots of the (e) direction for ADCP observations and the AdriSC ROMS 1-km model.

The findings of the ocean evaluation are fourfold. First (not presented in this report), 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). 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 4), 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 (e.g. Figure 5) 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.

2. Process-oriented simulations

For the process-oriented simulations, a new ocean ROMS model at 3-km of horizontal resolution (268x389 points) and with 45 terrain-following vertical levels, was set-up to cover the entire Ionian and middle Mediterranean region as seen in Figure 6 (left panel).



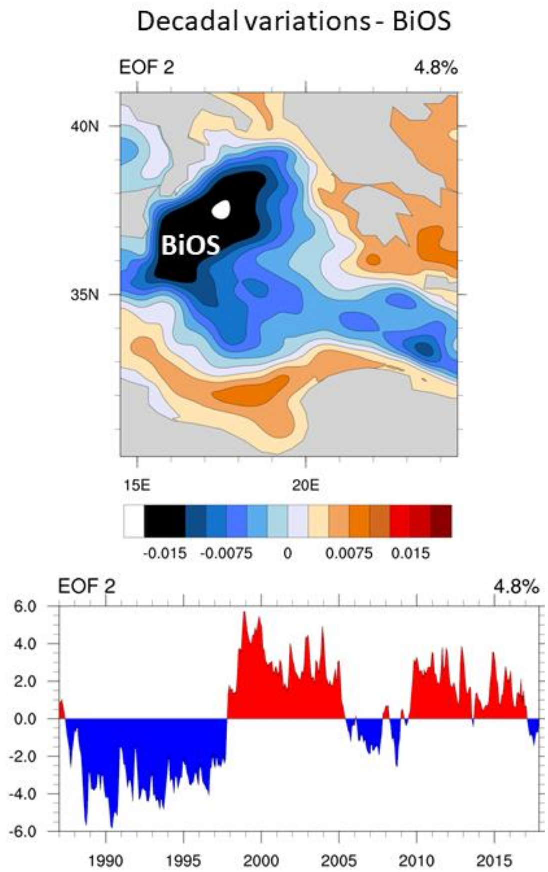


Figure 6. ROMS 3-km Ionian-Mediterranean domain and bathymetry used for the process-oriented simulations (left panel). Spatial and temporal variations of the second Empirical Orthogonal Function (EOF) – representative of the decadal variations of the BiOS – extracted from the MEDSEA re-analysis for the 1987-2017 period (right panels).

The new model (above described) simulates a year of ocean conditions in about 12 hours using 150 CPUs which is extremely fast compared to the realistic simulations which simulate a month of coupled atmosphere-ocean results in about a day using 260 CPUs. The reversal of the BiOS is thus mimicked by running in parallel “Cyclonic” and “Anti-cyclonic” conditions for 100-year long simulations and different conditions: e.g. increase/decrease of the dense water flowing from the northern boundary, flattening of the bathymetry at 800 m, etc. The (anti-) cyclonic conditions were determine by extracting the Empirical Orthogonal Functions from the Sea-Surface Height (SSH) re-analysis product from the MEDSEA database (also used to force the realistic simulations). In Figure 6 (right panels), it can be seen that the spatial pattern of the BiOS is well defined for the EOF 2 representing about 5 % of the total signal and associated with decadal variations. From these results two daily climatologies (temperature, salinity, currents and SSH) were calculated during the 1998-01-02 to 2005-06-02 period for the cyclonic conditions and during the 1987-06-01 to 1997-11-02 period for the anti-cyclonic conditions.

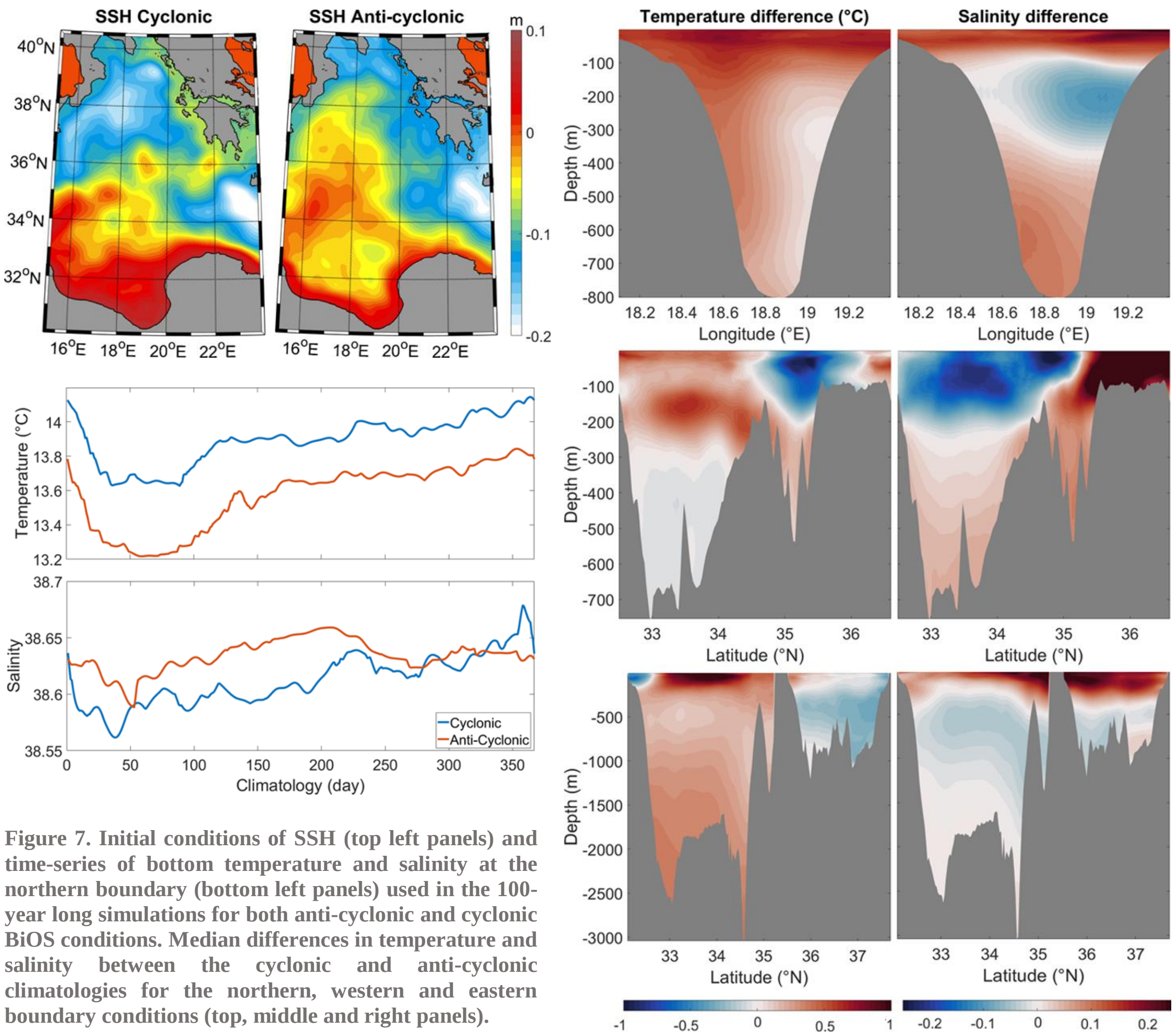


Figure 7. Initial conditions of SSH (top left panels) and time-series of bottom temperature and salinity at the northern boundary (bottom left panels) used in the 100-year long simulations for both anti-cyclonic and cyclonic BiOS conditions. Median differences in temperature and salinity between the cyclonic and anti-cyclonic climatologies for the northern, western and eastern boundary conditions (top, middle and right panels).

The background conditions are defined as the cyclonic and anti-cyclonic simulations forced with realistic bathymetry, no atmospheric input and original climatologies extracted from the MEDSEA dataset. The 100-year simulations of background conditions are presently running on the project but some interesting analyses of the forcing can already be presented in this report. The initial and boundary conditions of the background simulations are presented in Figure 7. The initial SSH figures clearly show the main differences between cyclonic (i.e. lower SSH at the centre of the BiOS gyre) and anti-cyclonic (i.e. higher SSH at the centre of the BiOS gyre) conditions while the time series of temperature in the northern boundary highlight that anti-cyclonic conditions are nearly constantly colder and less saline than cyclonic conditions. The vertical differences of temperature and salinity between cyclonic and anti-cyclonic conditions at the three open boundaries of the domain also reveal that: (1) there is a salinity increase in the anti-cyclonic conditions in the eastern part of the northern boundary, (2) for the western boundary, in surface till 500 m depth, the deepest southern part of the boundary is hotter and less saline for the cyclonic conditions while the northern and shallowest part is colder and more saline, and (3) for the eastern boundary, also in the surface till 500 m, overall the cyclonic conditions are hotter and more saline than the anti-cyclonic ones.

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. In particular, previous studies, done in the first 3 years of the project, have demonstrated the need for kilometre-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 project is forecasted to finish in fall 2021. By then, it is also expected that more analyses of the evaluation run will be performed and that next report (year 2022) will also include preliminary results of the climate change impact on the Adriatic Sea under RCP 8.5 conditions.

In the meantime, the fast process-oriented 100-year long Ionian-Mediterranean simulations will be run for different forcing conditions and, in collaboration with Prof. Michael Ghil, post-treated following the attractor/tipping point theory. It is thus expected that new insights concerning the processes involved in the BiOS reversal dynamics will also be presented in the next report (year 2022).

Overall, it is expected that the prolongation of the special project for the next two years will greatly contribute to build solid knowledge concerning the atmospheric and oceanic dynamical processes in the Adriatic region.

References

Bretherton, C. S., and Park, S.: A new moist turbulence parameterization in the Community Atmosphere Model, J. Clim., 22(12), 3422–3448, doi:10.1175/2008JCLI2556.1, 2009.

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., Quentin, F., Mihanović, H., and Vilibić, I.: Pseudo-global warming projections of extreme wave storms in complex coastal regions: the case of the Adriatic Sea, Clim. Dyn., 55, 2483–2509, doi:10.1007/s00382-020-05397-x, 2020a.

Denamiel, C., Tojčić, I. and Vilibić, I.: Far future climate (2060–2100) of the northern Adriatic air–sea heat transfers associated with extreme bora events, Clim. Dyn., 55, 3043-3066, doi:10.1007/s00382-020-05435-8, 2020b.

Denamiel, C., Tojčić, I. and Vilibić, I.: Balancing accuracy and efficiency of atmospheric models in the northern Adriatic during severe bora events, J. Geophys. Res. Atmos., 126, e2020JD033516, doi:10.1029/2020JD033516, 2021a.

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.

Janjić, Z.: The Step-Mountain Eta Coordinate Model: Further developments of the convection, viscous sublayer, and turbulence closure schemes, Mon. Weather Rev., 122, 927–945, doi:10.1175/1520-0493(1994) 1222.0.CO;2, 1994.

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., and Wulfmeyer, V.: Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble, Geosci. Model Dev., 7, 1297–1333, https://doi.org/10.5194/gmd-7-1297-2014, 2014.

Massonnet, F., Bellprat, O., Guemas, V., and Doblas-Reyes, F. J.: Using climate models to estimate the quality of global observational data sets, Science, 354 (6311), 452-455, doi:10.1126/science.aaf6369, 2016.

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.

Varga, Á. J., and Breuer, H.: Sensitivity of simulated temperature, precipitation, and global radiation to different WRF configurations over the Carpathian Basin for regional climate applications, Clim. Dyn., 55, 2849–2866, doi:10.1007/s00382-020-05416-x, 2020.

Warner, J. C., Armstrong, B., He, R., and Zambon, J. B.: Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system, Ocean Model., 35, 230–244, doi:10.1016/j.ocemod.2010.07.010, 2010.