SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	3rd year
Project Title:	The Adriatic decadal and inter-annual oscillations: modelling component
Computer Project Account:	spcrdena
Principal Investigator(s):	Cléa Denamiel
Affiliation:	Institute of Oceanography and Fisheries (IOF)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Ivica Vilibić (IOF); Ivica Janeković (University of Western Australia); Samuel Somot (Météo-France / CNRM-GAME); Manuel Bensi and Vedrana Kovačević (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS); Ivan Güttler (Meteorological and Hydrological Service – DHMZ) ; Darko Koračin (Faculty of Science of the University of Split, Croatia)
Start date of the project:	01/01/2018
Expected end date:	01/01/2021

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	20,000,000	20,000,000	23,000,000	13,600,000
Data storage capacity	(Gbytes)	25,000	25,000	25,000	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 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 will be 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 method.

Summary of problems encountered (10 lines max)

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 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 added this year. 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.

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

For this year our plans are (1) to finish the on-going evaluation of the AdriSC modelling suite results obtained for the 1987-2017 period, (2) to carry-on with the on-going RCP 8.5 climate simulation (only 7 years of the 31 year-long run are available at the moment) and (3) to perform a more thorough analysis of the evaluation run results.

List of publications/reports from the project with complete references

Already published:

- Denamiel, C., Šepić, J., Vilibić, I., 2018. Impact of geomorphological changes to harbor resonance during meteotsunamis: The Vela Luka Bay test case. Pure and Applied Geophysics, 175, 3839-3859.
- Denamiel, C., Šepić, J. Ivanković, D., Vilibić, I., 2019a. The Adriatic Sea and Coast modelling suite: Evaluation of the meteotsunami forecast component. Ocean Modelling, 135, 71-93. doi:10.1016/j.ocemod.2019.02.003
- Denamiel C, Šepić J, Huan X, Bolzer C, Vilibić I, 2019b. Stochastic surrogate model for meteotsunami early warning system in the eastern Adriatic Sea. Journal of Geophysical Research Oceans, 124, 8485-8499. https://doi.org/10.1029/2019JC015574
- Denamiel C, Šepić J, Huan X, Vilibić I., 2020a. Uncertainty propagation using polynomial chaos expansions for extreme sea level hazard assessment: the case of the eastern Adriatic meteotsunamis. Journal of Physical Oceanography, 50, 1005-2021. https://doi.org/10.1175/JPO-D-19-0147.1

Under review:

- Denamiel, C., Tojčić, I., Vilibić, I., 2020b. Sensitivity of northern Adriatic severe bora dynamics to atmospheric model resolution. Q J Roy Meteo Soc, in review.
- Denamiel, C., Pranić, P., Quentin, F., Mihanović, H., Vilibić, I., 2020c. Pseudo-global warming projections of extreme wave storms in complex coastal regions: the case of the Adriatic Sea. Clim Dyn, in review.
- Denamiel, C., Tojčić, I., Vilibić, I., 2020d. Far future climate (2060-2100) of the northern Adriatic air-sea heat transfers associated with extreme bora events. Clim Dyn, in review.

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 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 described in details in last year report. For this year report, we will thus summarize the results of the test of the PGW method for an ensemble of short-term simulations during extreme events in the Adriatic region. Additionally, we will also present the first results of our evaluation of the AdriSC climate model during the 1987-2017 period.

1) Test of the PGW methodology

1.1) AdriSC modelling suite set-up

Compare to the long-term simulations of the AdriSC climate model which only used the COAWST model (i.e. online coupling of WRF and ROMS/SWAN models) in the basic module (Table 1), the nearshore module of the suite is also used in this experiment. In this module, the fully coupled ADCIRC-SWAN unstructured model (Dietrich et al. 2012) – covering the entire Adriatic Sea with resolutions ranging from 5-km in the deepest part of the domain to 10 m at the coast (Table 1), 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.

Table 1. AdriSC modelling suite main features

	Basic module				Nearshore module	
	Atmosphere		Ocean		Atmosphere	Ocean
Models	WRF		ROMS-SWAN		WRF	ADCIRC-SWAN
Number of domains	2		2		1	1
Resolution	15 km	3 km	3 km	1 km	1.5 km	5 km to 10 m
Initial and boundary conditions	ERA-Interim		MEDSEA ERA-Interim		WRF 3-km	ROMS-SWAN 1-km
Duration of run (with d0 the day of the event at 0 h)	72 h from d0 – 48 h to d0 + 24 h				36 h from d0 - 12 h to d0 + 24 h	
Frequency of outputs	Hourly				1-min	

To test the PGW methodology, we reproduce the strongest historical storms driven by either bora or sirocco winds in the Adriatic Sea during the 1979-2019 period and we assess their behaviour under climate change projections (RCP 4.5 and RCP 8.5 scenarios). The SWAN wave model – originally unused in the AdriSC modelling suite, was thus set-up in both modules (basic and nearshore) to be coupled with the ocean and atmosphere models (i.e. WRF, ROMS, ADCIRC). The wave model receives forcing from WRF 3-km (wind fields) and ROMS 3-km/1-km (ocean surface currents, sea-level and friction) every 10 minutes in the basic module and from WRF 1.5-km (wind fields) and ADCIRC (ocean barotropic currents, sea-level and friction) every minute in the nearshore module. For the evaluation runs, during the 1979-2019 period, in order to reproduce the historical storms as accurately as possible, the basic module was set-up to run for three days. Initial conditions and boundary forcing were provided the 6-hourly ERA-Interim re-analysis fields (Dee et al. 2011; Balsamo et al. 2015), either the monthly or the daily re-analysis MEDSEA-Ocean fields (Pinardi et al. 2003), depending on whether the storm took place before or after the 1st of January 1987, and either the 6-hourly ERA-Interim wave fields or the hourly MEDSEA-Wave fields (Ravdas et al. 2018), depending on whether the storms took place before or after the 1st January 2006. The nearshore module, forced by the results of the basic module, was set-up to run for the last day and half of the basic module simulations.

1.2) Events, observations and AdriSC model evaluation

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).

The set of wave measurements – used to evaluate the skills of the AdriSC nearshore module to reproduce the 36 selected wave storms, spans between 1979 and 2019 and consists in 6 stations along the Italian coast, 4 stations along the Croatian coastline and one station in the middle of the northern Adriatic shelf. While the set of long-term land-based observations extracted at 9 different weather stations in the northern Adriatic from the databases of the NOAA's National Centers for Environmental Information (Smith et al. 2011; https://www.ncdc.noaa.gov/isd) were used to evaluate the 22 bora storms only.

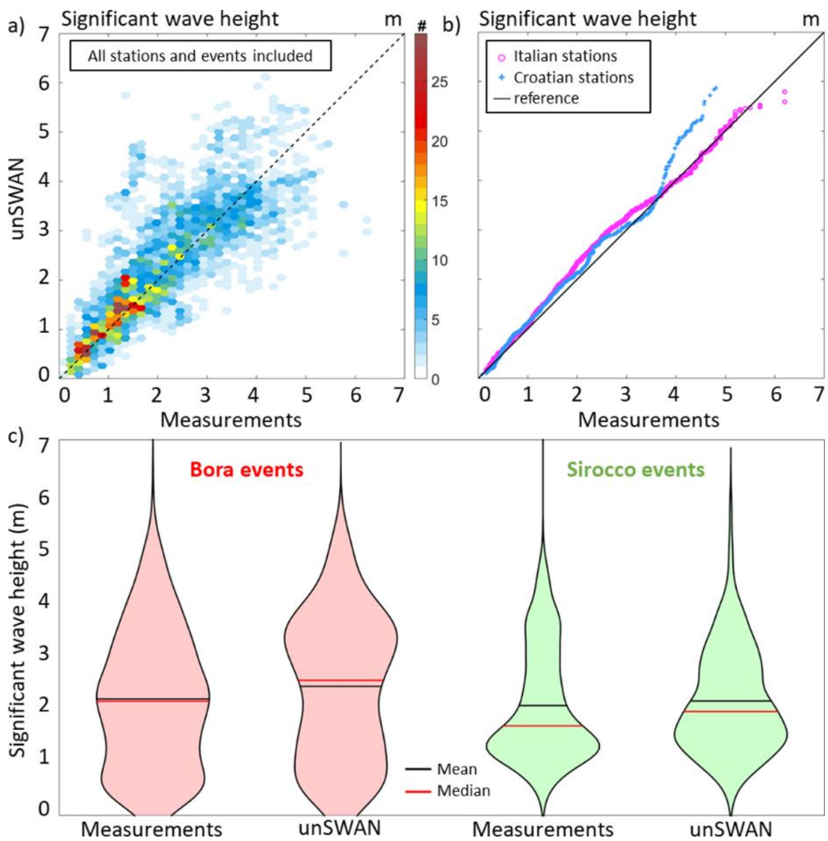


Figure 1. Evaluation of the AdriSC unSWAN significant wave height distributions against measurements (a) for all the available stations and selected storm events as a scatter plot showing the density (number of occurrences #) with hexagonal bins, (b) separately for the Italian and Croatian stations as a quantile-quantile plot, and (c) separately for the bora and sirocco events as violin plot distributions

For the evaluation of the waves, only the SWAN results from the ADCIRC-SWAN unstructured model (hereafter referred as unSWAN) are presented. In Figure 1 it can be seen that the unSWAN model seems to have more difficulties to represent the wave conditions during bora events than during sirocco events, which means that the WRF 1.5-km model is most probably overestimating the intensity of the bora winds. Further, the model is capable of reproducing the intensity of the extreme wave events (see quantile-quantile distributions) but not their timing (see spread of the scatter plots), and have better agreement with measurements along the Italian coast than along the Croatian coast. Beside these limitations, the evaluation of the unSWAN model has shown that the newly added wave component of the AdriSC modelling suite can be used to reproduce the historical Adriatic wave storms with a good level of accuracy.

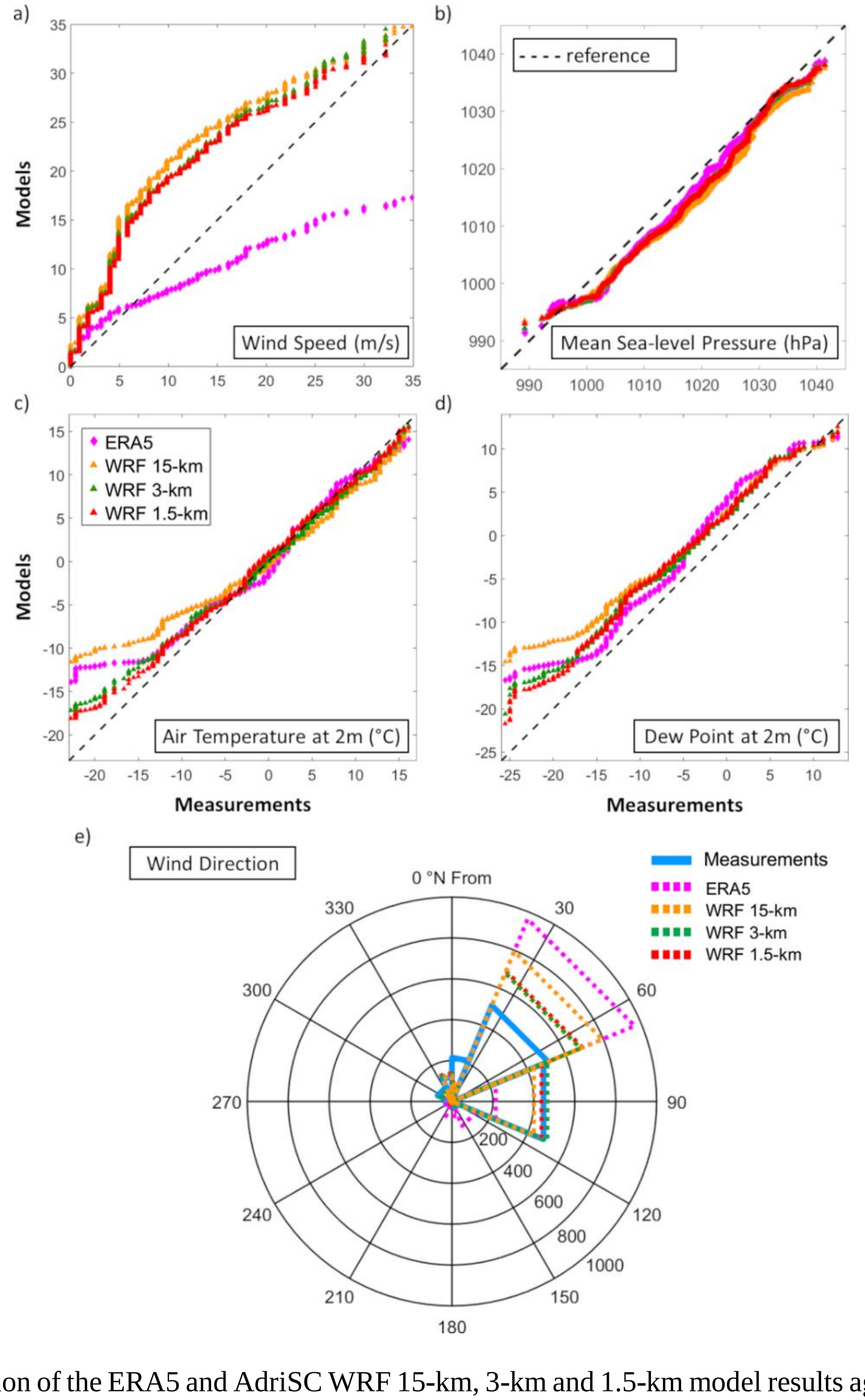


Figure 2. Evaluation of the ERA5 and AdriSC WRF 15-km, 3-km and 1.5-km model results against wind speed (quantile-quantile or q-q plot panel a) and direction (rose plot panel e) at 10 m, mean sea-level pressure (q-q plot panel b) and air temperature and dew point at 2 m (q-q plots panels c and d) measurements at the 9 available stations.

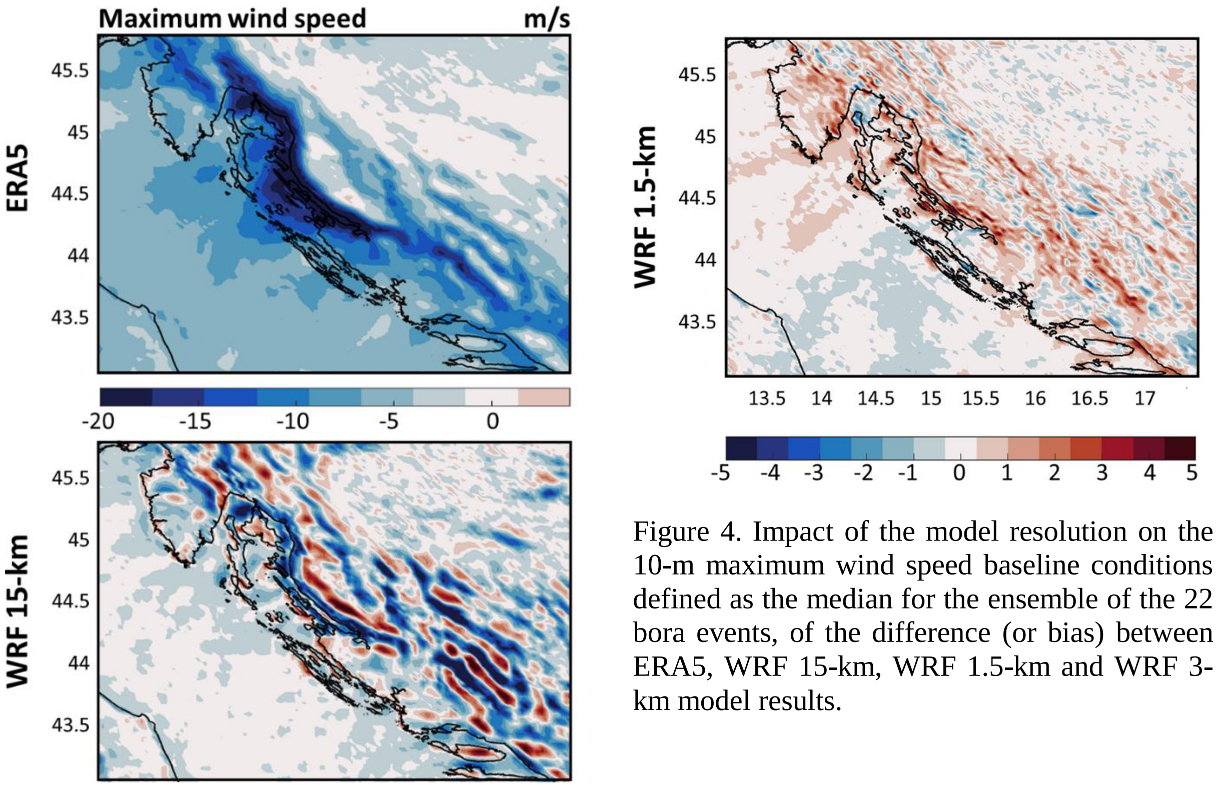


Figure 4. Impact of the model resolution on the 10-m maximum wind speed baseline conditions defined as the median for the ensemble of the 22 bora events, of the difference (or bias) between ERA5, WRF 15-km, WRF 1.5-km and WRF 3-km model results.

Concerning the evaluation of the atmospheric results during bora events presented in Figure 2: (1) ERA-5 reanalysis as well as the WRF 15-km, 3-km and 1.5 km models, are capable to reproduce, with a certain level of accuracy, the observed 2-m air temperature and dew point as well as the mean sea-level pressure independently of their resolution and physics; (2) the reproduction of the 10-m wind speed and direction highly depends on the model resolution – i.e. the representation of the Velebit mountain complex orography; (3) the lower-ground meteorological stations are likely to strongly underestimate extreme bora surface speed (not shown here) and (4) the ERA5 model seems incapable to reproduce the strength of severe bora surface winds over the whole northern Adriatic region (Figure 4).

1.3) Selected results

The test of the PGW method consisting in running ensembles of short simulations for extreme events, led to the statistical approach presented in Figures 5 and 6. Concerning the extreme bora events, this approach has 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 slighly increase in the future, even though not necesserarly 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).

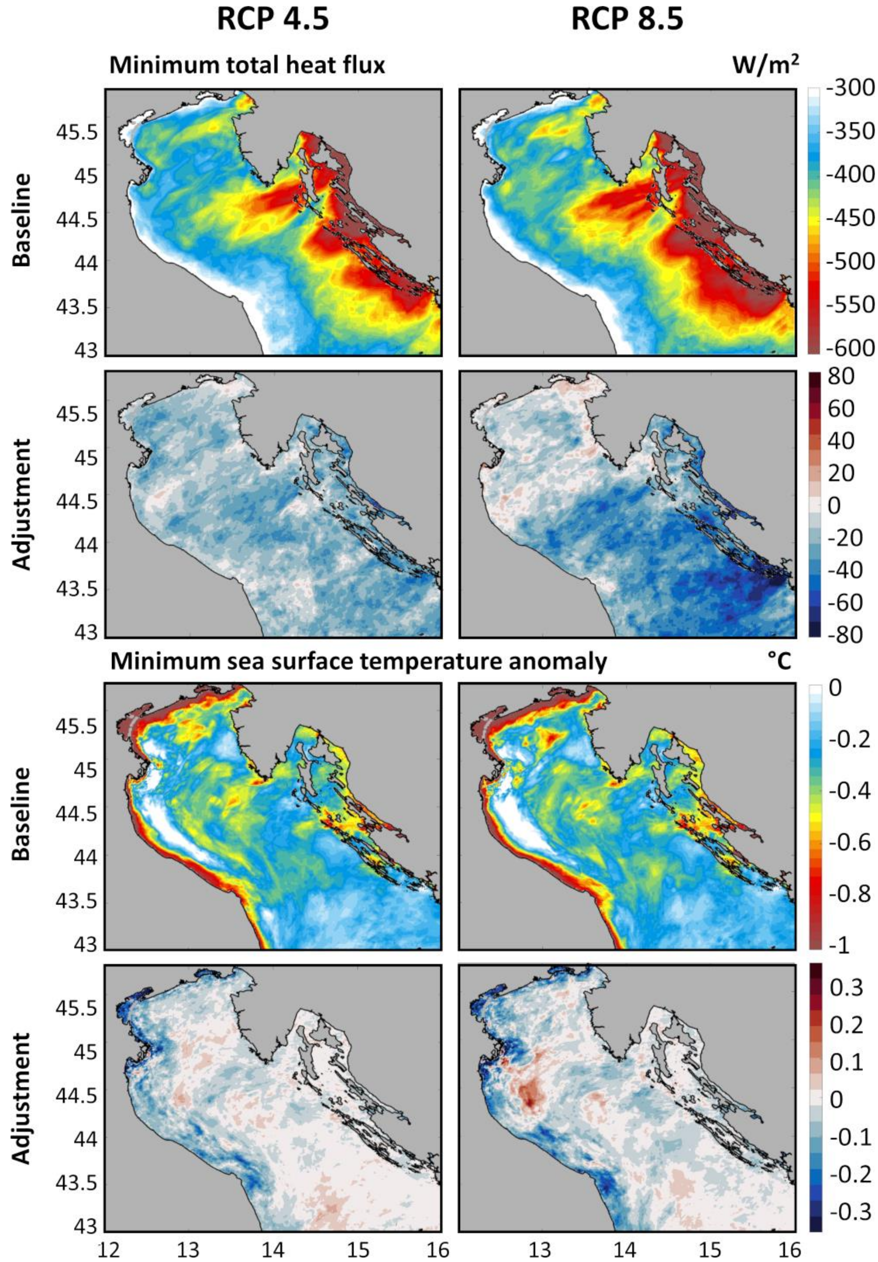


Figure 5 Baseline RCP 4.5 and RCP 8.5 conditions (median of the scenario results) and climate adjustment (median of difference between scenario and evaluation results) for the minimum of both the total heat flux and the sea surface temperature anomaly during each of the 22 selected events.

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 (Figure 1), and the storm surges against the Venice and Trieste tide gauges (Figure 6), 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.

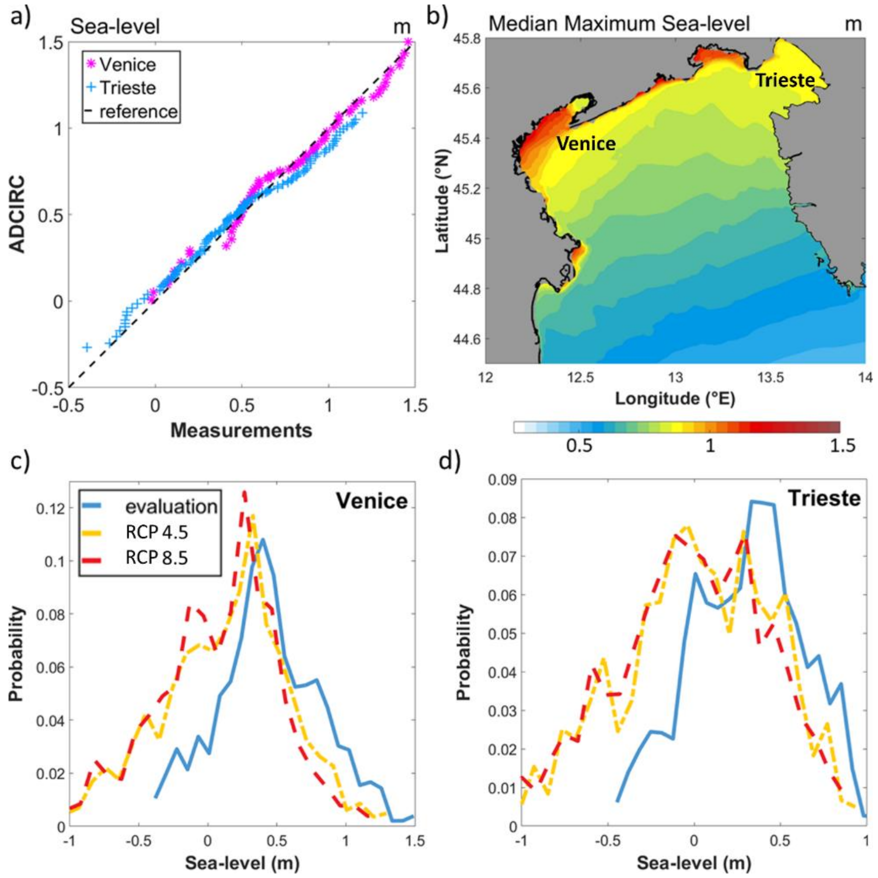
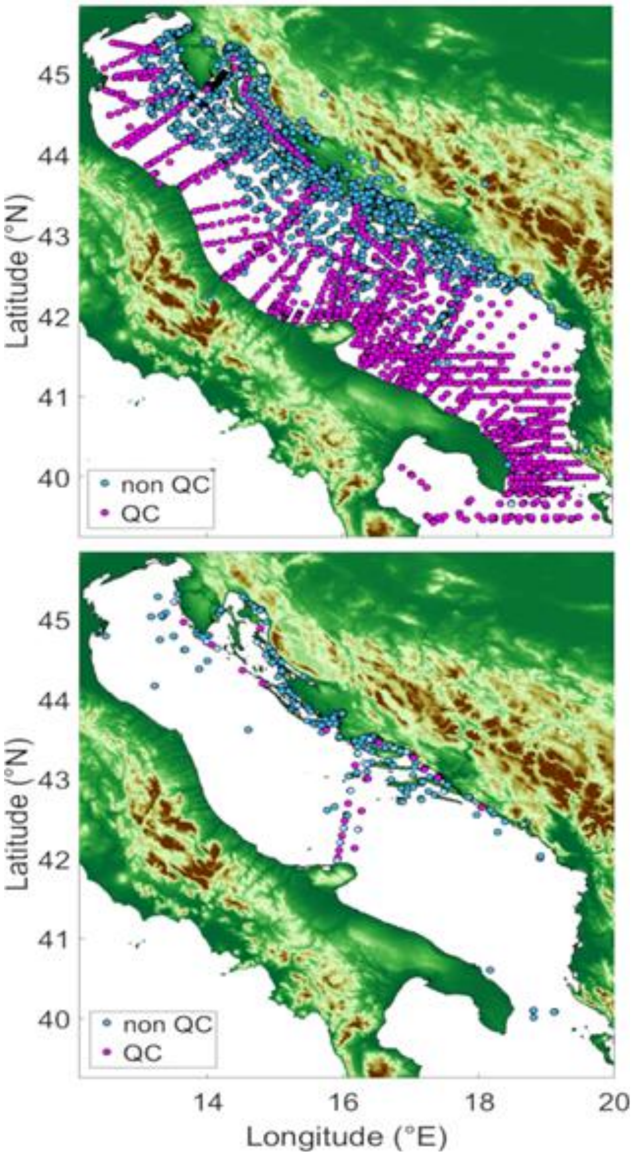


Figure 6 Analysis of the northern Adriatic storm surge distributions during the 14 sirocco events: a) quantile-quantile analysis of the AdriSC ADCIRC results and the measurements at Venice and Trieste tide-gauge stations, b) baseline sea-level plot defined as the median of the maximum sea-levels generated 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 respectively at Venice and Trieste tide gauge stations

2) Evaluation of the 31-year run for the 1987-2017 period

Another really important activity to undertake before analysing the results of the 31-year long run during the 1987-2017 period, is to evaluate the model results against in-situ observations. If numerous long-term datasets exist and are publicly shared in the atmospheric community (e.g. E-OBS products – https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php, ground-based weather stations – https://www.ncdc.noaa.gov/isd, soundings – http://weather.uwyo.edu/upperair/sounding.html) it is much more complex to find such observations in the ocean and particularly in the Adriatic and Mediterranean Seas. One the important task carried out during the special project was thus to compile as much data (CTD/Bottle for the temperature and salinity, RCM/ADCP for the ocean currents) over the Adriatic Sea and to ensure that all the datasets were properly quality checked before performing the comparison with the model results. Figure 7 shows the locations of all the datasets that we combined and quality checked (in blue) as well as preliminary results showing that the ocean model is overall in good agreement with the observations concerning the temperature and the salinity for the 1987-2017 period.



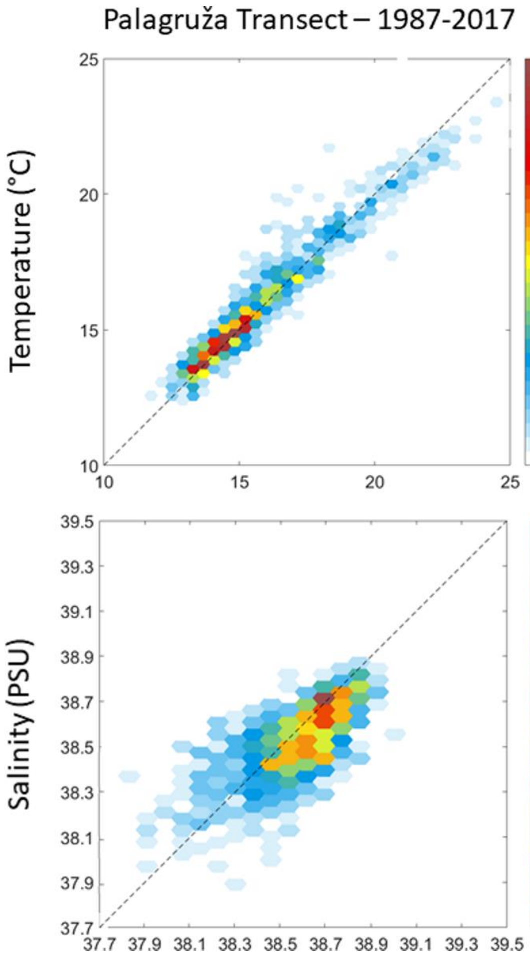


Figure 7. Evaluation of the ocean models with CTD/Bottles (top left panel) and RCM/ADCP (bottom left panel) measurements either moored for several months or along some boat transects shown as scatter plots of temperature and salinity for one long-term dataset (right panels). Quality check (QC) of the data was performed for all points presented in blue in the left panels.

To conclude, despite the known numerical cost and slowness of the AdriSC climate model with resolutions of 3-km in the atmosphere and 1-km in the ocean (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, in this study, 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 30 years in evaluation mode, 50 years in historical mode and 100 years in scenario mode. Additionaly, the preliminary results of the evaluation of the long-term run has been, till now, exceeding our expectations concerning the ocean model results.

References:

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