# 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** | 2nd 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) | 13,000,000 | 13,000,000 | 13,000,000 | 13,164,200 |
| **Data storage capacity** | (Gbytes) | 25,000 | 25,000 | 50,000 | 50,000 |

## 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 ADIOS 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 fully coupled atmosphere-ocean model based on the use and development of the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modelling System. 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 30-year re-analysis period (1987-2017) as well as two 30-year RCP scenarios (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 the result section, due to the general slowness of the modelling suite, a new strategy was implemented in order to be able to generate high resolution climate projections (at least one) within the three years of this special project. In addition, due to a misunderstanding of the ECMWF rules, not enough resources (SBUs) were asked when the special project was written in 2017.

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

Our first short term goal (August 2019, pending availability of the results), is to perform the evaluation of the AdriSC modelling suite results obtained for the 1987-2017 period. In addition to the EOBS datasets for the atmosphere, several in-situ measurements including ADCPs, CTDs, etc. for the ocean, as well as remote sensing products, will be used to perform a skill assessment of the climate component of the AdriSC modelling suite. Concurrently (the next 1.5 year), one of the climate projection simulation (rcp 8.5 most probably) will be run (using all the remaining allocated resources) and a more thorough analysis of the results will start being performed.

## List of publications/reports from the project with complete references

**Articles:**
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., 2019. 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

**Conferences:**
Denamiel, C. and Vilibić, I., 2018. The Adriatic Decadal and Inter-Annual Oscillations: Modelling Component. Poster presentation at Ocean Science meeting, Portland, Oregon, USA.
Denamiel, C. and Vilibić, I., 2018. Adriatic Decadal and Inter-Annual Oscillations: AdriSC Modelling Suite. Oral presentation at HYMEX meeting, Lecce, Italy.
Vilibić, I., Mihanović, H., Šepić, J., Dunić, N., Denamiel, C., Peharda, M., Somot, S., Sevault F., Gačić, M., 2018. The Adriatic-Ionian Bimodal Oscillating System: relevance, phenomenology, reproducibility. AGU 100 Fall Meeting, Washington DC, 10-14 December 2018.

## Summary of results

As planned, during the first 1.5 year of 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 the 30-year evaluation period run (1987-2017). Given the relative slowness of the AdriSC modelling suite, a major change of strategy was implemented in order to be able to simulate climate projections (RCPs 4.5 and 8.5): the Pseudo-Global Warming (PGW) method which will be described in details in this report. The structure of the report is as follow, the set-up of the AdriSC modelling suite is first discussed in section 1, then some preliminary results of the evaluation run are shown in section 2 and finally, in section 3, the PGW methodology and the forcing used for the climate projections are presented.

1) AdriSC modelling suite: climate component set-up

The Adriatic Sea and Coast (AdriSC) modelling suite (Denamiel et al., 2019) 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: (1) a basic module (presented below in Figure 1) providing atmospheric and oceanic Adriatic baroclinic circulation at the deep sea and coastal scales, and (2) a dedicated nearshore module (not presented here) used to better reproduce atmospherically driven extreme sea level events.

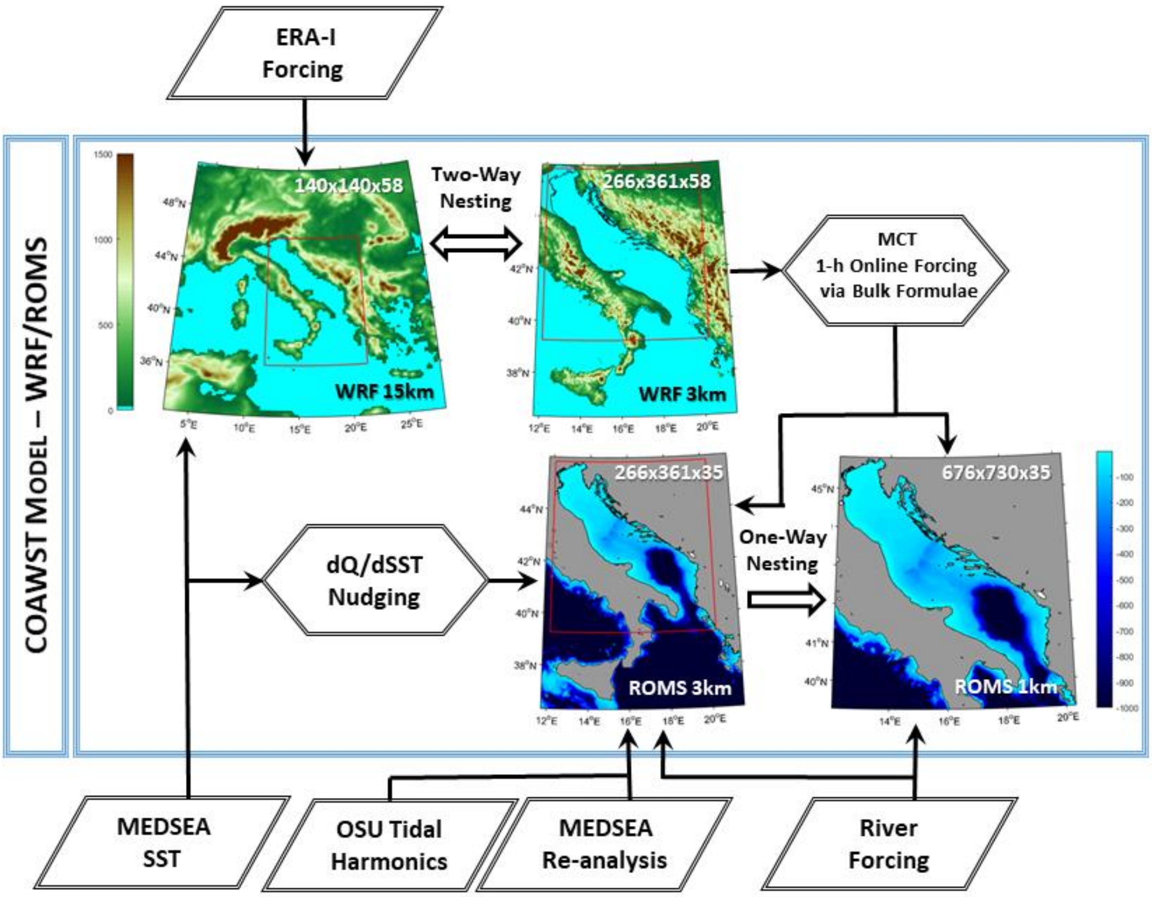


*Figure 1: Flow chart of the climate component of the AdriSC modelling suite representing the coupling between the two different models (WRF and ROMS), their grids (plotted with topography/bathymetry data) and their forcing.*

Modelling of the Adriatic baroclinic circulation at the coastal scale requires to properly resolve the orographic and bathymetric features of the studied area. For the atmosphere, the bora wind intensity, for example, highly depends on the capability of the model to capture the topography of the Velebit Channel where the speed of these winds can reach up to 30m/s with gusts surpassing 60 m/s (e.g. Belušić and Klaić, 2006; Gohm et al., 2008; Grisogono and Belušić, 2009; Ličer et al., 2016). For the ocean, the complex network of islands along the Croatian coast influences the coastal ocean circulation, driven by a combination of winds, freshwater discharges and thermohaline circulation and variability of the Adriatic-Ionian system (Orlić et al., 1992; Gačić et al., 2010; Vilibić et al., 2018). The basic module model domains presented in Figure 1 are thus defined accordingly. For the atmosphere, a 15km grid (horizontal size: 140 x 140) approximately covering the central Mediterranean basin and a nested 3km 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 3km grid identical to the atmospheric grid and a nested additional 1km 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. The vertical discretization of the grids 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, 2005, 2009) 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 15km, 3km and 1km atmospheric and ocean grids, with the Spherical Coordinate Remapping and Interpolation Package (SCRIP). More on the AdriSC modelling suite can be found in Denamiel et al. (2019).

2) Preliminary results of the evaluation run (1987-2017)

As the AdriSC climate component is used to produce historical and climate projection model results at 1km for the ocean and 3km for the atmosphere for the entire Adriatic basin (including the northern part of the Ionian Sea), the choice of the simulations was mostly driven by the availability of high-resolution RCMs covering the Mediterranean basin. In particular, for the 30-year control run – which is forced by ERA-Interim dataset and is also used as evaluation run, the simulation is undertaken between 1987 and 2017 due to the availability of the 9km MEDSEA results (Simoncelli et al, 2014) which are used to force the 3km outer ocean grid. Since June 2018, the AdriSC modelling suite runs continuously for the evaluation period (1987-2017) with perfect re-starts every day. As for the end of June 2019, 25 years of results have been produced and a PhD. student started working on the evaluation of the AdriSC evaluation run.

One of the main reason for setting up a dedicated high resolution Adriatic coastal coupled model is that the regional circulation models (RCMs) are generally enable to reproduce the BIOS cycles and most particularly the dense water formation in the northern part of the Adriatic Sea. As previous studies documented dense water formation during winter 1987 (Beg-Paklar et al., 2001), the results of the evaluation run obtained for the year 1987 were partially analysed to check the capability of the model to reproduce the event. Figure 2 shows the daily averaged bottom potential density associated with the wind vectors at 10m before the dense water formation (02/01/1987) and during four different events of strong Bora winds (18/01/1987, 23/02/1987, 04/03/1987 and 30/03/1987). From these results, it is clear that: (1) the WRF model is capable of representing the strong Bora events (more than 20m/s wind speed within the red boxes) and (2) the ROMS model seems to properly respond to the forcing as the bottom density is increased for each additional Bora event. In addition to the generation of dense water, the ROMS model seems to also reproduce its cascading along the Italian coastline towards the Otranto strait.

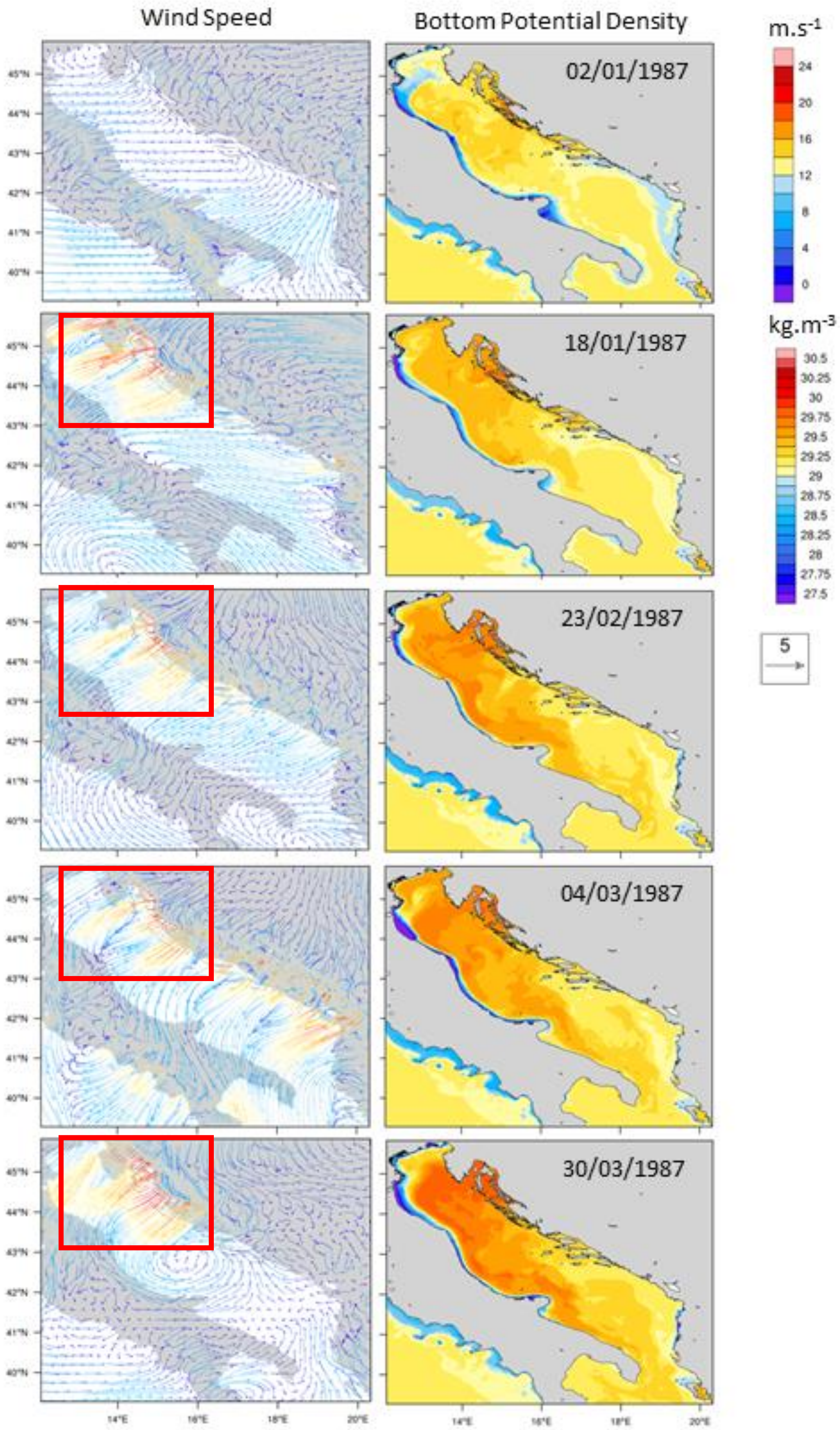


*Figure 2: Dense water generation in the northern Adriatic during four strong Bora events (red boxes) in 1987.*

3) Pseudo-Global Warming (PGW): generalization to coupled ocean-atmosphere models

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) presented below.

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 $\Delta T$ representative of the increase in temperature between past and future climate) 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 30-year periods.

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 $\left(T^{ERAI}\right)$, relative humidity $\left(RH^{ERAI}\right)$ and horizontal wind velocities $\left(U^{ERAI},V^{ERAI}\right)$ are modified between 1000hPa and 70hPa with respectively $\Delta T\left(x,y,p\right)$, $\Delta RH\left(x,y,p\right)$ and $\left(\Delta U\left(x,y,p\right),\Delta V\left(x,y,p\right)\right)$ derived from scen 4.5 and scen 8.5. The boundary and initial temperature, relative humidity and wind velocity conditions of the AdriSC scenario runs (respectively $T^{SCEN}$, $RH^{SCEN}$, $U^{SCEN}$ and $V^{SCEN}$) are thus given by:

$$\begin{aligned}
T^{SCEN}\left(x,y,p\right) &= T^{ERAI}\left(x,y,p\right)+\Delta T\left(x,y,p\right)\\
RH^{SCEN}\left(x,y,p\right) &= RH^{ERAI}\left(x,y,p\right)+\Delta RH\left(x,y,p\right)\\
U^{SCEN}\left(x,y,p\right) &= U^{ERAI}\left(x,y,p\right)+\Delta U\left(x,y,p\right)\\
V^{SCEN}\left(x,y,p\right) &= V^{ERAI}\left(x,y,p\right)+\Delta V\left(x,y,p\right)
\end{aligned} \quad (1)$$

In order to adjust the height of the surfaces of constant pressure to the temperature and relative humidity changes, the geopotential – depending on the virtual temperature $T_v^{SCEN}$ and the ERA-I geopotential $\phi^{ERAI}$ at the reference pressure $p_{ref}=1000hPa$, is recalculated as follow:

$$\phi^{SCEN}\left(x,y,p\right)=\phi^{ERAI}\left(x,y,p_{ref}\right)-\int_{p_{ref}}^{p}\frac{RT_v^{SCEN}}{p}dp \quad (2)$$

Finally, the 2m air temperature change $\Delta T_S$ derived from scen 4.5 and scen 8.5 runs is used to adjust the ERA-I surface (ground and 2m air) temperatures $\left(T_S{}^{ERAI}\right)$ such as:

$$T_S{}^{SCEN}\left(x,y\right)=T_S{}^{ERAI}\left(x,y\right)+\Delta T_S\left(x,y\right) \quad (3)$$

The spatial variations of the mean (yearly average) changes in air temperature, relative humidity and wind are illustrated in Figures 3 and 4 for 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 $\left(T_O{}^{MEDSEA}\right)$ and salinity $\left(S^{MEDSEA}\right)$ are modified on all the vertical levels with respectively $\Delta T_O\left(x,y,z\right)$ and $\Delta S\left(x,y,z\right)$ derived from scen 4.5 and scen 8.5 runs. The boundary and initial ocean temperature and salinity conditions of the AdriSC scenario runs (respectively $T_O{}^{SCEN}$ and $S^{SCEN}$) are thus given by:

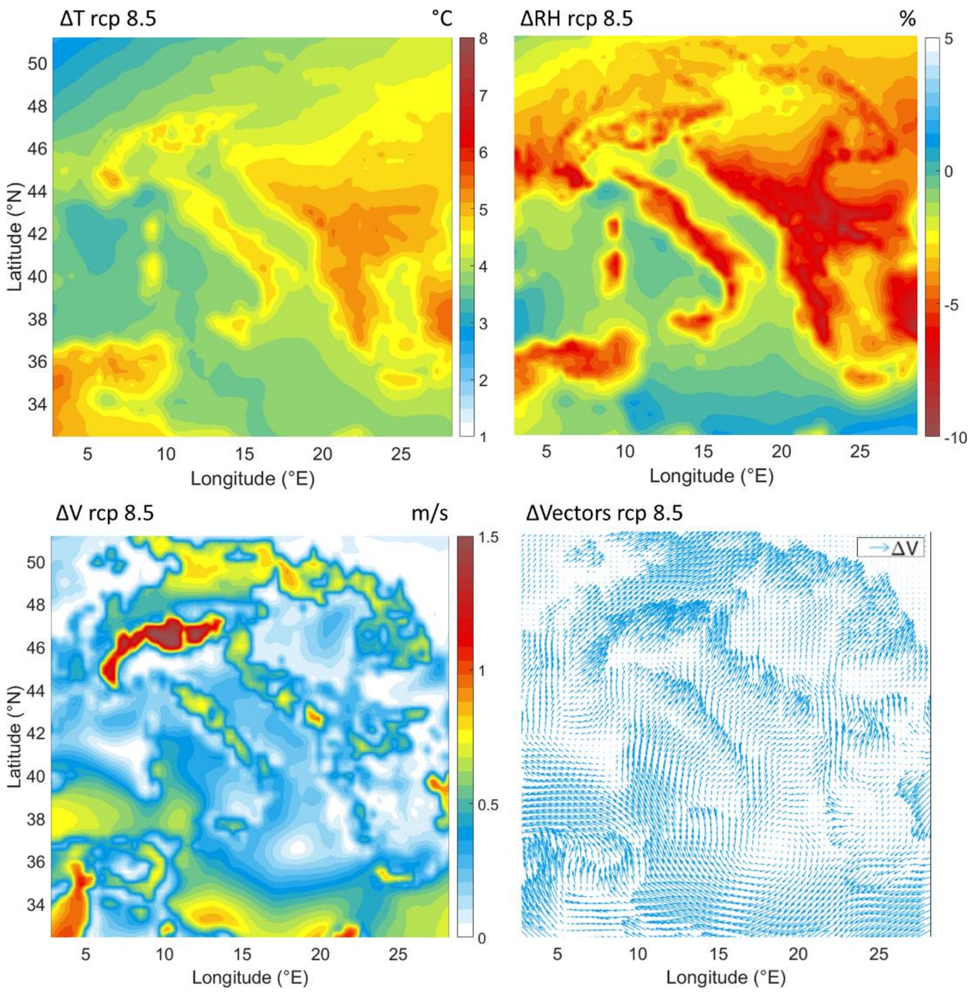


*Figure 3: Surface distribution of the mean (1) temperature ($\Delta T$), (2) relative humidity ($\Delta RH$) and wind ($\Delta V, \Delta Vectors$) corrections applied on the 15km atmosphere domain for the rcp 8.5 scenario.*

$$T_O^{SCEN}(x,y,z) = T_O^{MEDSEA}(x,y,z) + \Delta T_O(x,y,z)$$
$$S^{SCEN}(x,y,z) = S^{MEDSEA}(x,y,z) + \Delta S(x,y,z) \quad (4)$$

The ocean static stability depends on the density $(\rho)$ and the vertical variations of the local potential density $(\sigma_n)$ such as:

$$E(x,y,z) = -\frac{1}{\rho(x,y,z)}\frac{\delta\sigma_n}{\delta z} \quad (5)$$

Stability of the ocean forcing (at the boundaries and for the initial condition) is ensured by imposing $E^{SCEN} \geq 0$ at all vertical levels.

Finally, the MEDSEA ocean currents $(U^{MEDSEA}, V^{MEDSEA})$ and the sea surface elevation $(ssh^{MEDSEA})$ are modified in the surrogate climate approach such as:

$$U^{SCEN}(x,y,z) = U^{MEDSEA}(x,y,z) + \Delta U(x,y,z)$$
$$V^{SCEN}(x,y,z) = V^{MEDSEA}(x,y,z) + \Delta V(x,y,z) \quad (6)$$
$$ssh^{SCEN}(x,y) = ssh^{MEDSEA}(x,y) + \Delta ssh(x,y)$$

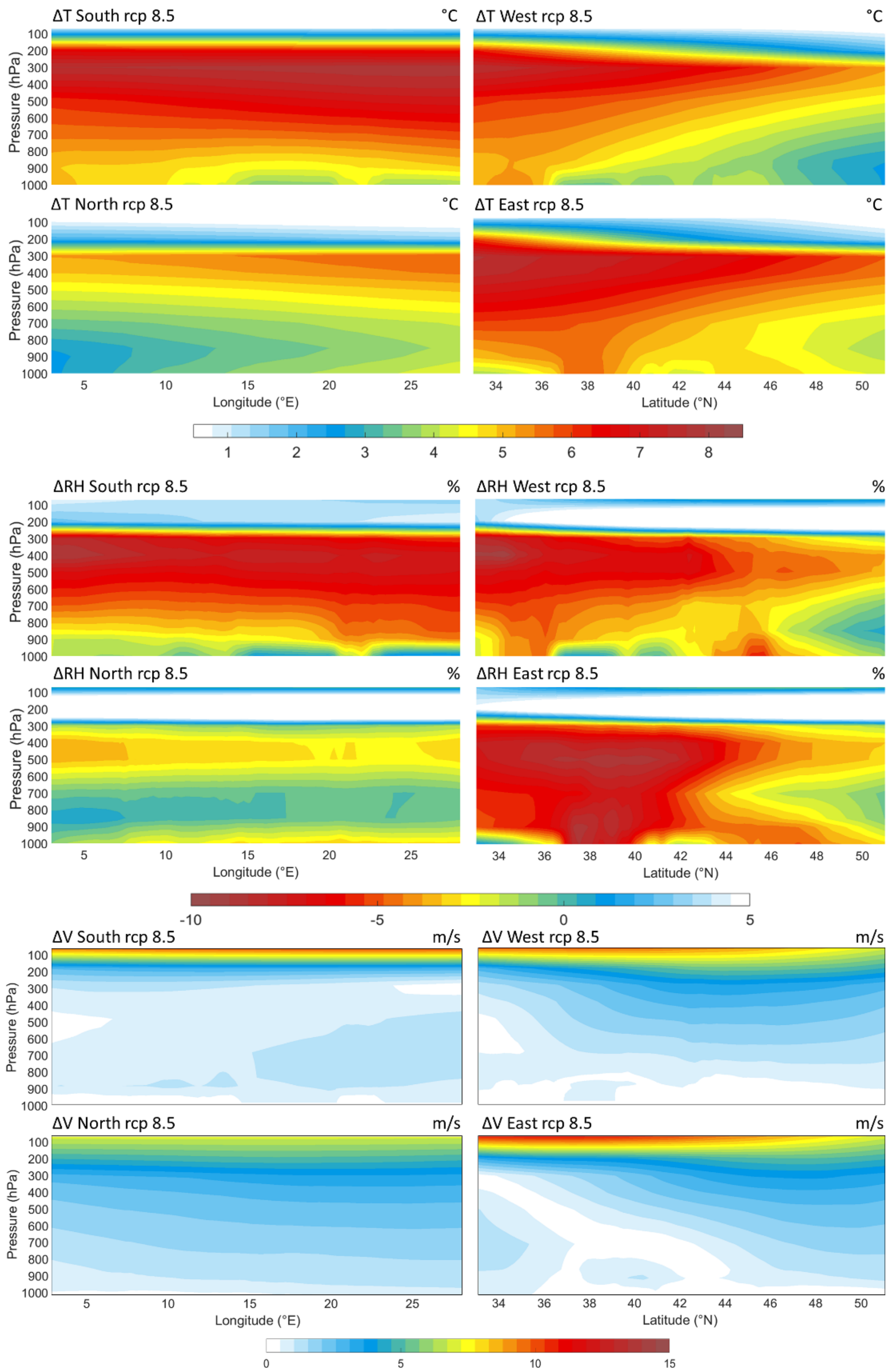


*Figure 4: Vertical distribution of the mean (1) temperature ($\Delta T$), (2) relative humidity ($\Delta RH$) and wind ($\Delta V, \Delta Vectors$) corrections applied to the boundaries of the 15km atmosphere domain for the rcp 8.5 scenario.*

The spatial variations of the changes in ocean temperature, salinity and currents are illustrated in Figures 5 and 6 for the rcp 8.5 scenario and vertical and temporal variations of the temperature changes (2m air and sea surface) for both rcp 4.5 and rcp 8.5 scenarios are presented in Figure 7.

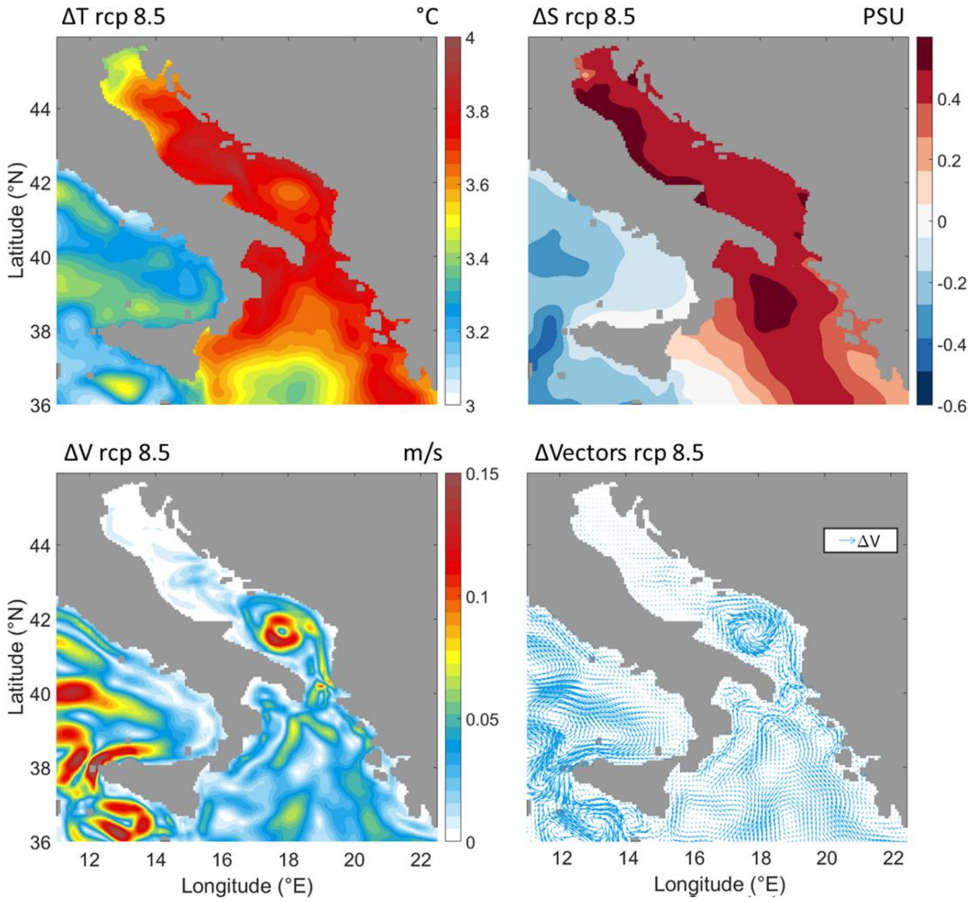


*Figure 5: Surface distribution of the mean temperature ( ΔT ), salinity ( ΔS ) and velocities ( ΔV as speed and vector plots) corrections applied on the 3km ocean domain for the rcp 8.5 scenario.*

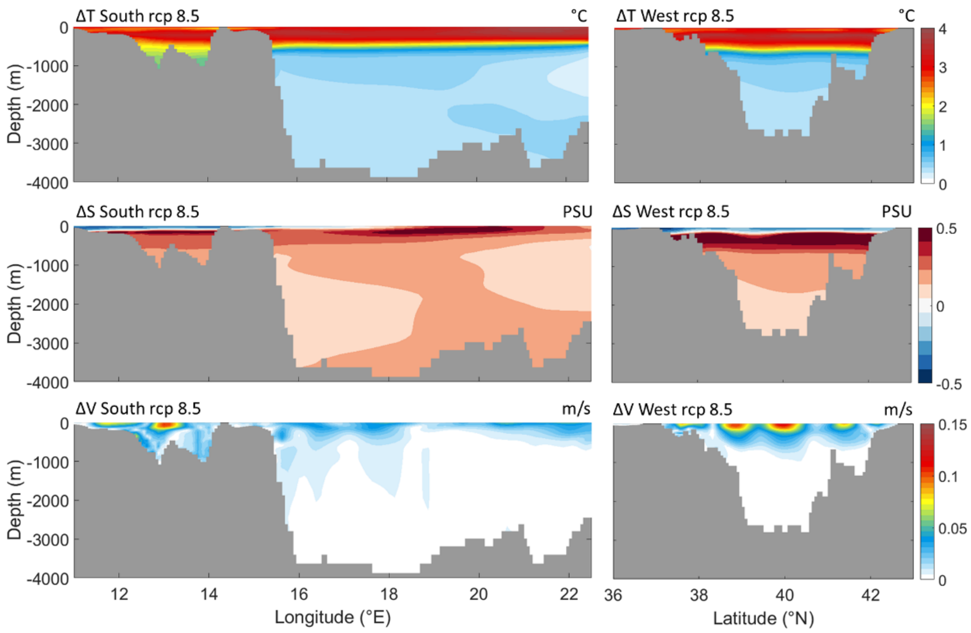


*Figure 6: Vertical distribution of the mean temperature ( ΔT ), salinity ( ΔS ) and velocities ( ΔV as speed plots) corrections applied to the southern and western boundaries of the 3km ocean domain for the rcp 8.5 scenario.*

Another important change for coupled climate simulations, is the fresh water input due to river discharges. Fortunately, a recent study from Macias et al. (2018) has clearly defined the rate of change of the river discharges along the Mediterranean coast and Figure 8 shows these changes for the Adriatic Sea.

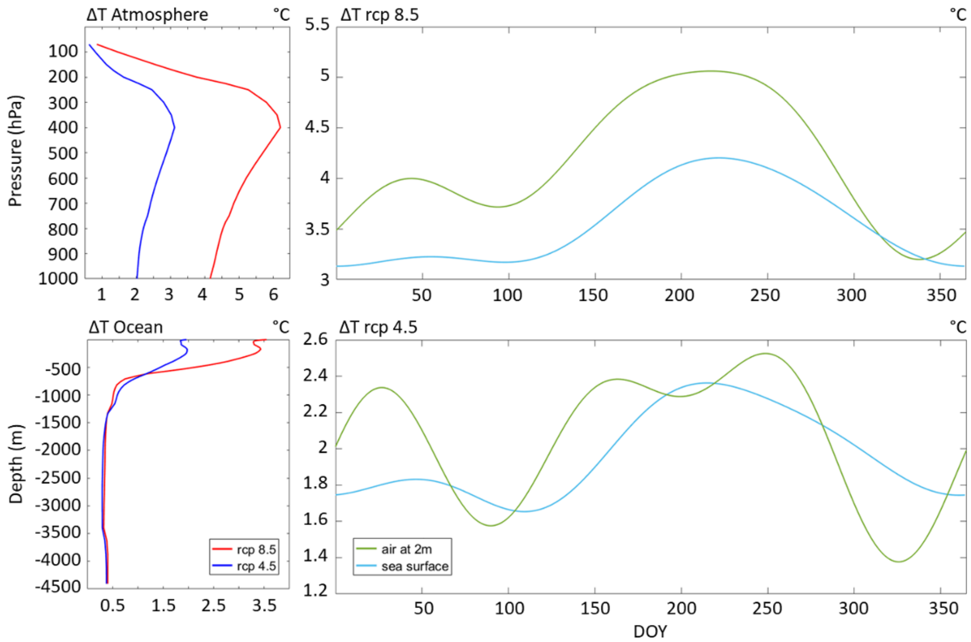


*Figure 7: Evolution of the temperature change ΔT for scenarios rcp 4.5 and rcp 8.5: vertical profiles following pressure level in the atmosphere and depth in the ocean (left panels) and time evolution depending on the day of year (DOY) for the air at 2m and the sea surface temperatures (right panels).*

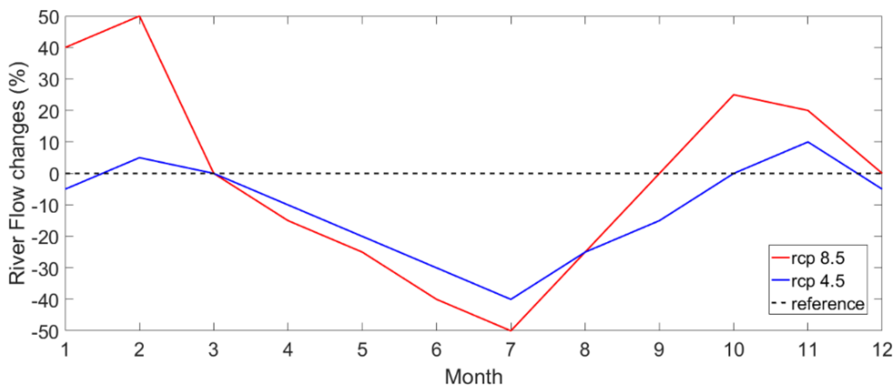


*Figure 8: Evolution of the monthly river flow changes (in %) for scenarios rcp 4.5 and rcp 8.5.*

In conclusion, during this first year and half of project, the AdriSC model was set-up and started producing the results of the evaluation run (25 years of results). Some of the first results have already been analysed in order to successfully demonstrate the capability of the models to reproduce dense water formation in the Northern Adriatic and the proper evaluation of the model skills is underway. Finally, a 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 thus, even if many challenges were faced (including (1) the forcing of the climate simulations, (2) the slowness of the model, (3) the computational resources needed to run such a model, etc.) during the implementation of the project, we believe that we can fulfil the aim of our project and provide to the Adriatic Sea scientific community a unique dataset of numerical results that can help study various physical but also biological processes in the past and project their behaviour in the context of future climate warning scenarios.

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