REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE:	CROATIA
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Project Title:	Numerical modelling of the Adriatic-Ionian decadal and inter-annual oscillations: from realistic simulations to process-oriented experiments

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPCRDENA**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2021	
Would you accept support for 1 year only, if necessary?	YES ☒	NO

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	20,000,000	10,000,000	10,000,000
Accumulated data storage (total archive volume)[2]	(GB)	25,000	50,000	75,000

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

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Extended abstract

1) State-of-the-art

Thermohaline oscillations of the Adriatic-Ionian System – as well as their biological consequences – have been extensively studied in the last 70 years (Buljan, 1953; Zore-Armanda, 1963; Buljan and Zore-Armanda, 1976; Grbec et al., 2009; Civitarese et al., 2010). In particular, the Adriatic-Ionian Bimodal Oscillating System (BiOS, Gačić et al., 2010), which consists on the decadal reversal of the cyclonic Northern Ionian Gyre (NIG) into anti-cyclonic circulation, has been found to strongly affect the thermohaline, biogeochemical, ecological and fishery conditions in the Adriatic Sea (see Figure 1). The BiOS regimes are also related to a wider Eastern Mediterranean oscillatory dynamics (Krokos et al., 2014; Theocharis et al., 2014). In particular, Klein et al. (1999) proved the interplay between dense water formation occurring in the Adriatic and Aegean Seas.

However, surprisingly, the physical explanation of the thermohaline oscillations is still under debate as two different theories are opposed. The first theory links the oscillations to the pressure and wind-driven patterns (Grbec et al., 2003). In particular, Molcard et al. (2002) and Pinardi et al. (2015) have been proving the relationship between wind stress curl and northern Ionian reversals. The second theory correlates the oscillations with the effects of dense water formation (Borzelli et al.,2009; Gačić et al., 2010). In particular, Vilibić and Šantić (2008) and Mihanović et al. (2013) demonstrate the direct link between the oscillations and the dense water formation in the southern and northern Adriatic. Recently, physical modeling of the inversions of the NIG circulation in an idealized Adriatic-Ionian/Eastern Mediterranean circulation system has confirmed that the Adriatic dense waters and not the wind are the main drivers of the NIG reversal (Rubino et al., 2020).

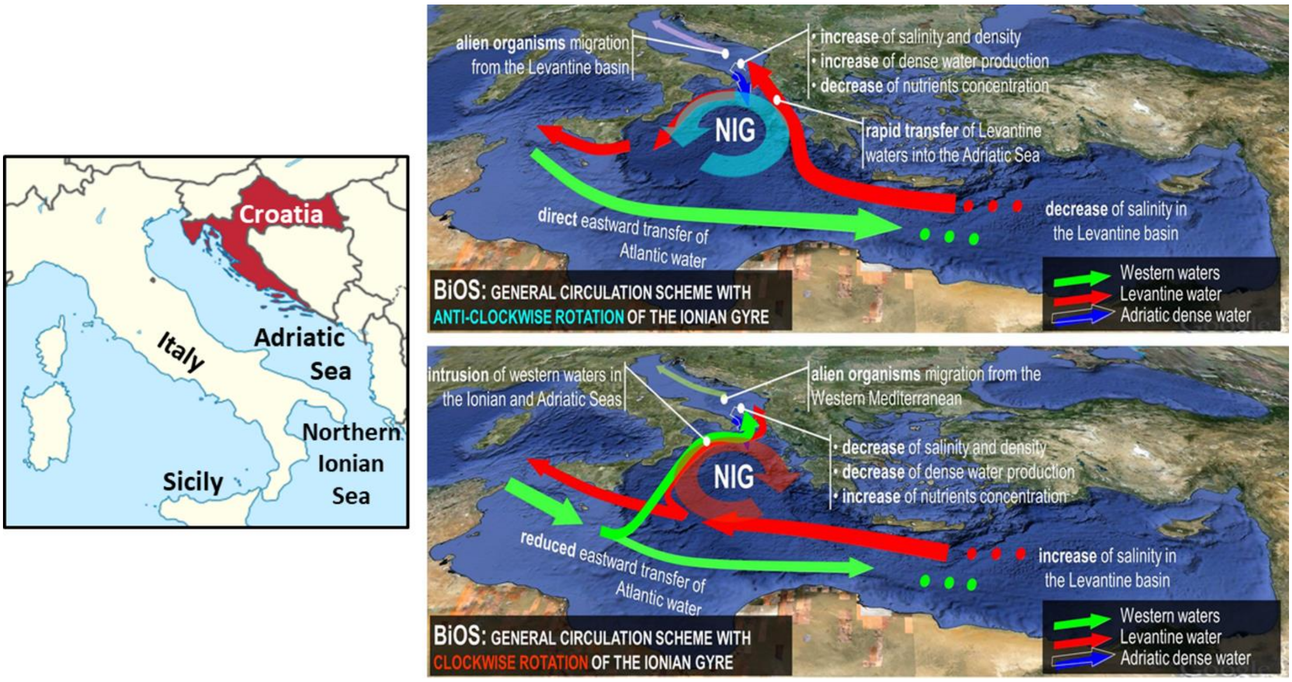

Figure 1: Scheme of the decadal Bimodal Adriatic-Ionian Oscillation System (BiOS) mechanism driving the Northern Ionian Gyre (NIG) adapted from http://nettuno.ogs.trieste.it/jungo/bios_cropex/.

2) Previous Numerical Modelling Efforts

This proposal is written in the continuation of previous efforts to carry out kilometer-scale coupled atmosphere-ocean simulations in the Adriatic-Ionian basin supported by both the Croatian project ADIOS and the ECMWF special project SPCRDENA.

In particular, the Adriatic Sea and Coast (AdriSC) modelling suite (Denamiel et al., 2019) has been developed during these two projects 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 2) 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.

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 – which 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), highly depends on the capability of the models to capture the topography of the Velebit Channel as found in Denamiel et al. (2020a). 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).

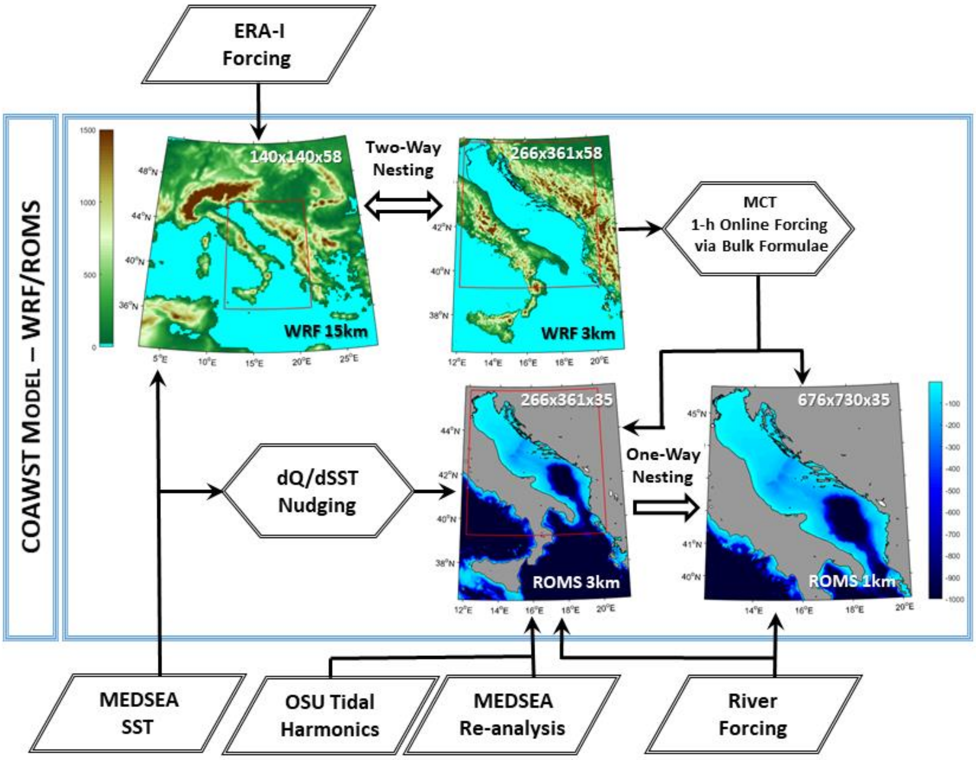

Figure 2: Flow chart of the climate component of the AdriSC modelling suite representing the coupling between the two different models (WRF and ROMS), their grids (plotted with topography/bathymetry data) and their forcing.

The basic module model domains presented in Figure 2 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 & McWilliams, 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).

As the AdriSC climate component was 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 regional climate models (RCMs) covering the Mediterranean basin. In particular, for the 31-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.

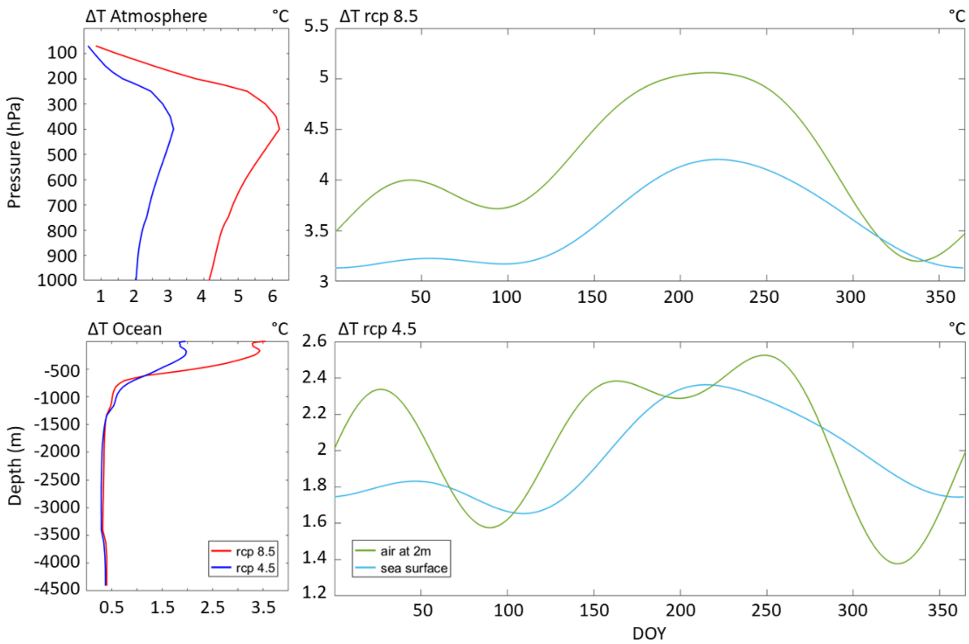

Figure 3: Evolution of the temperature change ΔT for scenarios rcp 4.5 and rcp 8.5: vertical profiles following pressure level in the atmosphere and depth in the ocean (left panels) and time evolution depending on the day of year (DOY) for the air at 2m and the sea surface temperatures (right panels).

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. The Pseudo-Global Warming (PGW) approach developed by Schär et al. (1996) for the atmospheric models was thus extended to coupled atmosphere-ocean models by Denamiel et al. (2020b) during the previous ECMWF special project. Concerning the practical 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 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 Figure 3) to the forcing used to produce a control run.

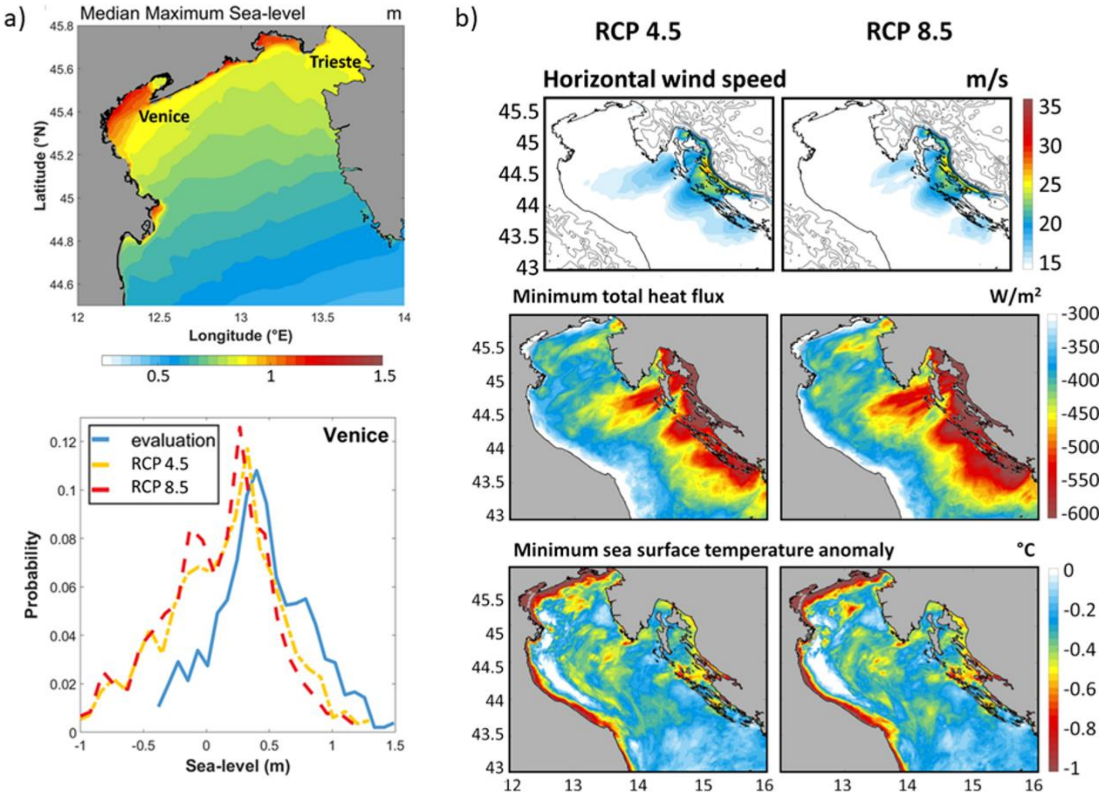

Figure 4: Panel (a): Analysis of the northern Adriatic storm surge distributions during the 14 sirocco events with baseline sea-level plot defined as the median of the maximum sea-levels generated by each storm and sea-level distributions derived from the evaluation and climate projection (RCP 4.5 and RCP 8.5) results at Venice tide gauge stations. Panel (b) RCP 4.5 and RCP 8.5 conditions (median of the scenario results) for maximum horizontal wind speed, minimum total heat flux and minimum sea surface temperature during the peak of 22 selected extreme bora events.

The robustness of the newly extended PGW methodology (Denamiel et al., 2020b) was tested for both RCP 4.5 and RCP 8.5 scenarios with an ensemble of 36 short simulations (3-day length) of extreme historical sirocco and bora events (the main winds blowing over the Adriatic Sea). Two different studies (Denamiel et al., 2020b, 2020c) reveal that the PGW methodology provided results aligned with the tendencies seen in the RCMs but was additionally capable of projecting the impact of climate change on the storm-surges in Venice (Denamiel et al., 2020b, Figure 4.a) or the bora dynamics and the associated sea-surface cooling in the northern Adriatic region (Denamiel et al., 2020c, Figure 4.b) which can both only be described with kilometre-scale models.

However, within the previous ECMWF special project, only the control/evaluation 31-year long run was finalized and evaluated against (1) a unique dataset of ocean measurements collected in the Adriatic Sea and (2) classical atmospheric observations including more than 300 ground-based weather stations, echo-soundings at 6 locations and E-OBS dataset. The model output of the 31-year long evaluation run are already available as it on a LDAP open access server (ftp://messi-nas.izor.hr/) and a web-interface is under construction in order to allow more sophisticated extraction of the results. Additionally, due to the slowness of the AdriSC modelling suite, only the 31-year long climate projection under RCP 8.5 scenario was undertaken for the far future projections (2070-2100 period). Further, this run could not be finalized during the previous project despite the generous allocation of additional credits each year.

To our knowledge, the AdriSC climate suite is the first climate coupled atmosphere-ocean model running at such high resolution (kilometre-scale). Despite the many challenges faced during the previous ECMWF special project (including the availability of the forcing for the climate simulations, the slowness of the AdriSC model, the computational resources needed to run such a model, etc.), we thus believe that such climate models can provide to the Adriatic Sea scientific community a unique dataset of numerical results which can be used to study various physical but also biological processes in the past and project their behaviour in the context of future climate warning scenarios.

3) Proposed Work

The proposed work builds on the achievements of the previous 3 years and is in fact twofold: on the one hand, the 31-year long RCP 8.5 run is planned to be finalized during the first year of the project with the aim to project the behaviour of the BiOS in a future warmer climate and, on the other hand, due to the complexity of the non-linear interactions involved in the BiOS mechanism, a process oriented approach testing various hypothesis of generation will be used in the next two years of the project in order to better understand the main drivers of the reversal of the Northern Ionian Gyre (NIG). Additionally, during the three years of the special project, analysis of the output from the different numerical simulations will also be performed in order to study the northern Adriatic dense water formation and its impact BiOS.

(i) Continuation of the AdriSC 31-year climate projections under RCP 8.5 scenario – ***first year of the requested ECMWF HPC resources***

At this very moment, 7 years of the RCP 8.5 31-year long simulation have been already performed within the previous ECMWF special project. We expect to obtain by the end of the year between 14 and 15 years of results which means that all the first year credits and storage allocated to another special project would be spend in order to finalized this run.

Computing resources needed: As the AdriSC climate component runs in parallel on 260CPUs, and takes about 24h of computation (elapse time) to produce 1 month of data, the amount of credits needed to run the extra 15 years of the RCP 8.5 simulation are: **260CPUs*200days*86400s*P ~ 20,000,000 SBUs**. Concerning the storage needed, we estimate that about 2**5,000 GB** will be needed.

(ii) Process-oriented simulations of the BiOS mechanism – ***last two years of the requested ECMWF HPC resources***

For this part of the project, a simplified ocean domain will be used covering only the southern Adriatic Sea and the northern Ionian Sea and forced with simplified boundary and atmospheric conditions. As the AdriSC modelling suite is numerically extremely costly, the main idea of the experiments, that will be performed in these two years, is to test several hypothesis concerning the processes responsible for the reversal of the NIG. To some extent, we consider that the results derived from the physical modelling performed by Rubino et al. (2020) could be confirmed and further developed via the use of simplified numerical experiments. These additional simulations will also help us to better analyse the long-term AdriSC results (evaluation and RCP 8.5 runs) as the main drivers of the BiOS mechanism will already be identified with more controlled simulations.

Computing resources needed:
Following our first estimate, for these experiments, **20,000,000 SBUs** and up to **50,000 GB** will be used in the framework of the two last years of the ECMWF special project.

It is also planned that the model outputs will be disseminated to the research community and users via a LDAP open access server already existing: ftp://messi-nas.izor.hr/.

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