



# The Impact of Ocean–Atmosphere Coupling on the Prediction of Mediterranean Cyclones: A Case Study of Medicane Ianos <sup>†</sup>

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**Abstract:** Intense cyclones with tropical-like characteristics (also known as “medicanes”) occasionally develop in the Mediterranean. They can cause extreme weather phenomena with catastrophic potential due to excessive precipitation, windstorms, and coastal flooding. In this work, the impact of air–sea interactions on the track and intensity of a Mediterranean cyclone is evaluated using an atmosphere-only configuration (WRF) and a two-way coupled ocean–atmosphere configuration (NEMO-WRF). As a case study, we focus on a medicane that evolved over the central Mediterranean basin during 15–20 September 2020 (named “Ianos”), causing severe damage to western Greece. The atmosphere-only simulations were carried out using constant initial SST throughout the model integration, while in the coupling setup, the SST was consistent with the air–sea fluxes and updated every 6 min by the ocean model. The results from the two modeling approaches highlight the importance of air–sea feedbacks for predicting Mediterranean cyclone intensity, along with the forecast initialization time.

**Keywords:** ocean–atmosphere coupling; Mediterranean cyclones; medicane Ianos; WRF; NEMO; coupled air–sea simulations



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## 1. Introduction

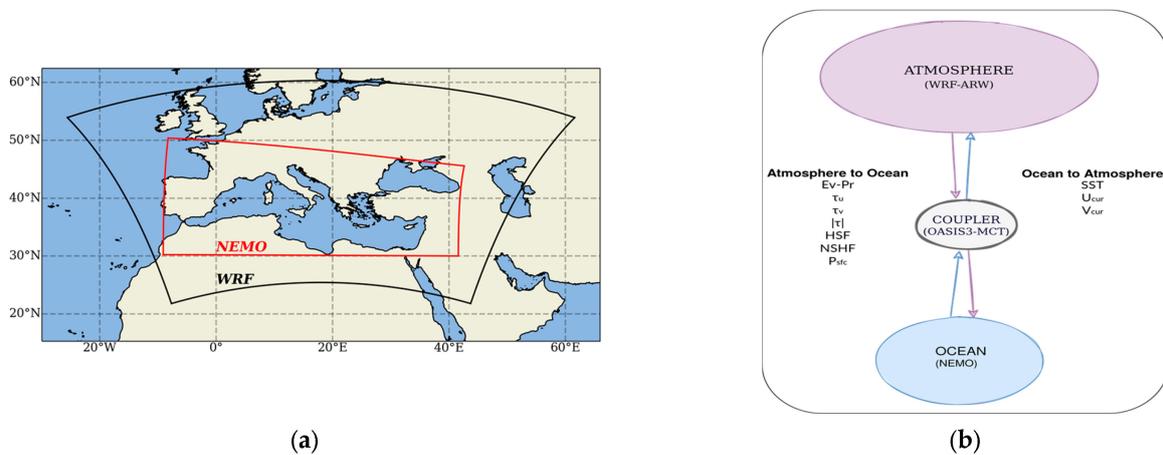
The Mediterranean Sea is known for its potential to generate intense cyclones with tropical-like features, usually called medicanes (i.e., MEDiterranean hurriCANES [1]), which can have devastating impacts on the surrounding coastal regions. The accurate forecasting of these events depends on many factors, including model initialization time, physics parameterization schemes, horizontal grid resolution, and the status of the cyclone in terms of its intensity and duration (e.g., [2–6]). Another factor that plays a key role in the simulation of Mediterranean cyclones is the cooling of the sea surface along their path, which affects the air–sea fluxes and, consequently, their formation, trajectory, and intensity (e.g., [7–9]). Moreover, a recent study [10] highlights the interplay between a medicane and the pre-existing upper-ocean conditions (e.g., a cyclonic gyre). Thus, including coupled ocean–atmosphere models to better simulate these complex air–sea interaction processes can improve the simulation quality of medicanes.

This study investigates the impact of air–sea coupling and forecast initialization time on the evolution of one of the most intense medicanes (in terms of duration and intensity), named “Ianos”, which occurred over the period 15–20 September 2020 in the central Mediterranean. This medicane initially formed in the Gulf of Sidra and rapidly intensified, moving north–northeast towards Italy and reaching its maximum intensity when it moved eastward, affecting the Ionian Sea and Greece from the 17 to 20 of September 2020, with wind gusts reaching 120 km/h, heavy rainfall, storm surge, and flooding [11,12]. In this

paper, we evaluate the impact of ocean coupling on the simulated trajectory and intensity, as well as the surface heat fluxes, of the medicane Ianos.

## 2. Data and Methodology

To investigate the ocean–atmosphere feedback on the evolution of medicane Ianos, two simulation approaches were conducted using an atmosphere-only and a coupled ocean–atmosphere configuration covering the Mediterranean region (Figure 1a). The first configuration is uncoupled (atmosphere-only simulations, hereafter referred to as ATM), comprising a 9 km horizontal resolution implementation of the WRFv4.3.3 [13] atmosphere model with 60 vertical levels stretching up to 50 hPa and a timestep of 30 sec. The main physics options and parameterizations used are summarized in Table 1. Atmospheric initial and boundary conditions were created via the 3-hourly operational forecasts of the European Centre for Medium-Range Weather Forecasts Global Integrated Forecasting System (ECMWF IFS) at  $0.1^\circ \times 0.1^\circ$  grid resolution. The ATM configuration is forced with a fixed initial ECMWF SST analysis at the lower boundary throughout the model integration.



**Figure 1.** (a) The simulation domain used for the coupled and uncoupled simulations. The lines indicate the extension of the WRF configuration (black) and of the NEMO domain (red). (b) Schematic illustration of the exchange fields through the OASIS coupler in the fully coupled ocean–atmosphere model. Ovals are proportional to code size.

**Table 1.** WRF physical schemes.

Physical Mechanism	Scheme
Microphysics	WRF Single-Moment 3-class scheme [14]
Cumulus	Tiedtke [15]
Radiation	RRTMG (shortwave and longwave) [16]
Planetary boundary layer	Mellor–Yamada–Janjic (MYJ) [17]
Surface layer	Eta-similarity
Land surface	Unified Noah Land Surface Model [18]

The second configuration (ocean–atmosphere coupled simulations, hereafter referred to as CPL) consists of an identical WRF configuration at 9 km resolution coupled to the NEMOv4.2.0 dynamical ocean model (<https://www.nemo-ocean.eu> (accessed on 3 July 2023) [19]) through the OASIS3-MCT\_4.0 coupling libraries [20]. The ocean model has a horizontal resolution of  $1/12^\circ$  and 50 vertical levels covering the Mediterranean and Black Seas, connected explicitly through the Marmara Sea from the Dardanelles and Bosphorus straits. The NEMO model setup is very similar to the one used by [9] (same domain, tidal forcing, river runoffs, parameterizations, ocean bathymetry, and model mesh). Oceanic

initial and open boundary conditions were obtained from daily ocean reanalysis fields (GLORYS12 product of Copernicus Marine Environment and Monitoring Service (CMEMS, <http://marine.copernicus.eu/> (accessed on 3 July 2023) at the same  $1/12^\circ$  horizontal resolution as the ocean model configuration; there is no local data assimilation within the model domain in the forecast.

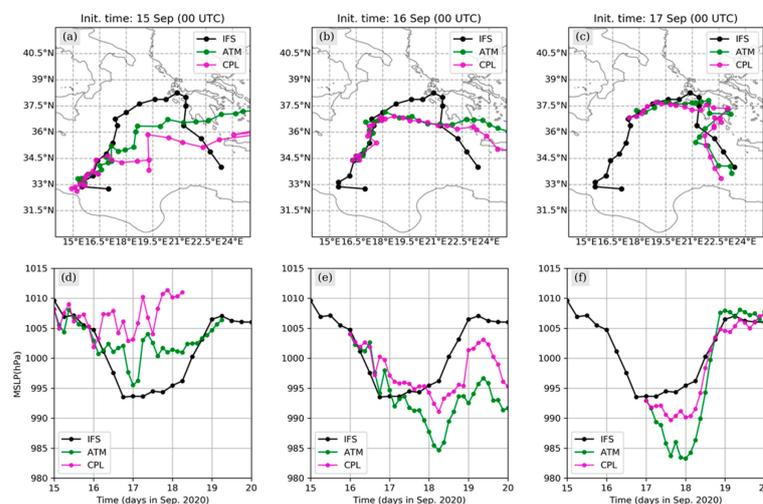
Ocean and atmosphere models exchange physical fields through the OASIS coupler every 6 min to fully capture high-frequency air–sea interactions. WRF receives sea surface temperature (SST) and surface ocean velocity ( $U_{\text{cur}}$  and  $V_{\text{cur}}$ ) and sends to NEMO wind stress ( $\tau_u$ ,  $\tau_v$ , and  $|\tau|$ ), surface fluxes (shortwave (solar, SHF) and longwave (non-solar, NSHF) radiations), and freshwater fluxes (precipitation minus evaporation,  $Ev-Pr$ ), as well as the atmospheric pressure (P<sub>sfc</sub>) (Figure 1b).

The numerical experiments cover the period of medicane Ianos' evolution from 15 (00 UTC) to 20 (00 UTC) September 2020. A set of sensitivity experiments on the forecast initialization time was also performed, comparing the results to the ECMWF IFS benchmark analysis. Model analyses are compared with the available satellite gridded L4 sea surface temperature (SST) dataset [21] derived from the CMEMS.

### 3. Results

#### 3.1. Track and Intensity

The cyclone's track and along-track intensity (in terms of minimum sea level pressure) from the ATM and CPL simulations and from ECMWF IFS analysis are shown in Figure 2 for different forecast initialization times: 15 (00 UTC), 16 (00 UTC), and 17 (00 UTC) September 2020, respectively. We note a clear sensitivity of the simulated trajectories to the cyclone development phase and, consequently, the forecast initialization time (Figure 2a–c). Larger track errors are produced when the forecast is initialized in the early stages of Ianos cyclogenesis on the 15 (00 UTC).

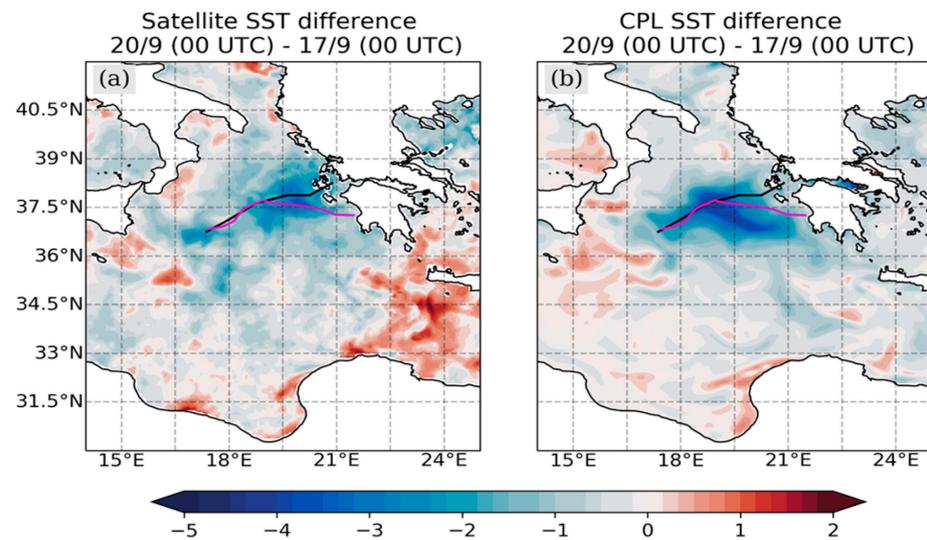


**Figure 2.** (a–c) Track and (d–f) intensity (in terms of mean sea level pressure; MSLP in hPa) of medicane Ianos derived from ECMWF IFS analysis (black lines; 6-h intervals) and the ATM (green lines) and CPL (magenta lines) simulations at 3-h intervals and for different initialization times on 15 September (00UTC), 16 September (00UTC), and 17 September (00UTC), respectively. The simulated track of medicane is computed from the position of minimum mean sea level pressure.

The trajectories in the ATM and CPL simulations are quite similar and comparable to the IFS analysis during the cyclone's intensification stage and before its eastward acceleration (Figure 2b,c). However, the location of landfall in Western Greece is shifted southeastward in both simulations. Overall, the CPL runs systematically produce less intense cyclones than the ATM, enhancing the predictability to closer to the IFS analysis (Figure 2e,f).

### 3.2. Oceanic Impact

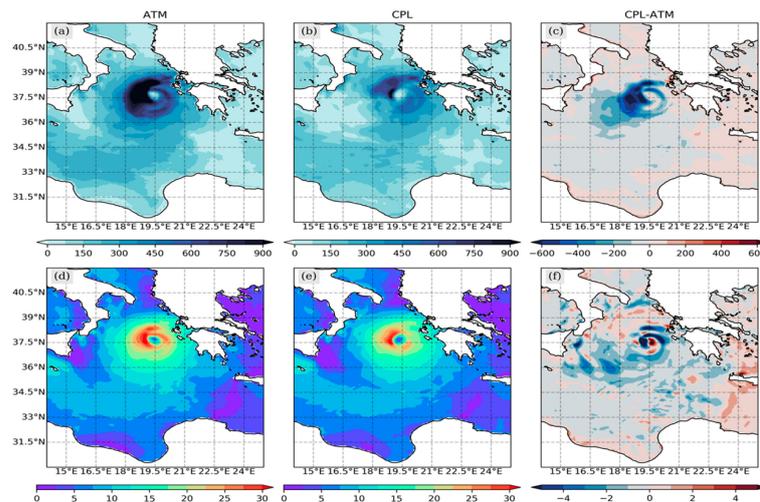
The imprint on the SST during the medicane Ianos passage between the 17 and 20 of September is shown in Figure 3. A decrease in SST is seen along the cyclone track (up to 5 °C) simulated by CPL (Figure 3b), with a cooling bias compared to the satellite SST dataset (Figure 3a) but a similar spatial structure. The model data cooling bias may be related to the overestimation of vertical mixing in the model, combined with the fact that satellite measurements are affected by the presence of clouds overlooking smaller-scale features due to the scarcity of observations along the cyclone track. The representation of SST cooling in the CPL simulation agrees with previous studies using coupled models (e.g., [8,9]) that reach similar results along the cyclone’s track. This cooling is not represented in the ATM simulations (e.g., SST is constant over simulation time).



**Figure 3.** SST (°C) anomaly between 20 September 2020 at 00 UTC and 17 September 2020 at 00 UTC from (a) CPL simulation and (b) satellite data including the medicane Ianos path derived for ECMWF IFS analysis (black line) and CPL simulation (magenta line).

### 3.3. Atmospheric Impact

To highlight the impact of ocean–atmosphere coupling on medicane Ianos development, we present a snapshot of the enthalpy flux (latent plus sensible heat fluxes) and wind speed at 10 m from both simulations on 18 September 2020 at 18 UTC (Figure 4) when the cyclone is well captured. Coupling with the ocean causes a significant reduction of the surface enthalpy flux from the sea surface (Figure 4a–c), with differences reaching up to 600 W/m<sup>2</sup> at the rear part of the medicane, resulting in a weaker asymmetry. Cyclone intensity also decreased at the eyewall of the medicane in terms of maximum 10-m wind speeds but increased near the center or eye (Figure 4d–f), with differences exceeding 5 m/s. These changes are directly linked to the SST cooling induced by the cyclone’s passage, as shown in Figure 3b.



**Figure 4.** (a–c) Surface enthalpy heat flux ( $W/m^2$ ) and (d–f) 10-m wind speed (m/s) for ATM (first column), CPL (second column), and their difference (CPL minus ATM) (third column) on 17 September 2020 at 18 UTC.

#### 4. Conclusions

In this study, we examined the predictability of a Mediterranean cyclone across different coupling approaches and initialization times. A case study of an intense medicanne, Ianos (15–20 September 2020), was simulated using high-resolution numerical models for the atmosphere and the ocean. Two modeling approaches were conducted using an atmosphere-only and a two-way coupled ocean–atmosphere configuration. The results indicate that the cyclone predictions strongly depend on the forecast initialization time, as well as the intensity and duration of the cyclone. In the coupled simulations, sea surface cooling up to  $5\text{ }^\circ\text{C}$  is simulated along the medicanne’s track, in apparent agreement with the satellite-derived SST observations. The SST cooling leads to a strong reduction in heat fluxes, affecting the cyclone’s dynamical structure. Ocean–atmosphere coupling also weakened the cyclone in terms of minimum mean sea level pressure and wind speed at 10-m, improving forecasts closer to the ECMWF IFS analysis. Further investigation of these results enriched by additional case studies are included in authors’ plans for future work.

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