https://doi.org/10.5194/acp-2020-1312
Preprint. Discussion started: 11 February 2021

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Influence of sea salt aerosols on the development of Mediterranean tropical-like cyclones

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Abstract. Medicanes are mesoscale tropical-like cyclones that develop in the Mediterranean basin and represent a great hazard for the coastal population. The skill to accurately simulate them is of utmost importance to prevent economical and personal damages. Medicanes are fuelled by the latent heat released in the condensation process associated to convective activity, which is regulated by the presence and activation of cloud condensation nuclei, originated mainly from sea salt aerosols (SSA) for marine environments. Henceforth, the purpose of this contribution is twofold: assessing the effects of an interactive calculation of SSA on the strengthening and persistence of medicanes; and providing insight on the casuistry and sensitivities around their simulation processes. To this end, a set of simulations has been conducted with a chemistry/meteorology coupled model considering prescribed aerosols (PA) and interactive aerosol concentrations (IA). The results indicate that IA produces longer-lasting and more intense medicanes. Further, the role of the initialization time and nudging strategies for medicane simulations has been explored. Overall, the results suggest that (1) the application of spectral nudging dampens the effects of IA; (2) the initialization time introduces a strong variability on the storm dynamics; and (3) wind-SSA feedback is crucial and should be considered when studying medicanes.

1 Introduction

Mediterranean tropical-like cyclones, also known as medicanes (from **medi**terranean hurri**canes**), are mesoscale perturbations that exhibit tropical characteristics, such as an eye-like feature and warm core. These storms are characterized by high wind speeds and vertically aligned geopotential height perturbations along different pressure levels. Just like regular tropical cyclones, medicanes represent a hazard for the population of coastal areas. However, given the relatively small extent of the Mediterranean basin and the lower sea surface temperatures of the Mediterranean Sea, they do not reach the size and intensity of actual hurricanes. Still, they can produce heavy precipitation and intense wind gusts, reaching up to Category 1 in the

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Saffir-Simpson scale (Fita et al., 2007; Miglietta and Rotunno, 2019). Thus, our ability to understand and accurately simulate medicanes with current meteorological modeling systems stands as a key factor to prevent their associated damages.

Tropical-like cyclones in general, and medicanes in particular, are usually considered to be a hybrid between tropical and extratropical cyclones. Although their triggering and development mechanisms differ from those of tropical cyclones (Tous and Romero, 2013; Cavicchia et al., 2014; Miglietta and Rotunno, 2019), such storms are maintained in the same way as tropical cyclones, at least in their mature stage, in which moist and warm air is advected towards the low pressure storm centre at surface and the lower tropospheric levels. This produces and maintains a thermal disequilibrium in the vertical direction that enhances convection, consequently producing condensation through adiabatic cooling. The condensation process releases latent heat that warms the cyclone core, which is the dominant mechanism that sustains the vortex structure (Lagouvardos et al., 1999).

Numerous studies have addressed the sensitivity of medicane simulations to different factors related to their intensification and track. Some authors have studied the effects of an increased sea surface temperature (SST) (Pytharoulis, 2018; Noyelle et al., 2019), while others focus on the role of air-sea interaction and surface heat fluxes (Tous et al., 2013; Akhtar et al., 2014; Ricchi et al., 2017; Gaertner et al., 2018; Rizza et al., 2018; Bouin and Lebeaupin Brossier, 2020) or the influence to various physical parameterizations (Miglietta et al., 2015; Pytharoulis et al., 2018; Ragone et al., 2018; Mylonas et al., 2019). However, less attention has been focused on the microphysical processes and aerosols-cloud interactions, still a great source of uncertainty in the understanding of convective systems (Fan et al., 2016). In fact, according to the Fifth Report of the Intergovernmental Panel on Climate Change (Boucher et al., 2013), the quantification of cloud and convective effects in models, and of aerosol–cloud interactions, is still a challenge. In this type of storms, the microphysics of both cold and warm clouds are essential. The activation of aerosols as cloud condensation nuclei (CCN), the water absorption during the droplet growth, and the auto-conversion processes are main drivers in the core heating and dynamic evolution. Hence, the microphysics parameterization, along with the explicit solving of aerosols, seem to be fundamental for the development of the medicane. Gaining insight on these cloud microphysics processes is a key step for reaching a complete process-understanding. In this sense, the working hypothesis in this contribution is that aerosols play a part in a positive feedback with the surface winds, and thus that an interactive calculation of SSA emissions and concentrations is fundamental for the development of the medicane, as happens in tropical cyclones (Rosenfeld et al., 2012; Jiang et al., 2019a, b, c; Luo et al., 2019).

In addition, provided the special cyclogenetic mechanisms of medicanes, which usually need a specific atmospheric configuration to start deepening the convective activity, the initial conditions feeding the simulations highly affect the medicane development. In consequence, initialization time is an important source of variability (Cioni et al., 2016). In this respect, constraining the synoptic scales to follow reanalysis while allowing the model to develop the small-scale dynamics, which is exactly the function of spectral nudging, stands as a good method to reduce that variability.

Within this framework, this article aims at analysing the role played by aerosols in the development of medicanes, together with the influence of the initialisation time and the potential benefits or caveats of using nudging techniques.

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2 Methods

In this section, the main techniques applied to perform and analyze the simulations are outlined, along with some details about the model parameterizations and the synoptic conditions associated to the studied events. It also contains a brief explanation on the interactive calculation of the SSA concentration, as included in the meteorology-chemistry coupled mesoscale model WRF-chem.

2.1 Simulations setup

2.1.1 Interactive vs non-interactive calculation of SSA

The Weather Research and Forecasting (WRF) Model (V3.9.1.1) is used to conduct the simulations object of this study (Skamarock et al., 2008). The same model configuration is employed for all simulations contained herein unless otherwise indicated. No physics suite (WRF preconfiguration of a set of well-tested physics parameterizations as a suite) is used for the model run, provided the importance of choosing specific parameterizations, such as a double-moments microphysics scheme. The Morrison et al. (2009) bulk microphysical scheme is used (*mp_physics=10*). This scheme allows for a double-moment approach, in which droplet number concentration, along with the mixing ratio, is considered for each hydrometeor species included in the subroutine. In its single-moments version (progn=0), only aerosols mass (i.e. mixing ratio) is taken into account. Thus, while for the single-moment approach a constant concentration of an aerosol with a prescribed size is used, second-moment introduces the complexity degree of considering a size distribution for the aerosol population, thus being a more realistic approach.

In the WRF-chem model, the dynamic core of WRF is coupled to a chemistry module (Grell et al., 2005). The model simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology. Its main advantage with respect to using WRF alone is the possibility to perform an online calculation of the chemistry processes, which allows for chemistry-meteorology feedbacks. In the particular case under study in this paper, when using WRF alone, a fixed concentration of a given type of aerosols is prescribed everywhere. By contrast, WRF-chem calculates the aerosols distribution interactively. Specifically, the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model simulates major tropospheric aerosol components, including sulfate, dust, black carbon (BC), organic carbon (OC), and sea-salt aerosols, the latter being dominant in marine environments (Hoarau et al., 2018), which is our case study. GOCART includes Sea Salt Aerosol (SSA) emission as a function of the surface wind speed, initially introduced by Gong (2003) and after modified to account for SST dependence and some other corrections (Bian et al., 2019). For the emission, particles dry size is considered but the scheme also considers particles hygroscopic growth, dependent on relative humidity, according to the equilibrium parameterization by (Gerber, 1985). This dependence of SSA emission on surface wind intensity allows for the positive feedback between SSA concentration and surface wind speed that will take a main part in the medicane deepening process. When GOCART is used along with a double-moments microphysics scheme, the emission for five bulk sea salt size bins in the range of 0.06 to 20 μm in dry diameter is interactively calculated. Single-moments microphysics makes useless considering interactive aerosols.

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With regard to the physical configuration, radiation is parameterized with the Rapid Radiative Transfer Model for GCMs (RRTMG) by Mlawer et al. (1997), both for short and long wave radiation, solved each 30 minutes. Additionally, the selected option for the surface layer parameterization solves with the MM5 scheme based on the similarity theory by Monin and Obukhov (1954), while the *Unified NOAH LSM* option is used for the land-surface calculation (Mitchell, 2005). The number of soil layers in land surface model is thus 4. Yonsei University scheme is employed for the boundary layer (Hong et al., 2006), solved every time step (*bldt*=0). For the cumulus physics, Grell 3D ensemble (*cu_physics*=5; *cudt*=0) is chosen to parameterize convection (Grell and Dévényi, 2002). Heat and moisture fluxes from the surface are activated (*isfflx*=1), as well as the cloud effect to the optical depth in radiation (*icloud*=1). Conversely, snow-cover effects are deactivated (*ifsnow*=0). Landuse and soil category data come from WPS geogrid but with dominant categories recomputed (*surface_input_source* = 1). Urban canopy model is not considered (*sf_urban_physics*=0), and the topographic surface wind correction from Jiménez and Dudhia (2012) is turned on. Both feedback from the parameterized convection to the radiation schemes and SST update (every 6 hours, coinciding with boundary conditions update) are also turned on.

2.1.2 Initial and boundary conditions

ERA-interim global atmospheric reanalysis is used to provide the simulations with the required initial and boundary conditions (every six hours). This dataset comes from ECMWF's Integrated Forecast System (IFS), configured for a reduced Gaussian grid with approximately uniform 79 km spacing for surface and other grid-point fields (Berrisford et al., 2011).

All simulations are performed at a 9 km of horizontal grid spacing. A different non-nested domain is utilized for each medicane. Domains cover the regions [16ºW, 25ºE, 30ºN, 49ºN], [4ºW, 35ºE, 29ºN, 48ºN] and [3ºW, 41ºE, 26ºN, 45ºN] in Lambert projection for Rolf, Cornelia and Celeno medicanes, respectively. All the simulations inside the ensemble of a medicane (24 per medicane) are run with the same domain.

2.1.3 Spectral nudging

Spectral nudging is a technique for constraining the synoptic scales to follow reanalysis while allowing the model to develop the small-scale dynamics (Miguez-Macho et al., 2004). Initially conceived for reducing the sensitivity of regional climate simulations to the size and position of the domain chosen for calculations, it has been suggested that this technique is necessary for all downscaling studies with regional models with domain sizes of a few thousand kilometers and larger embedded in global models, in order to avoid the distortion of the large-scale circulation. With this premise, we analyze the effects of considering the introduction of spectral nudging for the simulation of medicanes. Particularly, a wavelength of 999 km in both horizontal directions has been used to ensure that only synoptic scale dynamics are constrained; wind, temperature and water vapour mixing ratio fields are nudged above the PBL.

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2.1.4 Run-up time

Run-up time makes reference to the time period (in hours) since the start of a simulation to the time in which the medicane appears. To follow a consistent criterion, this reference time is extracted from the complete ensemble of each medicane. For example, for Celeno medicane the start reference time is considered to be 1995 January 14 12:00 GMT, as can be extracted from Figure 1 on the main text. Hence, six different initialization times are considered for Celeno medicane simulations ensemble: from 1995 January 09 00:00 GMT to 1995 January 14 00:00 GMT with 1 day intervals, corresponding to 132, 108, 84, 60, 36 and 12 hours of run-up time, respectively. The same six run-up times are considered for Rolf (reference time 2011 November 06 12:00 GMT) and Cornelia (reference time 1996 October 06 12:00 GMT) medicanes. By considering an ensemble of initialization times, in practice we are perturbating the initial conditions to reduce the possible uncertainty associated to this factor, thus producing more consistent results for the sensitivity of using or not an interactive aerosols calculation.

2.2 Synoptic environments of the events

Rolf medicane, also known as Tropical Storm Rolf, Tropical Storm 01M (NOAA) or Invest 99L (NRL) was a Mediterranean tropical storm occurred on 2011 November 06-09. It started from the alignment of a surface low-pressure system which evolved into a baroclinic environment near the Balearic Islands, and an extensive upper-level trough early on November 06. On November 07, the system revealed tropical characteristics such as a warm core and convective bands organized around a quasi-symmetric structure. Early on November 08, Rolf reached its maximum intensity, and NOAA officially declared the system a tropical storm (Win). Reaching its peak intensity on that same day (991 hPa of central pressure and maximum 1-minute sustained winds of 82 km/h), Rolf started to weaken, transitioned to a tropical depression and finally lost its structure late on November 09 when it made landfall in Southeast France (Dafis et al., 2018; Miglietta et al., 2013). Rolf was the first tropical cyclone ever to be officially monitored by the NOAA in the Mediterranean Sea.

Known to have formed from the interaction of a large compact low-pressure area that approached to Greece from the Ionian Sea, and a middle tropospheric trough that extended from Russia to the Mediterranean, Celeno started its convective activity early 1995 January 14. Initially remaining stationary between Greece and Sicily with a minimum atmospheric pressure of 1002 mbar, the newly formed system began to drift southwest-to-south in the following days influenced by northeasterly flow incited by the initial low. It acquired a cloud-free distinct eye and a spiralling rainband, rapidly deepening. Its track is generally depicted crossing the Ionian Sea southwards, from Southern Greece to the coast of Lybia (Pytharoulis et al., 2000). A strong disagreement seems to exist between the different sources of information about the maximum wind speed and minimum central SLP reached by Celeno tropical-like cyclone. The German research ship Meteor noted winds of 135 km/h, and SLP of 980 hPa was registered in the North Coast of Malta. ERA5 reanalysis provides an SLP under 990 hPa on 1995 January 14 10:00 GMT for this cyclonic structure.

Lastly, Cornelia medicane took place between the Balearic Islands and Sardinia, with an eye-like feature clearly developed. It appeared on 1996 October 06 to the north of Algeria, and strengthened before temporarily losing its structure. On October 09, the system strengthened again over the Tyrrhenian Sea and passed north of Sicily, reporting winds of 90 km/h at 100 km

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from the storm's center. The lowest estimated atmospheric pressure reached in the storm center was 998 hPa (Pytharoulis et al., 2000; Cioni, 2014; Cavicchia and Von Storch, 2011).

2.3 Methods for the analysis of the simulations output

2.3.1 Tracking algorithm

TITAM (Pravia-Sarabia et al., 2020) is an algorithm specifically suited to allow for the detection and tracking of medicanes even in adverse conditions, such as the existence of a large low in the domain, or the coexistence of multiple medicane structures. This algorithm, based on a time-independent approach, has been used to study the intensity and duration of the medicanes reproduced in the different simulations presented in this paper. Given the different nature of each medicane in duration, intensity and spatial extent, the namelists parameters for TITAM must be consistently defined prior to its execution on each medicane. Specifically, the 4th Hart condition (thermal wind magnitude greater for the lower than for the upper tropospheric layer) is not checked for medicane tracking in Celeno simulations.

2.3.2 Medicanes duration and intensity

When talking about duration, two different measures will be distinguished. Duration will be associated to the number of points in which the algorithm detects a medicane. By contrast, support will be the total length calculated as the more compact points set. This compact set, as shown in Figure 1 on the main text (grey boxes), serve as an objective measure of the real duration of the medicane, removing early starts and late endings in which medicane structure is not well defined, repeatedly gaining and losing medicane condition. To calculate this compact set for a given simulation, after having run the tracking algorithm on it, take a vector X in which elements x_i, each one corresponding to a time step, are 1 if a medicane is found for the time step, and 0 if not. For each i in $1 : N_t$, and each j in $i : (N_t - 1)$, find pair $[i, j]$ such that:

$$Q_{i,j} = \sum_{m=i+1}^{m=j} x_m + \sum_{m=i+1}^{m=j} (x_m - 1) \qquad (1)$$

is maximum, being Nt the number of time steps in the simulation. Once found the pair $[i_m, j_m]$ that makes this quantity $Q_{i,j}$ maximum, i_m and j_m are respectively the initial and final positions of the medicane more compact set, and thus its difference is an objective measure of the medicane duration.

3 Results

The results presented below are based on the analysis of an ensemble of 72 simulations, which consists of all the possibilities resulting from the combination of: three medicanes (Rolf, Cornelia and Celeno), two nudging configurations (no nudging and spectral nudging), two configurations for the aerosols concentration calculation (interactively-calculated aerosols and prescribed aerosols, hereinafter referred to as IA and PA, respectively) and six run-up times (12, 36, 60, 84, 108 and 132 hours).

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As an initial example, a detailed view of each ensemble member for the Celeno medicane (the most intense out of the three simulated) during its lifetime when no nudging is applied is shown in Figure 1. Note that although the discussion below is mostly based on this case, analogous figures for the rest of cases are presented in Section S1.1 of Supplement, and the coherence across cases, as well as relevant differences, are commented here. For each run-up time, the pair PA/IA is depicted; a dot represents a time step where a medicane is found, being its colour the sea-level pressure (SLP) value for the medicane center. If a medicane is not found for a given time step, a grey cross is placed. Figure 1 shows how longer and deeper storms are systematically reproduced for IA simulations. The application of spectral nudging (see Figure S5 in Supplement) makes IA produce weaker medicanes than for the no nudging case. The role of initialization time is also clearly depicted in this figure: it induces a noticeable but nearly random behavior on the medicane response, with differences up to 5 hPa on the center SLP of the medicanes for two consecutive run-up times (i.e., initialization times separated 1 day), but in opposite directions without a discernible pattern. Similar results of longer and deeper tracks for IA, the variability introduced by initialization time and the spectral nudging reduction of the IA influence are found for the other two storms (associated plots are included in Section S1.1 of Supplement).

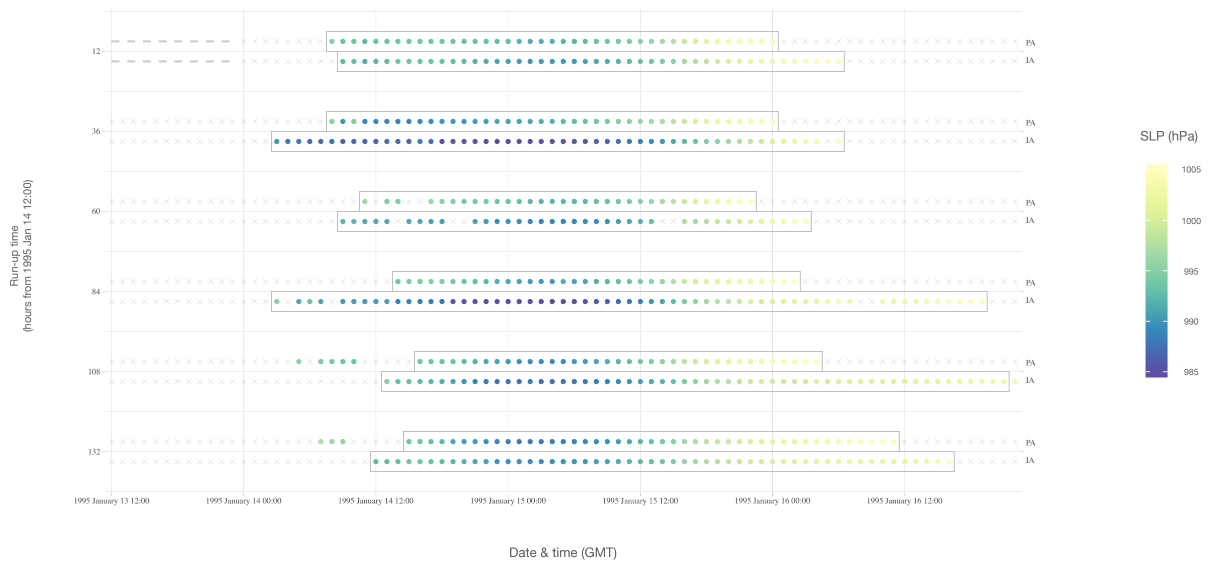

Figure 1. PA/IA pair of simulations without nudging represented for each run-up time of initialization for medicane Celeno. A dot represents a time step where a medicane is found, being its colour the SLP value for the medicane center. A grey cross is placed for the time steps in which no medicane is found. The grey frames include, for each simulation, the time steps inside the medicane more compact points set, as described in Subsection 2.3.2.

In order to study not only the track duration, but also their spatial differences, Figure 2 illustrates the trajectories of the different simulations without nudging for Cornelia medicane (the longest-lasting event of the three considered). The data is aggregated across different run-up times through the calculation of a Kernel Density Estimation (KDE) from most likely

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cyclone locations (Rosenblatt, 1956) built on top of the medicane center positions along the tracks belonging to the PA (green) and IA (red) ensembles of simulations without nudging. KDEs for all cases can be found in Section S1.2 of Supplement. A threshold of 0.2 is used to convert KDEs, normalized to the [0,1] range, to binary density clouds as those included in Figure 2. In addition to how the storm severity is increased for the IA ensemble (as previously shown), the figure showcases that their tracks are more spatially constrained and longer when IA is considered. With the introduction of spectral nudging (see Figure S9 of Supplement), tracks are spatially constrained, thus limiting the intensification potential of the medicane. Similar results can be drawn from the analysis of the Rolf and Celeno medicanes, as extracted from Figures S7, S8, S11 and S12 of Supplement.

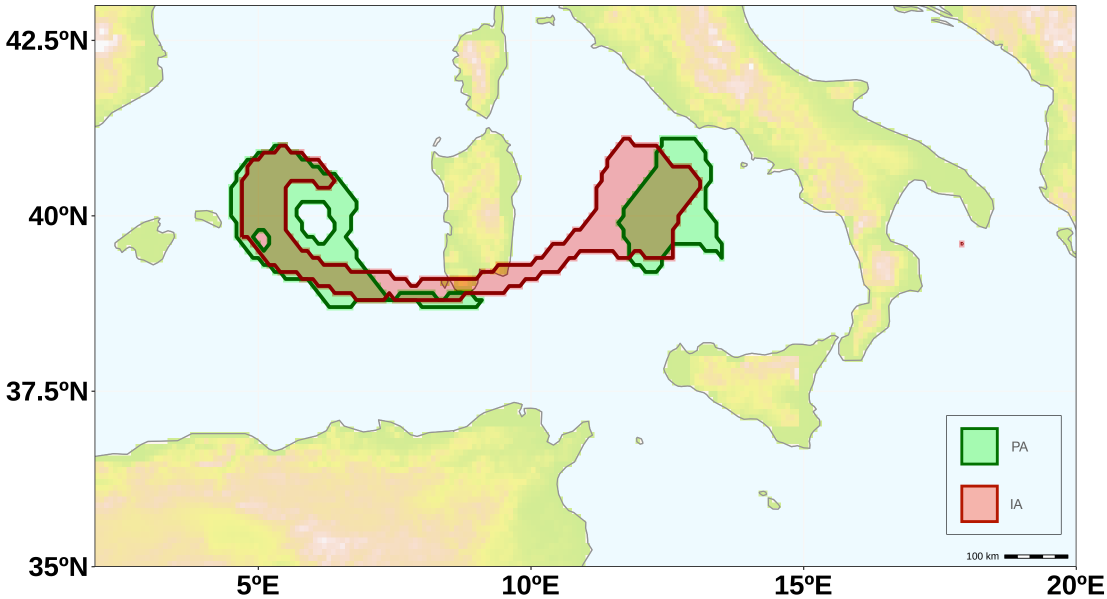

Figure 2. Figure shows the binary KDEs built on top of the medicane positions along the tracks belonging to the PA (green) and IA (red) simulations without nudging ensembles for medicane Cornelia.

To offer a complete view of the results, Figure 3 summarizes the main outcome of the simulations ensemble, focusing both on the differences in the minimum SLP reached at the center of the medicane during its lifetime and its total duration. Medicanes are separated in rings and colours indicate the difference in depth of the storm when SSA interactive calculation is considered or not (reddish colours indicate deeper storms when IA is considered), while ring sector widths are proportional to the relative duration of the events (with respect to the maximum duration of a simulation inside the event simulations ensemble). Both panels are based on identical calculations, but illustrate the impact of using spectral nudging (right) versus leaving simulation free (left). Differences are clearly positive for most cases, which involves that, in general, IA leads to more intense medicanes. Moreover, medicane tracks are also longer for IA simulations. Spectral nudging does not change this general conclusion, but

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reduces the effect of introducing IA, and generally leads to shorter medicane tracks. With respect to the initialization time, there seems to be a random response to the initial conditions.

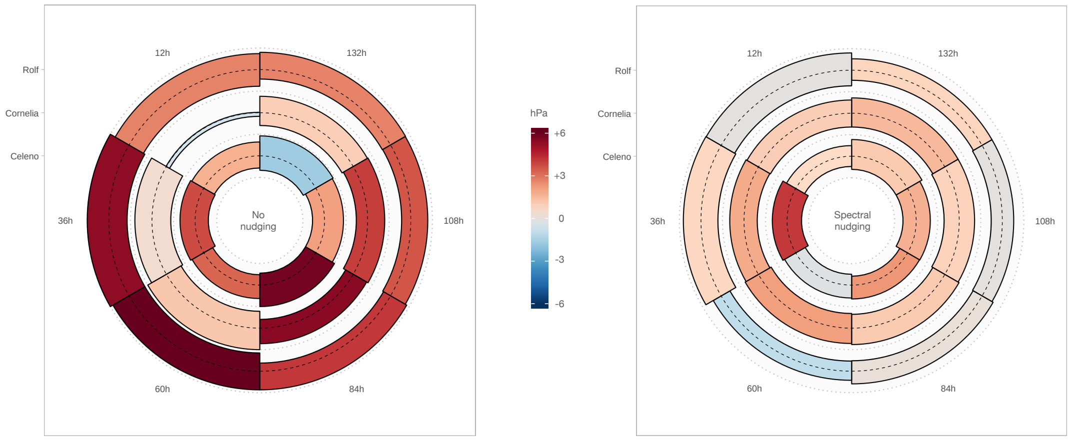

Figure 3. Absolute difference (colours) in the minimum SLP among the medicane centers reached during the medicane lifetime between the IA and PA simulations, for each medicane and run-up time. Medicanes are separated in rings (inner Celeno, middle Cornelia, outer Rolf). Different run-up times are shown in the six ring portions. For each ring portion, the width of the upper half is proportional to the number of points in which a medicane is found in the IA simulation, and that of the lower part to the number of points in the PA simulation. A dashed line separates both. Widths of each medicane are durations relative to the maximum duration among all the simulations for the medicane (24 simulations). Thus, red colour represents a deeper SLP minimum of the medicane centers SLP values for the IA simulations, and the more the asymmetry between the widths of the upper and lower halves of each portion of the rings, the higher the influence of using IA in the track length.

4 Proposed intensification mechanism: SSA-wind feedback

As aforementioned, it seems clear that IA calculation leads to deeper and longer medicane tracks. As introduced in Section 1, our main initial hypothesis, provided the close nature of medicanes to tropical cyclones, is that the explicit calculation of SSA in the model aerosol scheme (GOCART) allows for the existence of a positive feedback with surface wind. Although this feedback is irrelevant for an early emergence of convective activity, generally fostered by a cold cut-off low in upper levels when it comes to medicanes (Emanuel, 2005), it becomes essential once the core circulation is established. For the sake of examining the hypothesis of the existence of this feedback, we choose two simulations of medicane Rolf without nudging starting on 2011 November 05 00:00 GMT. Figure 4 depicts the temporal evolution of the differences in equivalent potential temperature (θ_e) between the IA and PA simulations along the vertical of the medicane center. In general, higher (orange to red colours) θ_e values are found for the IA case, which means that higher convective potential energy comes into play in the form of hot moist air presence in the low troposphere when aerosols are interactively solved in each timestep of the model. This is

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specially true for timesteps later than November 07, when medicane starts to gain strength. Another related aspect is shown in Figure 5 by means of the differences between the IA and PA time-averaged height-longitude cross sections of θ_e. It clearly reveals that the core temperature is up to 4 degrees higher for the IA case, and even the divergence aloft can be appreciated in this figure.

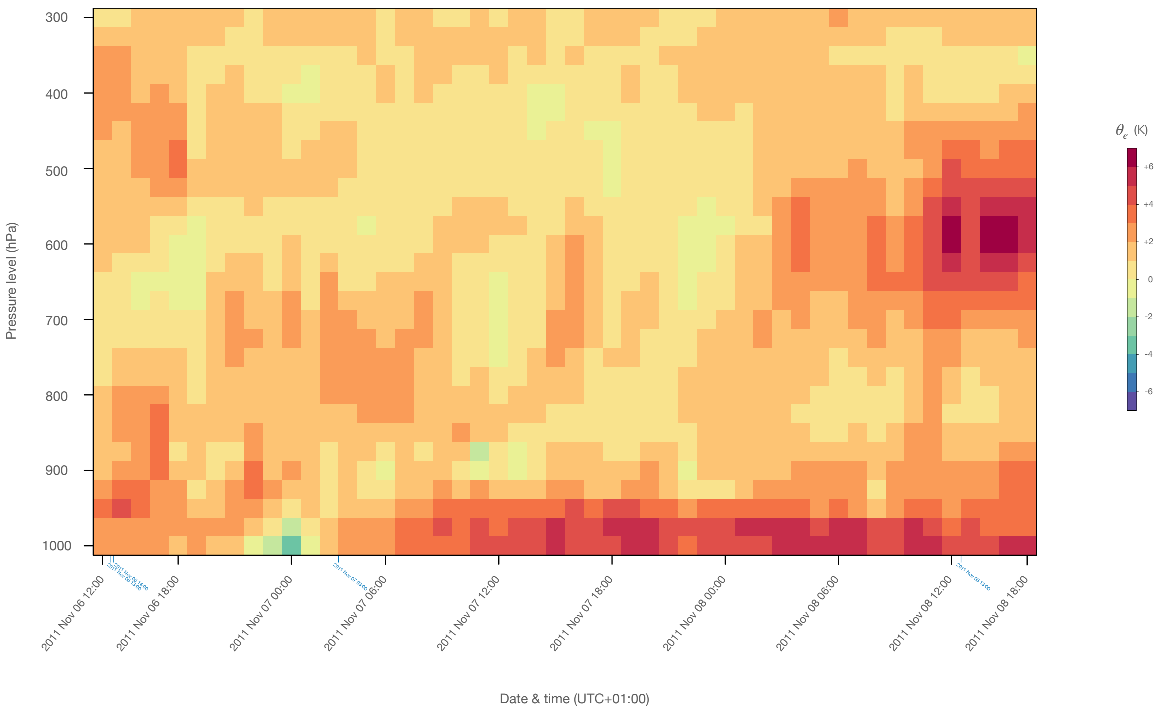

Figure 4. For each time step (horizontal axis) in which both the PA and IA simulations find a medicane for Rolf medicane starting on 2011 Nov 05 00:00 GMT, the difference in equivalent potential temperature (in the medicane center point) between the IA and PA simulations is presented for each pressure level (vertical axis). Red colours indicate higher equivalent potential temperatures, and thus more available energy, for the IA simulation. Blue marks in the horizontal axis refer to the time steps in which the medicane structure is lost and, therefore, the tracking algorithm does not find a medicane center.

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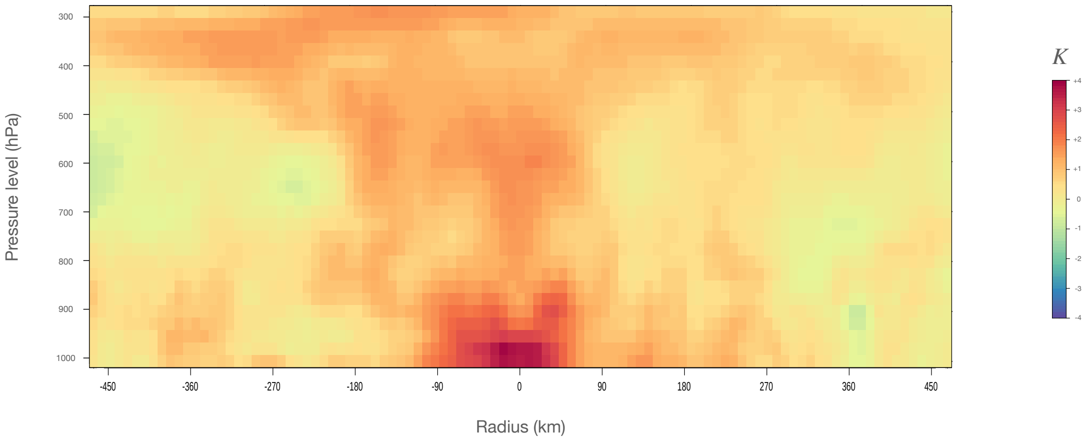

Figure 5. Figure shows differences between the IA and PA time-averaged height-longitude cross sections of θ_e along the medicane center latitudes during the medicane lifetime. The simulations are the PA and IA Rolf medicane cases without spectral nudging starting on 2011 November 05 00:00 GMT. Distance from the medicane center is represented in the horizontal axis, and atmospheric pressure levels in the vertical axis.

To fully understand the processes undergone by aerosols and clouds, the hydrometeors distribution is examined, revealing the form in which the thermal energy is handled by the system. This is shown in Figure 6, in which a time-averaged height-longitude cross section is presented along the latitudes of the medicane centers found for the simulations without nudging starting on 2011 November 05 00:00 GMT. In this plane, the following projections are presented (from top to bottom): cloud water mixing ratio, droplet number mixing ratio and rain water mixing ratio, for both the PA (left column) and IA (right column) simulations.

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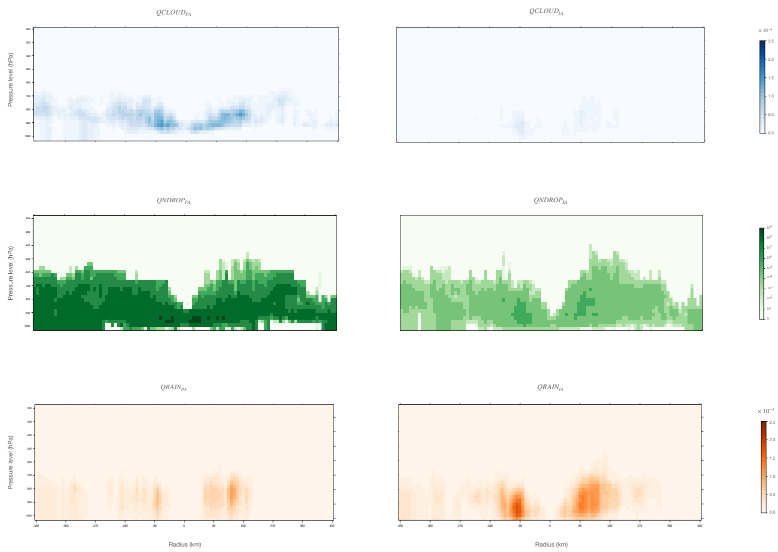

Figure 6. From top to bottom: cloud water mixing ratio ($kg\ kg^{-1}$), droplet number mixing ratio (kg^{-1}) and rain water mixing ratio ($kg\ kg^{-1}$). For the three fields, a time-averaged height-longitude cross section along the medicane center latitudes during its lifetime are shown for PA (left column) and IA (right column) simulations starting on 2011 November 05 00:00 GMT, both without spectral nudging. Distance from the medicane center is represented in the horizontal axis, and atmospheric pressure levels in the vertical axis. Logarithmic scale is used for the droplet number mixing ratio.

Figure 6 indicates that in the case where the largest medicane deepening is found, although being accompanied by a higher thermal energy, lower cloud droplet numbers and less cloud water content come into play, but more rain water is produced. Diving into the microphysics, a plausible explanation resides in the Köhler curves and mechanism of CCN activation as cloud droplets. Intense wind blowing over the ocean surface creates sea spray, which contains organic matter and inorganic salts that form SSA (Gong et al., 1997). SSA are coarse particles quickly reaching the critical radius and being early activated as CCN at low supersaturation rates according to Köhler theory (Köhler, 1936), thus being highly prone to condensational growth (Jensen and Nugent, 2017). The existence of SSA enables an early, rapid and strong latent heat release in the lower troposphere, which enhances deep convection, ultimately leading to an intensification of surface winds under low supersaturation conditions in the early medicane stage. Conversely, prescribed aerosols concentrations used in PA simulations lead to a high amount of fine particles with low hygroscopicity hardly activated as CCN and competing for water vapour uptake, thus producing a higher number of small droplets which are barely converted into raindrops.

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5 Summary and conclusions

In this contribution, an ensemble of simulations have been conducted to analyze the role of SSA feedbacks in the development and intensification of three different medicanes. Results show a clear dependence on interactive aerosols calculation of both the track and intensity of the medicanes simulated, as their consideration leads to reproducing longer and deeper medicanes. The proposed mechanism to explain this difference is that by contrast with simulations with prescribed aerosols (as usually included in meteorological models), when interactive aerosols are introduced the presence of coarse particles is accounted, and the hygroscopic characteristics of sea salt aerosols are considered, thus allowing an early reaching of critical radius and an enhancement of a strong latent heat release in the lower tropospheric levels. Conversely, when aerosols are prescribed and constant, finer particles are considered and less activation of aerosols to CCN is produced, which lowers the velocity of condensational growth, leading to lower rates of latent heat production and suppression of warm rain provided the difficulty of small aerosols to grow up to droplet size. Hence, the coupling of the meteorological model to an online chemistry module results of paramount significance for the formation and evolution of a medicane. An interactive calculation of aerosols provides realistic SSA concentrations which, combined with the ability of the model to introduce hygroscopic and microphysical properties for the different species, favours deep convection development.

Initialization time largely modulates medicane simulations output, thus being a source of great variability. Highly influenced by the initial conditions, these simulations are prone to lose the necessary conditions for a medicane to be triggered and maintained. Despite this sensitivity, there seems to be no privileged run-up time to simulate medicanes, and no systematic deviation is produced by this factor. Hence, modifying initialization time is analogous to perturbing the initial conditions in a system highly sensitive to initial conditions. This result is important, as the different run-up times can thus be regarded as an ensemble of perturbed initial conditions, and thus the results obtained related to the importance of an interactive aerosols calculation are robust within this ensemble.

Spectral nudging leads to shorter and less intense medicane tracks. Given the deep vertical character of medicane structures, any forcing introduced by synoptic scale dynamics may provoke a misalignment in the medicane core. Specifically, the asymmetric upper-lower tropospheric forcing derived from the spectral nudging technique without in-PBL influence deviates the vertical alignment of medicane core, introducing an artificial vertical shear that hampers the formation of deep convection. However, further analysis on the wavelength and in-PBL spectral nudging is required to completely determine whether spectral nudging could be beneficial for medicane simulations.

Finally, this contribution discusses differences between simulations with and without SSA feedbacks, but no assessment is provided on whether differences imply a better agreement with actual medicanes. The main reason for this is the lack of reliable observations in the sea to carry out a comprehensive validation of the simulations. Therefore the contribution focuses on the physical mechanisms reproduced by the model, and provides arguments that support their feasibility. Given the great similarities of medicanes with tropical cyclones on their mature stage, it seems clear that the possibility for medicanes to produce its own SSA within a feedback process needs to be accounted by the simulations. The analysis included here indeed shows that enabling this possibility leads to deeper and longer medicane tracks. Therefore the natural question emerging is to

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what extent this deepening of the storm is realistic. Although the lack of observations to carry out validations hampers such an assessment, including these processes can only lead to a more realistic simulation of medicanes. Models, and specifically their microphysics processes or the presence and effects of aerosols, are strongly parameterized. Even if an eventual validation could demonstrate that simulations without SSA feedback, i.e. shallower storms, are closer to observations, this would not mean that ignoring this feedback produces better results. Instead, it would demonstrate that the model is heavily tuned to produce better results when important feedback processes are ignored. Therefore, it becomes evident that the inclusion of SSA feedback is a fundamental mechanism in the development of tropical-like storms, and simulations aiming at studying these phenomena should not neglect its importance.

Author contributions. EPS carried out the WRF simulations and performed the calculations of this paper. JPM contributed to the design of the simulations and their analysis. He also provided ideas for new approaches in the analysis of the simulations that have been integrated in the final manuscript. JJGN, PJG and JPM provided substantial expertise on the topic that contributed to its understanding. The paper has been written by EPS, JJGN and JPM, and all authors have contributed reviewing the text.

Competing interests. The authors declare no conflict of interest.

Acknowledgements. The authors are thankful to the WRF-Chem development community and the G-MAR research group at the University of Murcia for the fruitful scientific discussions.

Financial support. This study was supported by the Spanish Ministry of the Economy and Competitiveness/Agencia Estatal de Investigación and the European Regional Development Fund (ERDF/FEDER) through project ACEX-CGL2017-87921-R project.

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