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Simulation of extreme heat events over the Valencia coastal region: sensitivity to initial conditions and boundary layer parameterizations

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ABSTRACT

The Valencia coastal region (Western Mediterranean) is especially sensitive to extreme heat events, where they are really common. However, due to its geophysical characteristics and climatic conditions, the incidence of high and extreme temperatures may still be modulated over this area by means of sea breeze circulations, defining a Sea Breeze Convergence Zone (SBCZ) due to the meet and interaction of these mesoscale conditions and Western synoptic-scale wind regimes. A proper definition of this convergence zone is of significant importance over the study area for the simulation and forecast of intense-heat meteorological events. This study analyses a week period in August 2010 over this area, which alternates the presence of meteorological conditions

prone to high and extreme temperatures with sea breeze conditions that temper these extreme temperatures. The simulations have been performed using the mesoscale model Regional Atmospheric Modeling System (RAMS). The analysis focuses on the ability of different initial conditions and technical features and two widely used planetary boundary layer parameterizations to forecast and reproduce the observed high and extreme temperatures, as well as to properly capture the main associated atmospheric patterns. It has been found that an increased horizontal resolution in the initial atmospheric fields produces a better representation of the regional and local wind flows simulated by the mesoscale model, leading to an accurate characterization of the temperature fields when these wind circulations dominate over the area of study. However, no significant differences are obtained within the intense-heat situations, associated with atmospheric synoptic-scale forcings. Regarding PBL parameterizations, the local PBL scheme tends to underestimate the daytime temperatures, while the non-local scheme produces higher temperatures than the local scheme, skilfully reproducing the observations. Additionally, the non-local scheme overestimates temperatures at night-time, but it suitably captures the observed high minimum temperatures produced by the Western synoptic conditions.

Keywords: Mesoscale modelling; Model initialization; Boundary layer parameterizations; PBL parameterization schemes; Summer temperatures; Extreme heat

1. Introduction

In the ongoing discussion on climate change, and considering any hypothetical increase both in the frequency and severity of extreme heat events (Fischer and Schär, 2010), summer temperatures are a parameter of interest because they greatly affect

human societies and ecosystems (IPCC, 2014). In this regard, a relation has been found between increase in mortality and temperature extremes or heat wave events. Furthermore, high and extreme temperatures have different economic and ecological impacts, such as energy consumption, water resources management or forest fire hazards, among others. In addition, there is a relationship between high and extreme temperature and increases in potential evapotranspiration and water deficit (Fischer et al., 2007; Teuling et al., 2010; Stéfanon et al., 2012), closely based on the land-atmosphere coupling through the soil state (Gómez et al., 2018a,b,c).

Intense-heat events are typical in the Valencia coastal region during the summer season. In fact, previous studies conducted over this Mediterranean region (Miró et al., 2006; Miró et al., 2015; Miró et al., 2016) point towards a positive trend in extreme temperatures. They are in general associated with Westerly synoptic winds that reach the coast, producing higher and extreme temperatures (Gómez et al., 2014a,b,c). However, due to its geophysical situation and climatic conditions, the development of daily sea breeze circulations mitigates these high and extreme temperatures, not only in areas near the coast but also inland (Gómez et al., 2016b). Additionally, it is common that these synoptic-scale regimes alternate with mesoscale circulations in a daily basis, producing a notable impact on the Valencia region (Gómez et al., 2015a). The meeting of a dryer and warmer environment, advected towards the coast by the Western synoptic flow, with a moister and cooler air, generated by the sea breeze circulations, produces the well-known Sea Breeze Convergence Zone (SBCZ) (see e. g. Millán et al., 1998; Azorin-Molina and Chen, 2009a; Azorin-Molina et al., 2009b; Azorin-Molina et al., 2014). The location of this area depends on the intensity of the Western synoptic flow and its ability to block the development of sea breeze conditions closer to the coast or more inland (Gómez et al., 2016c).

Due to the high risk of vulnerability provoked by the temperature extremes and heat wave events, as well as their sensitivity to climate change, greater efforts are needed in order not only to better understand these extremes, but also with the aim of improving the forecast skill of Numerical Weather Prediction (NWP) models (Gouda et al., 2017; Sathyanadh et al., 2017). Therefore, considering the particularities of intense-heat events over coastal areas, such as the Valencia region, forecasting the scope and convergence of the distinct atmospheric systems involved in the development of these meteorological events is a key point in order to properly simulate the temperature field.

Among other factors, the skill of NWP models is due to the improved initial conditions and the improved representation of physical processes (Kalnay, 2003). Considering the physical parameterizations implemented in a NWP model, the Planetary Boundary Layer (PBL) plays a key role in the accuracy of the forecast PBL processes (Kotroni et al., 2011; Sathyanadh et al., 2017). The current paper deals with these two factors using the Regional Atmospheric Modeling System (RAMS). RAMS was previously implemented in a meteorological real-time forecasting system over the coastal Valencia region in order to produce high-resolution forecasts of local weather conditions, especially focused on meteorological hazards (Gómez et al., 2014a,b,c; Gómez et al., 2015a).

Considering land-atmosphere coupling, it becomes essential to suitably characterize the initial soil state to be used in the corresponding NWP system (Gómez et al., 2016c; Gómez et al., 2018a,b,c). In this regard, Seneviratne et al. (2006) proved the importance of soil moisture-temperature feedbacks in recent and future conditions in Europe, and Fischer et al. (2007) demonstrated that soil moisture-temperature feedbacks can increase heat wave duration in their study of four past events in Europe. Accounting for both land-atmosphere coupling and initial soil state, Gómez et al. (2016c) developed

a methodology to incorporate into the RAMS modelling environment not only the Land Surface Temperature (LST), but also the Soil Temperature (ST) parameters corresponding to deeper soil levels derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (Dee et al., 2011). Besides, the LST parameter was also updated in this mentioned study using the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) LST product (Trigo et al., 2008). They found no improvement when the LST parameter was assimilated into the model. However, they found a marked improvement in simulating extreme heat events when incorporating ST in the mesoscale model. Additionally, LST and ST in addition to Soil Moisture (SM) derived from the uncoupled Land Surface Model (LSM) Global Land Data Assimilation System (GLDAS; Rodell et al. 2004) datasets have recently been incorporated into RAMS in order to better represent the soil state for the simulation of surface energy fluxes and meteorological fields (Gómez et al., 2018a,b,c).

Even though considerable research has been devoted to SM regarding land-atmosphere coupling in climate and NWP models (e. g. Seneviratne et al., 2010; Stéfanon et al., 2013; de Rosnay et al., 2014; Gómez et al., 2015b; Dillon et al., 2016; Dirmeyer and Halder, 2016; Gómez et al., 2016b; Gómez et al., 2018a,b,c), less attention has been paid to ST (Gómez et al., 2016c). However, ST plays a significant role in land surface processes (land-atmosphere coupling) with implications as important as SM in climate and meteorology. The land energy budget can be determined by ST, as longwave radiation and ground heat flux are a function of this magnitude (Park et al., 2017).

Taking into account the initial conditions incorporated into the RAMS model, all this information is used in the current study, considering previous developments in the

model code, such as ECMWF ERA-Interim (Gómez et al., 2016c) and GLDAS (Gómez et al., 2018a), as well as considering new developments of the model for the integration of available higher resolution reanalysis datasets, such as the ECMWF ERA5. A detailed description of this information may be found in the following section. LST and ST derived from these reanalysis datasets have therefore been used as initial and lower boundary conditions in the simulation of high and extreme summer temperatures using RAMS. Additionally, SM derived from GLDAS dataset has also been included into the model in these terms. Similarly, and making use of the meteorological fields provided by both the ECMWF ERA-Interim and ERA5 datasets, we analyse the sensitivity of the model to input atmospheric data of different horizontal resolution used as initial and boundary conditions for RAMS. Finally, two distinct technical features of the model are tested: the application of distinct spin-up times and the horizontal resolution of the mesoscale model. Even though there is a lack of consensus on the spin-up to be used in a specific simulation (Kleczek et al., 2014), a minimum of 12-h should be used to avoid instabilities in the mesoscale NWP model and to properly develop large-scale and mesoscale circulations if they are not operated in a data assimilation cycle. Nevertheless, it likely depends on the state of the soil and quality of the model input fields (Kleczek et al., 2014). Likewise, the effect of finer horizontal resolutions in the mesoscale model has been previously evaluated in the simulation of distinct physical processes, such as strong and weak synoptic flows and local air circulation patterns (Bonnardot et al., 2009), wind simulation for the wind power sector (Carvalho et al., 2012), nocturnal temperatures forecasting (Battisti et al., 2017), or the simulation of surface meteorological conditions over complex and steep terrain (Zhang et al., 2013, Jiménez-Esteve et al., 2018), among others. The use of a finer horizontal resolution is

expected to result in more precise and better-resolved small-scale processes (Kleczek et al., 2014).

Regarding PBL processes, there are different boundary-layer parametrization schemes available in NWP and climate models. Many of these schemes were designed to simulate specific weather conditions (see e. g. Steeneveld et al., 2011; Carvalho et al., 2012; Xie et al., 2012; Kleczek et al., 2014; Banks et al., 2016; Gómez et al., 2016b; Kalverla et al., 2016; Avolio et al., 2017; Tymvios et al., 2018), but not all of the parametrizations have been evaluated thoroughly (Kleczek et al., 2014). Such an evaluation is essential for both researchers and operational forecasters interested in weather prediction and especially when using models within real-time forecasting systems focused on meteorological hazards, such as extreme heat events. However, few studies have been found in the literature related to the application of different PBL schemes on the simulation of extreme heat events. In this regard, Kotroni et al. (2011) used previously developed local and non-local PBL schemes for the simulation of a heatwave event over Greece, while Sathyanadh et al., (2017) investigated the performance of the different PBL schemes in the context of a dry event over the complex terrain of the Ganges valley.

Based on initial and boundary conditions, technical features and PBL parameterization schemes, the current study performs a comprehensive sensitivity analysis to these modelling parameters with the aim of evaluating the ability of mesoscale modelling to simulate and forecast intense-heat events over coastal areas, particularly focused on the Valencia coastal region. To do this, we have selected an extreme heat episode that took place on August 2010. Therefore, we would like to answer the following questions: (1) what is the role of initial soil state in the simulation of these sensitive meteorological events according to the conditions applied by different

initialization datasets, (2) is it possible to improve the mesoscale model performance by means of higher horizontal resolution meteorological fields used as initial and boundary conditions for this model, (3) does an increased horizontal resolution in the mesoscale model improve the simulation results, and what about the selection of a proper spin-up time, (4) what are the strengths and weaknesses of widely used local and non-local PBL parameterization schemes in the simulation and forecast of intense and extreme heat events.

This paper is structured as follows. Section 2 includes a detailed description of the modelling strategy as well as the different sensitivity experiments and the observations used to evaluate the model results. Section 3 presents the corresponding results. Finally, section 4 summarizes the main conclusions and some final remarks are provided.

2. Datasets and methodology

2.1. Modelling strategy

The selected weather event (22 to 28 August 2010) has been simulated using the 6.0 version of the RAMS model (Cotton et al., 2003; Pielke, 2013). The main configuration used is that previously used by Gómez et al. (2016c). This set-up includes a full-column two-stream single-band radiation scheme that calculates short-wave and long-wave radiation and accounts for clouds (Chen and Cotton, 1983), the Mellor and Yamada (1982; MY) level 2.5 turbulence parameterization, and the Land Ecosystem-Atmosphere Feedback (LEAF) scheme, version 3 (Walko et al., 2000). In addition to the MY local scheme Turbulent Kinetic Energy (TKE) closure, the non-local Boundary Layer schemes Yonsei University (YSU) PBL is used in the current study (Hong et al., 2006; Gómez et al., 2016b).

Regarding geographical and domain configuration, RAMS uses 45 levels in the vertical following a stretched scheme. A 30-m spacing is fixed near the surface increasing gradually up to 1,000 m near the top of the model at about 16,000 m, with a total of 15 levels in the lower 1,000 m. In the current study, initial and boundary conditions for RAMS are taken from two different datasets. On the one hand, ECMWF ERA-Interim reanalysis (Dee et al., 2011), at 0.75 x 0.75 degree resolution globally has been used as the simulation reference, as previously used in Gómez et al. (2016c). On the other hand, ECMWF ERA5 reanalysis, at 0.25 x 0.25 degree resolution globally has been used as well. A daily simulation with a forecast horizon of 36 h and a temporal resolution of 1 h, starting at 12 UTC the previous day, has been performed. Therefore, the first 12 h are left out as a spin-up period and only the corresponding complete day is considered in the model assessment.

Considering ERA-Interim, RAMS has been set-up with three nested domains at 48 km, 12 km and 3 km horizontal grid resolution (EXP1), respectively, as in Gómez et al. (2016c). EXP1 uses the LST and ST state provided by the ERA-Interim dataset, while GLDAS soil state has also been incorporated together with ERA-Interim meteorological fields (EXP2). Additionally, using EXP2 RAMS configuration, the period of study has been simulated using the YSU PBL parameterization (EXP3). The effect of spin-up has been tested using the MY scheme, considering a spin-up time of 24-hours (EXP4). A summary of these experiments is included in Table 1.

In relation to the ERA5 reanalysis dataset, two additional domain configurations are used over a specific area within the Valencia coastal region. Firstly, two domains at 12 km and 3 km horizontal grid resolution (EXP5), and secondly, a third nested domain at 750 m is incorporated to this latest RAMS modelling configuration (EXP6). The area simulated in this case has been selected based on the hotspot area within the Valencia

region where high temperature warnings are activated in a high percentage of summer days (Gómez et al., 2014a,b).

2.2. Observational datasets

Besides analysing the differences among the distinct sensitivity experiments performed, the corresponding simulations have also been compared to different near-surface observational datasets available over study area, considering the model results over the finer domain (3 km and 750 m horizontal resolution, depending on the corresponding simulation, as described in the previous section). We have used the SIAR (*Sistema de Información Agroclimática para el Regadío*; Agroclimatic Information System for Irrigation: <http://portal.magrama.gob.es/websiar/Inicio.aspx>) automatic surface weather station network operated by the Spanish Ministry of Agriculture, Food and Environment. Hourly measurements of 2-m temperature, 2-m relative humidity and near-surface wind components from 8 automatic meteorological stations from this network and distributed throughout the whole study region are used to be compared with the RAMS results in order to obtain a deeper insight of this meteorological event. From all these weather stations, we especially focus on the Valencia coastal region above mentioned hotspot area. Measurements are quality controlled taking advantage of other independent weather station networks, such as the Spanish AEMET and the Mediterranean Center for Environmental Studies (CEAM) Foundation, in order to evaluate differences with nearby stations. In this regard, meteorological fields from stations located close to each other or presenting similar climatic patterns, but linked with each independent network, are evaluated in order to check the consistency of the data used in the current study. Specific humidity is not directly recorded by the SIAR system sensors, but it can be obtained through relative humidity and air temperature. As relative humidity is directly related to air temperature, due that warm air can hold more

vapour than cold air, in the current study we use specific humidity as a measure of the water vapour content. This magnitude is calculated by means of the simulated pressure at the corresponding weather station location. Still, this procedure can introduce small errors (Jiménez-Esteve et al., 2018).

2.3. Evaluation procedure

To perform an statistical verification of the model results, several statistical scores have been calculated for individual stations, considering the day and nighttime records as well as considering the whole daily measurements. The statistical calculations include the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE), as used in previous studies (e. g. Gómez et al., 2016c):

$$MBE = \frac{1}{N} \sum_{i=1}^N (F_i - O_i) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (F_i - O_i)^2} \quad (2)$$

where N is the number of observations included in the calculations. O represents the observed value and F the simulation results. MBE (or Bias), defined as the average of the simulated value minus the observed value is a measure of the mean deviation of the model, and shows the tendency of the model to overestimate or underestimate the observed values. The RMSE is the square root of the individual differences between simulated and observed values. This statistical score quantifies the accuracy of the model.

Besides these two statistical measures, we use the correlation coefficient in the evaluation procedure, defined as follows:

$$r = \frac{\sum_{i=1}^N (F_i - \bar{F})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^N (F_i - \bar{F})^2 \sum_{i=1}^N (O_i - \bar{O})^2}} \quad (3)$$

where $\bar{F}$ and $\bar{O}$ represent time average simulated and observed, respectively. r measures the correlation between forecasts and observations. The model correlates with observations if the value of r is near 1. Regarding this statistical score, we have performed a correlation analysis in order to evaluate the correlation significance association between air temperatures provided by different RAMS simulations.

3. Results and discussion

3.1. Sensitivity to initial soil conditions, spin-up time and boundary layer parameterizations

3.1.1. Simulated patterns of air temperature and wind field

Considering the whole simulation period, only the 23 and 27 August 2010 were dominated by a Western synoptic advection situation (Fig. 2a,c), producing extended high air temperatures over the study area. In this regard, the 24 August 2010 was also dominated by these atmospheric conditions, but only over a specific region and during the first half of the day (Fig. 2b). The other days were characterized by the development of mesoscale circulations, producing the entrance of sea breeze during the day, reaching inland regions (Fig. 2d on 26 August 2010). Fig. 3 shows the 2-m temperature and the 10-m wind field at 15 UTC on 26 August. In general, differences below 1 °C are found between EXP1 and EXP2, even though some regions show differences up to -2 °C (Fig. 3b). The greatest negative divergences between EXP2 and EXP3 are found especially near the coast. In this case, using the YSU PBL scheme instead of MY leads to higher day-time air temperatures, practically for the whole simulation region. Likewise, the

effect of a longer spin-up, such as EXP4, leads in general to higher air temperatures with the exception of some areas near the coast.

Regarding the Western synoptic advection on 23 and 27 August, the second is more extreme than that obtained on 23 August (Fig. 4a and Fig. 5a). Focusing on the simulation results this day (Fig. 4), the Western synoptic advection is able to reach areas very near the coast, especially in the hotspot Valencia coastal region (Fig. 1). This area delimits the convergence of two different wind regimes, a Western synoptic advection inland and the development of the sea breeze flow that is blocked by this synoptic forcing near the coast. Comparing EXP2 with EXP1 (Fig. 4b), there is a boundary defined by the corresponding convergence area (SBCZ). Besides, comparing the model results between the simulation performed using MY and YSU PBL schemes (Fig. 4c), differences below 2 °C are obtained inland, under the influence of the Western synoptic advection. However, divergences up to 3 °C and higher are obtained in areas near the coast, under the influence of the sea breeze wind flow. In this case, the SBCZ marks an area of larger differences over the coast, with YSU producing higher air temperatures than MY. Nearly the same results are found on 27 August (Fig. 5), but in this latter case, the Western synoptic advection reaches the coast, triggering extreme air temperatures over the area. The same trends among the distinct RAMS simulations are basically maintained in this case. However, confronting the PBL simulations, higher air temperatures (with differences larger than -5 °C over some areas) are obtained using the YSU PBL scheme over the coast. In addition, the divergences comparing EXP2 with EXP4 points towards higher air temperatures in case a shorter spin-up is applied to the simulation, as on 27 August (Fig. 5d), but with higher negative differences (up to 5 °C; Fig. 5d) in the area centred around (lon=-0.5 degrees; lat=39.5 degrees). In the case of keeping a longer spin-up, a sea breeze field is developed by RAMS over this area in

comparison to the Western synoptic advection maintained by EXP1, thus changing the SBCZ configuration.

Fig. 6 shows the 2-m temperature and the 10-m wind field at 06 UTC on 26 August. Contrasting the daytime air temperatures (Fig. 3b) with the nighttime air temperatures (Fig. 6b), a different trend is observed, with EXP2 producing in general higher air temperatures than EXP1. However, the comparison of the nighttime air temperatures simulated by YSU and MY PBL parameterizations show a different trend, that seems to be related to the orography of the study area. In this regard, higher air temperatures are obtained with YSU scheme over more complex terrain while the opposite trend is found over flatter areas (Fig. 1).

Once again, a similar trend is observed on 23 (Fig. 7) and 27 (Fig. 8) August for the nighttime air temperatures when the soil state is initialized using GLDAS or ERA-Interim. As a difference between these two days and the 26 August, in the first case, the incidence of North-Westerly winds in the area centred around ($\text{lon}=-0.4$ degrees; $\text{lat}=40.2$ degrees) produces higher air temperatures, which is more relevant on 27 August (Fig. 8b). However, the wind flow over this area produces lower wind speeds (Fig. 7b). Additionally, confronting the RAMS-MY (EXP2) with RAMS-YSU (EXP3) at night on 23 and 27 August, higher air temperatures are once again obtained using YSU than those obtained using MY. This is especially true on 27 August, where a clear Western synoptic flow is well-established over the area of study not only during the day, but also at nighttime (Fig. 8c). In the case of this Western advection, there is a clear relation in the wind flow with orography (Fig. 1).

Considering different initial conditions used in the current study, it can be said in general that using GLDAS as initial soil conditions for RAMS leads to higher air temperatures than those observed using ERA-Interim data under the influence of higher

wind speeds, both considering synoptic and mesoscale flows. This is clear during the day, when these larger wind speeds are reached, as it could be related to the higher air temperatures imposed by GLDAS in contrast to those introduced by ERA-Interim in the whole soil profile (not shown). However, the opposite trend is found at night over those areas characterized by calm and light winds.

In light of the wind field simulated by RAMS (Figs. 3-5), Fig. 5b shows a larger development of the sea breeze over the study area centred around ($\text{lon}=-0.5$ degrees; $\text{lat}=39.6$ degrees), which is not simulated by RAMS when using ERA-Interim as initial soil state conditions. In this latter case, the Western synoptic flow is able to reach coastal areas, thus producing a warmer and dryer environment, and blocking the sea breeze circulation, that is limited to the locations over the near coast. Likewise, YSU PBL scheme produces a stronger Western synoptic advection over the middle-North of the region on 27 August, reaching the coast, as in CAS weather station (Fig. 5c), leading to an increase in the daytime air temperatures over this area, that is not reproduced by the other simulations due to the development of the sea breeze flow. Similarly, a stronger and more channelling Southern wind flow focuses on the South region this day. This wind circulation is not simulated by the other RAMS experiments. Following this statement, the RAMS-YSU (EXP3) run already develops the Western synoptic advection on 27 August during the night (Fig. 8c), going through the whole region and reaching the coast with a stronger channelling in comparison to the lighter winds simulated by the other RAMS simulations.

3.1.2. Observed and simulated air temperatures

Comparing the 2-m temperature simulated by RAMS with the observations, EXP1 is able to properly reproduce the main features observed over the study area (Fig. 9). In relation to the night-time air temperatures, there is a tendency to overestimate the

observations over pre-coastal weather stations (located inland), such as MON (Fig. 9e), under the presence of mesoscale circulations, as on 25 and 26 August. However, EXP1 properly captures the nocturnal cooling over other weather stations, such as XAT or PLA these days. For instance, the difference between the forecast and observed minimum air temperature on 23 August is of 3 °C over BET and of 4 °C over MON while this difference is reduced to 1.8 and 1.0 °C over PIC and XAT, respectively (Fig. 10).

Considering air temperatures produced by EXP2 and EXP1 at daytime (Fig. 11), the same result is found in general in terms of the simulated and observed maximum air temperature difference. However, there is a tendency to slightly increase this difference in EXP2 in comparison to EXP1. This result could be related to the different SM initialization used in both simulations. In the case of EXP1, RAMS is initialized with homogeneous SM at 38 % of field capacity. In contrast, an heterogeneous SM initialization is used in EXP2, based on the soil state field provided by GLDAS (Gómez et al., 2018a). Nevertheless, there is a general significant correlation between these two simulations. For instance, correlation coefficients of 1.0 are obtained in this regard over XAT, PIC, and PLA (not shown). At night, similar results are found as well between EXP1 and EXP2, but in some weather stations, such as BET and PIC, RAMS produces higher air temperatures using EXP2. The opposite trend is found however in other stations, such as MON or ALM. There seems to be a different trend between these two RAMS simulations considering the southern weather stations, such as MON and ALM, and the northern weather stations. In the first case, there is a tendency in EXP1 to produce higher air temperatures than EXP2 (Fig. 9). However, this trend is reversed over the middle to north areas within the study region. EXP1 and EXP2 have exactly the same configuration except the initial soil state incorporated into RAMS. Thus, the

corresponding differences should be related to this initialization, taking into account the heterogeneity performed by ERA-Interim and GLDAS considering the wide extension of the study area. It has been found that the differences simulated by RAMS are related to the LST and ST fields used in EXP1 and EXP2, respectively, producing the divergences observed in Fig. 9 depending on the specific weather station. Regarding the average 2-m temperature for the weather stations used (Fig. 9a), hourly differences lower than 3 % are found between EXP1 and EXP2, with a global difference for the whole simulation period of 0.9 %, indicating a compensation due to the mentioned divergences over individual locations, which are based on the specific initialization conditions.

In order to detect how these differences are translated into the RAMS environment, MON and PIC weather stations are compared. The incoming shortwave radiation simulated by EXP1 and EXP2 differs only in values lower than 0.5 %. In this regard, EXP1 produces larger outgoing longwave radiation at night over MON on 24 August, around 15 W m^{-2} . This overestimation of the outgoing longwave radiation at night produced by EXP1 in comparison to EXP2 is related to a similar pattern in the LST and ST fields. In contrast, EXP2 produces larger outgoing longwave radiation at night over PIC, higher than 10 W m^{-2} . The lower outgoing longwave radiation simulated by EXP1 in this case are as well related to the LST and ST fields. In this regard, it is shown in Fig. 12a,c that differences in the 2-m temperature vary positively with differences in LST. Besides, the EXP2 simulated specific humidity is higher than that produced by EXP1 over MON (Fig. 13), but lower over PIC, probably related to the different initial SM used in both simulations (Fig. 12b,d). Therefore, there is a cooler and in general more humid soil in the case of MON using EXP2, while the soil is warmer and drier in

EXP2 than EXP1 over PIC weather station, producing the differences observed in Fig. 9 in terms of the 2-m temperature.

From Fig. 9, it is clear that YSU PBL scheme produces higher air temperatures than those simulated by MY parameterization, as mentioned before. This is maintained both at day and nighttime. Confronting both RAMS simulations with the 2-m temperature observations on 24 August at night, there is a general trend to overestimate the observations (Fig. 9a). However, YSU scheme remains closer to the measurements, especially over MON, thus reproducing the high minimum air temperatures observed that day, higher than 25 °C (Fig. 9e). In this case, differences of 25 W m⁻² between EXP2 with EXP3 are found at night and up to 60 W m⁻² at 13 UTC in the outcoming longwave radiation term, which are translated in differences in LST of 4 °C and 11 °C, respectively, higher in the case of EXP3 (Fig. 12c). A look at the sensible heat flux shows that even though negative values are simulated by both EXP2 and EXP3 at night, differences higher than 100 W m⁻² are obtained between these two RAMS runs, especially over MON (Fig. 14d). Such a large negative sensible heat flux at night is also obtained on 27 August and lower than this on 28 August. A negative sensible heat flux implies a downward flux to the surface. Fig. 15 shows the differences between LST and 2-m temperature as simulated by EXP2 and EXP3. In some cases, the differences between EXP2 and EXP3 are reduced to values lower than 1 °C, such as over MON on 25 and 26 August, which are well reflected in terms of 2-m temperature (Fig. 9e). However, differences higher than 3 °C between these two RAMS simulations are produced over MON on 24 and 27, and still higher than 2 °C on 28 August (Fig. 15b). Differences found in Fig. 15 vary positively with the results obtained in Fig. 14 for the surface sensible energy flux. The lowest differences, around 4 °C, between LST and 2-m

temperature are obtained on 24, 27 and 28 August, under well established Western synoptic conditions, using EXP3.

In terms of the 2-m maximum temperature, both EXP1 and EXP2 produces on average an underestimation of this magnitude for the whole simulation period (Fig. 9a). This is a general trend over the study area, but these simulations produces an accurate forecast of the observed daytime air temperature over XAT and PLA on 23 and 27 August. The cold bias obtained by EXP1 and EXP2 is corrected using the YSU PBL scheme, producing skilful results, but it tends to overestimate the observations in some cases, such as PIC. The sensible heat flux does not seem to be the responsible for this higher air temperature simulated by YSU parameterization in contrast to the results obtained using MY scheme, as EXP2 produces in general higher sensible heat fluxes than EXP3. In contrast, these differences seems to be related to the lower latent heat fluxes simulated by EXP3, which are in agreement with a simulated decreased specific humidity (Fig. 13). At noon on 27 August, EXP3 reproduces the observed 6 g kg^{-1} over PIC, while EXP2 produces larger values of this magnitude. Comparing the results obtained in the specific humidity and the air temperature field (Fig. 9), there is a positive relation between these two magnitudes (Fig. 13). In general, EXP2 produces a more humid environment than EXP3, which remains drier, thus reducing the simulated latent heat flux (Fig. 14a,c). The results found in the current study in terms of the water vapor content under mesoscale circulations and sea wind flows are in agreement with those previously been found using the YSU PBL parameterization scheme within the RAMS modelling framework over inland regions of the Eastern Iberian Peninsula (Gómez et al., 2018b). Nevertheless, the current study shows an skilful agreement between the simulated and observed water vapor content under the Western synoptic advections.

Considering local and non-local schemes, the study conducted by Kotroni et al. (2011) for the simulation of a heatwave event over Greece, showed that non-local schemes were more efficient than local schemes for the simulation of the 2-m temperatures observed in the corresponding event. But, Sathyanadh et al. (2017) in their study of a dry event over the Ganges valley, found a similar behaviour for all PBL schemes tested in terms of the 2-m temperature, with an overestimation of the observations up to 5 °C. In this case, the maximum differences between observations and their modelling results was produced using a MY-related scheme. The current study shows that the YSU non-local PBL scheme produces a general trend towards warmer, drier and windier environments than the MY local scheme, which is the general behaviour of these PBL parameterizations (Kleczek et al., 2014). Besides, MY tends to produce, on average, an underestimation of the day-time 2-m temperature, while YSU shows an average overestimation of this simulated magnitude in comparison to the observations (Fig. 9).

Regarding the impact of a longer spin-up (EXP4), in general there is a trend towards lower air temperatures than those simulated when a shorter spin-up is considered (EXP2), but it depends on the simulation day and weather station location. Not in all cases the spin-up time produces an improvement in the air temperature forecast (Fig. 10 and Fig. 11). However, results over stations such as BET and PIC in general improved at nighttime when the situation is dominated by mesoscale circulations. Considering the whole simulation period, rather similar results are obtained in terms of MBE and RMSE between EXP2 and EXP4, with differences in general lower than 0.6 °C, taking into account all available data as well as when separating day from nighttime in the computation of MBE and RMSE (Fig. 16 and Fig. 17). The results are in agreement with those obtained by Kleczek et al. (2014). They found rather small

differences in most of the physical variables analysed in their study when applying a shorter spin-up time in their simulations. Differences were found in the beginning of the corresponding simulation, with stronger potential temperature.

3.2. Sensitivity to increased horizontal resolution in the initial atmospheric datasets

Using the ERA5 instead of ERA-Interim reanalysis as meteorological data for the initialization of RAMS produces in general similar results over the study area (Fig. 18 and Fig. 19), with a correlation coefficient of 1.0 for the 2-m temperature between EXP1 and EXP5 over XAT and PIC weather stations (not shown). However, if we focus on the simulation of the 2-m maximum temperature by EXP5 over XAT (Fig. 20b), differences higher than 3 °C are obtained in relation to EXP1 on 22, 24 and 26 August, better reproducing the observations. In this case, the 2-m maximum temperature simulated by EXP1 of -3, -1.5 and -4 °C is reduced to -0.7, 1.1 and -0.2 °C, for these three days, respectively. In the case of PIC weather station (Fig. 20a), the 2-m maximum temperature difference on 26 August of -1.4 °C simulated by EXP1 reverses to 1.0 °C for the EXP5 simulation. Considering this magnitude, similar divergences between the modelling results and the observations are found under the extreme heat days (23 and 27 August) both over XAT and PIC weather stations. Differences between EXP1 and EXP5 are based on the meteorological and soil state fields used for RAMS initialization. As stated before, no significant differences are in general found between these two simulations under the Western synoptic conditions. However, significant differences are obtained under mesoscale circulations, due to the development of the SBCZ. A higher horizontal resolution in the initial fields, such as that provided by ERA5, does not seem to improve the modelling results under well established Western synoptic conditions. In contrast, it improves the simulated 2-m temperature under sea breeze conditions, probably related to a better depiction of the mesoscale circulations. It

is expected that an increased horizontal resolution in the initial conditions fields could better represent these wind flows when incorporated to the mesoscale model, as shown here. Fig. 21 shows the 2-m temperature and 10-m wind field at 18 UTC on 22 August 2010. This figure clearly shows a wider extension of the simulated SBCZ in the case of RAMS EXP1 experiment in contrast to that obtained with EXP5. Results shown in Fig. 15b are supported by wind measurements over XAT weather station (not shown). The encounter of the Western synoptic and the sea breeze wind flows produces the SBCZ over the area of study, that is located far inland in the EXP1 simulation. An skilful location of this convergence area is of significant importance when forecasting the day-time air temperatures over the area of study. In the study by Gómez et al. (2016c), some difficulties were found in terms of the definition and location of this convergence area using lower resolution meteorological datasets as input data to the RAMS model when mesoscale circulations are still able to completely develop under the influence of a dominant Western synoptic advection. The current study shows that using higher resolution meteorological datasets as input data is really useful for these situations.

3.3. Sensitivity to increased horizontal resolution in the mesoscale model

Finally, the use of a finer horizontal resolution has little effect on the air temperature forecasts. Comparing the 2-m temperature simulated by EXP5 and EXP6, a correlation coefficient of 1.0 is obtained both over PIC and XAT, respectively. The outcome of the correlation test shows p-values below 0.001, showing a significant correlation greater than 99.9% confidence interval. Fig. 22a,b show the correlation of EXP6 in relation to EXP5 for PIC and XAT, respectively, located in the hotspot of the Valencia coastal region. Considering this area, an increased horizontal resolution, even though representing the surface characteristics with a greater level of detail (not shown), does not suppose any significant improvement in the simulation results. Even though it

is expected that finer horizontal resolution grids would lead to a better depiction of small-scale processes and, correspondingly, in the surface atmospheric magnitudes forecasting skilfulness, the 2-m temperature biases regarding horizontal resolution were rather negligible in the study by Kleczek et al. (2014), with a small sensitivity of the distinct physical processes and magnitudes over their study area. Additionally, using the RAMS model, Bonnardot et al. (2009) found that increasing horizontal resolution of the simulation grid did not necessary provided better results with a strong synoptic flow. But, under a weak synoptic flow with prevailing local circulations, increasing the resolution displayed relevant meteorological information for their area of study in terms of sea and slope breezes. Even though more accurate representation of the local terrain and of the lower atmosphere is obtained using higher resolution grids, slight improvement is found on the simulations accuracy (Carvalho et al., 2012). A recent study performed by Battisti et al. (2017) showed that larger horizontal resolutions has little effect on the air temperature forecasts, reducing the cold bias of the MY scheme used in their simulations only to -0.2°C , that could be due to a better representation of the given weather station by a closer grid point. Following this reasoning, Zhang et al. (2013) did not find air temperature forecast improvement due to enhanced horizontal resolution in most cases. Only better results were obtained in complex terrain using finer resolutions, as has also been recently observed by Jiménez-Estève et al. (2018). In this case, a reduced air temperature bias is obtained at nighttime due to a reduced model elevation error using higher resolution grids (500 m). However, maximum air temperature values are not improved in the finer simulations and no significant differences are found over flatter terrain. This could be compared with the results obtained in the current study (Fig. 1).

4. Summary and concluding remarks

The Valencia coastal region is prone to intense-heat events. However, due to its geophysical and climatic characteristics, the development of sea breeze conditions play a role in the mitigation of these high and extreme temperatures. Mesoscale circulations are the most predominant meteorological and atmospheric conditions over this region, but the progression of synoptic-scale Westerly advections that reach the coast is really common during the summer. Two main features arise over this coastal region under the influence of these two distinct wind flow patterns: high and extremes temperatures and the development of a convergence zone (SBCZ) due to the meet and interaction of a Western synoptic advection together with sea breeze circulations. In fact, the configuration of the SBCZ plays a key role for the location of high and extreme temperatures, leading to a modulation of these intense-heat by sea breeze flows due to the proximity of this area to the coast. Furthermore, both atmospheric patterns typically alternate in temporal scales of a few days. This study simulates a 7-days period during the summer 2010 using the RAMS model. The selected period presents intense-heat events alternated with typical atmospheric summer conditions (mesoscale circulations) over the coastal Valencia region. We have performed a number of sensitivity tests considering different modelling features, such as initialization, grid resolution, spin-up time and PBL scheme choice. Although the analysis of results is mainly focused on air temperatures, other atmospheric magnitudes, such as moisture content and wind field or surface energy fluxes, have been included in order to obtain a deeper insight of the model strengths and limitations. This study shows that, in general, the distinct experiments performed regarding initialization data and model technical features proposed using RAMS produces a similar distribution of the above mentioned SBCZ and the air temperature field. Some differences have been found comparing RAMS simulations performed using ERA-Interim and GLDAS soil state as initial and lower

boundary conditions for the model, due to the differences applied by the corresponding soil parameters used in both simulations. In this regard, divergences in the initial soil state provided by ERA-Interim and GLDAS has an impact on the sea breeze development (as in the case of BET station on 27 August), affecting the configuration of the SBCZ and the 2-m temperature distribution. However, using GLDAS soil state as initial and lower boundary conditions for RAMS does not show significant improvements in comparison to GLDAS regarding the observations, even though some differences in the simulated air temperature field are obtained between these two RAMS simulations. Similar conclusions are derived when including a longer spin-up time. The effect of a longer spin-up during the day produces in general differences lower than 1 °C. However, more differences are obtained at night-time, but with a notable variability depending on the corresponding simulation day. A longer longer spin-up time still shows some divergences regarding the location of the SBCZ. But, once again, not a general improvement is obtained confronting the simulation results with the observations.

In contrast, using higher horizontal resolution data, such as the ERA5 reanalysis dataset, as input to the mesoscale model produces a more accurate characterization of the air temperature fields due to a better capture of the dominant wind flow location. This is especially true when regional or local circulations are developed, such in the case of sea breeze conditions, but provides little effect under large synoptic-scale forcings. Thus, using this information instead of that provided by ERA-Interim is really useful to account for this issue under the influence of mesoscale circulations over this coastal region and properly reproduce the air temperature field. However, using a higher horizontal resolution in the mesoscale model does not produce significant differences with those obtained at 3 km.

The largest differences obtained in the current modelling study, besides those mentioned in the previous paragraph regarding ERA5 dataset, are related to the PBL parameterization scheme used in the RAMS simulations. In general, MY PBL scheme tends to underestimate the 2-m daytime temperature, while YSU better captures the observations. In this latter case, however, the model tends to overestimate the observations over some of the weather stations analysed. Regarding 2-m temperatures at night-time, a larger variability is obtained for both PBL schemes considering the extension of study area. MY PBL scheme shows a general skilful agreement with the observations under mesoscale circulations, while the general trend of YSU is towards a significant overestimation of the minimum air temperatures. Despite this issue, although MY is not able to capture the high minimum air temperatures, above 25 °C, observed over some weather stations on 24 and 27 July, YSU is able to accurately reproduce these observed air temperatures. According to the results produced in the current study, it is interesting to make use of the particular characteristics offered by these two local and non-local PBL schemes.

Intense-heat and extreme summer temperatures has become an important problem under a changing climate. Therefore, a correct forecast of these atmospheric and meteorological conditions is essential considering economic, social and environmental issues. The current study yields different remarkable results that should be considered for mesoscale modelling not only of such events, but also for the simulation of mesoscale circulations developed over coastal regions and for the meeting and interaction of different atmospheric patterns prone to intense and extreme heat conditions. The current study is focused on the analysis of a 7-days simulation period. Therefore, the database used here should be enlarged in the future with the aim of providing more general conclusions regarding the right choices of initial and boundary

conditions and PBL schemes. Even though these model features must be tested on other extreme temperature events before they can be used, the current results are representative of the different physical and atmospheric processes observed over the study area. Additionally, the results found are important as well given that only a few studies have previously applied distinct PBL parameterization schemes to the simulation of such events.

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Figure captions

Fig. 1. Location of the study area and orography (m), together with observational stations within the finer resolution grid. The centred rectangle area highlights the Valencia Region hotspot.

Fig. 2. Observed near-surface wind field (wind direction in °; wind speed in m s^{-1}) over PIC weather station on: 23 (a), 24 (b), 27 (c) and 26 (d) August 2010.

Fig. 3. RAMS EXP1 simulated 2-m temperature ($^{\circ}\text{C}$) and 10-m wind speed (m s^{-1}) at 15 UTC on 26 August 2010 (a). EXP1-EXP2 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP2 simulated 10-m wind speed (m s^{-1}) (b), EXP2-EXP3 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP3 simulated 10-m wind speed (m s^{-1}) (c), and EXP2-EXP4 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP4 simulated 10-m wind speed (m s^{-1}) (d) at 15 UTC on 26 August 2010.

Fig. 4. Same as Fig. 3, but on 23 August 2010.

Fig. 5. Same as Fig. 3, but on 27 August 2010.

Fig. 6. RAMS EXP1 simulated 2-m temperature ($^{\circ}\text{C}$) and 10-m wind speed (m s^{-1}) at 06 UTC on 26 August 2010 (a). EXP1-EXP2 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP2 simulated 10-m wind speed (m s^{-1}) (b), EXP2-EXP3 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP3 simulated 10-m wind speed (m s^{-1}) (c), and EXP2-EXP4 simulated 2-m temperature difference ($^{\circ}\text{C}$) and EXP4 simulated 10-m wind speed (m s^{-1}) (d) at 06 UTC on 26 August 2010.

Fig. 7. Same as Fig. 6, but on 23 August 2010.

Fig. 8. Same as Fig. 6, but on 27 August 2010.

Fig. 9. Observed (black) vs. RAMS EXP1 (blue), EXP2 (purple) and EXP3 (green) simulated 2-m temperature ($^{\circ}\text{C}$) time series over PIC (b), XAT (c), PLA(d), MON (e)

and ALM(f) stations, as well as the averaged observed and simulated 2-m temperatures ($^{\circ}\text{C}$), considering all observational stations (a).

Fig. 10. Difference between the simulated and observed minimum 2-m air temperature ($^{\circ}\text{C}$), for the RAMS sensitivity tests EXP1, EXP2, EXP3 and EXP4 over the distinct observational weather stations and different days within the corresponding simulation period: 23, 24, 26, 27 and 28 August 2010.

Fig. 11. Same as Fig. 10, but for the maximum 2-m air temperature ($^{\circ}\text{C}$).

Fig. 12. RAMS EXP1 (blue), EXP2 (purple) and EXP3 (green) simulated skin temperature ($^{\circ}\text{C}$) time series over PIC (a) and MON (c). Soil moisture content of the uppermost soil layer ($\text{m}^3 \text{ m}^{-3}$) for the same weather stations: PIC (b) and MON (d).

Fig. 13. Observed (black) vs. RAMS EXP1 (blue), EXP2 (purple) and EXP3 (green) simulated 2-m specific humidity (g kg^{-1}) time series over PIC (a) and MON (b).

Fig. 14. RAMS EXP2 (purple) and EXP3 (green) simulated surface latent heat flux (W m^{-2}) time series over PIC (a) and MON (c). Simulated surface sensible heat flux (W m^{-2}) for the same weather stations: PIC (b) and MON (d).

Fig. 15. RAMS EXP2 (purple) and EXP3 (green) simulated skin and 2-m temperatures difference ($^{\circ}\text{C}$) time series over PIC (a) and MON (b).

Fig. 16. MBE for the simulated 2-m air temperature ($^{\circ}\text{C}$) over the distinct weather stations and considering the RAMS sensitivity tests EXP1, EXP2, EXP3 and EXP4. The results are presented for both daytime and night-time, as well as considering the whole simulation period.

Fig. 17. Same as Fig. 16, but considering the RMSE statistical score ($^{\circ}\text{C}$).

Fig. 18. MBE for the simulated 2-m air temperature ($^{\circ}\text{C}$) considering the RAMS sensitivity tests EXP1, EXP5 and EXP6 over the observational stations located within

the Valencia Region hotspot area: BET, PIC and XAT. The results are presented for both daytime and night-time, as well as considering the whole simulation period.

Fig. 19. Same as Fig. 18, but considering the RMSE statistical score (°C).

Fig. 20. RAMS EXP1 (blue) and EXP5 (red) simulated 2-m temperature (°C) time series over PIC (a) and XAT (b) weather stations, considering the complete simulation period.

Fig. 21. RAMS 2-m temperature (°C) and wind field at 18 UTC on 22 August 2010, as simulated by EXP1 (a) and EXP5 (b) experiments.

Fig. 22. Comparison of RAMS EXP6 with EXP5 simulation for the 2-m temperature (°C) over PIC (c) and BON (d) weather stations, considering the complete simulation period.

Table 1. Sensitivity experiments performed using the RAMS model and the corresponding settings in terms of initialization features.

Experiments	Meteorological Input Data	Soil Temperature (D1, D2, D3)	Soil Moisture (D1, D2, D3)	PBL Scheme	Finer Grid Resolution	Spin-up time
EXP1	ERA-Interim	ERA-Interim	HOMO	MY	3 km	12 h
EXP2	ERA-Interim	GLDAS	GLDAS	MY	3 km	12 h
EXP3	ERA-Interim	GLDAS	GLDAS	YSU	3 km	12 h
EXP4	ERA-Interim	GLDAS	GLDAS	MY	3 km	24 h
EXP5	ERA5	ERA5	HOMO	MY	3 km	12 h
EXP6	ERA5	ERA5	HOMO	MY	750 m	12 h

Highlights

- ERA-Interim and GLDAS initial soil state impact 2-m temperature and wind field

- ERA5 initial conditions improve mesoscale simulated patterns compared to ERA-Interim
- A longer spin-up produces in general differences lower than 1 °C during the day
- Higher horizontal resolution in the mesoscale model does not improve results
- YSU and MY produce very different results for heat extreme events

Figure 1

(a)

(b)

(c)

(d)

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

EXP1 EXP2 EXP3 EXP4

Figure 16

EXP1 EXP2 EXP3 EXP4

Figure 17

EXP1 EXP5 EXP6

Figure 18

EXP1 EXP5 EXP6

Figure 19

Figure 20

Figure 21

(a)

PIC

(b)

XAT

Figure 22